ENRICHED POTATO CHIPS WITH PHENOLIC COMPOUND OF RED BEETROOT

A Thesis

by

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ABSTRACT

There has been an interest in increasing the functionality of snack foods in the USA. Beetroot contain a high level of antioxidants. In this study, vacuum impregnation (VI) was used to impregnate a beetroot solution into potato slices to increase their health benefits while maintaining the same quality attributes of potato chips after frying.

Potato slices were pre-treated with different concentrations of beetroot solutions (3, 5, and 7% w/w), vacuum pressures (300, 450, 600 mmHg), and vacuum and restoration times (5, 10, 15 minutes). Potato slices were evaluated in terms of impregnated liquid (IL), moisture content (MC), and total phenolic content (TPC). The optimum VI condition was 7% solution, 600 mm-Hg vacuum pressure for 10 min vacuum time and 60 min for the restoration time.

Kinetic studies were performed to evaluate the effect of the process on moisture content (MC), oil content (OC), and total phenolic content (TPC) of enriched vacuum fried potato chips at different temperatures (110, 120, and 140°C).

The final OC of enriched vacuum fried chips was 9.31±0.35, 11.96±0.78, and 12.12±0.81 % d.b. for frying temperatures of 110, 120, and 140°C, respectively. The higher the oil temperature, the higher the OC of the chips.

The maximum TPC was 27% higher than the initial TPC of the chips fried at 140°C. The chips fried at 120°C and 110°C had a maximum TPC of only 20% and 11% higher than the initial TPC, respectively. The VI treatment with red beetroot extract improved the process by making potato chips with the same or better TPC than the raw material. The higher the temperature, the better the TPC in vacuum fried chips.

In this study, the VI potato slices fried at different frying methods (vacuum (VF) at 140°C, dual-stage (DSF) at 140°C, and traditional frying (TF) at 165°C) were evaluated in terms of MC, OC, TPC, bulk and true density, porosity, diameter shrinkage, thickness expansion texture, color, and sensory analysis.

The chips fried under TF had a 19% reduction in TPC after frying, while chips fried under VF and DSF had a 38% and 23% increase in TPC after frying, respectively. The VF and DSF methods contributed to the release of bound phenolic acids in the potato. The TPC released from the potato during VF and DSF might have been more stable due to the lower temperature, pressure, and frying times compared to the TF.

Color a* (redness) was lower for potato chips fried under TF than the VI potato slices and chips fried under the other frying methods. The chips fried under TF lost the red pigment of the impregnated red beetroot solution, while the chips fried under VF and DSF maintained their red color. The color b* (yellowness) of chips fried under the DFS and TF were significantly higher ($p < 0.05$) than chips fried under VF. The texture of the chips was not significantly different ($p > 0.05$) among the different frying methods.

All potato chips fried under different frying methods were acceptable by the consumer panelists. However, potato chips fried under VF and DSF were more acceptable than the potato chips fried under TF.

In conclusion, VF at 140°C for 120 sec after enriched the potato slices with phenolic content by using VI is an alternative technology to produce healthy functional snacks with desired quality attributes.

DEDICATION

To my parents, Lulwah Albadi and Abdulrahman Almohaimeed.
To my sister, Sahar Almohaimeed.

Without you it would not be possible to be the person I am today.
I am grateful to have you, and I will keep trying every day to be a better daughter and sister.
I love you all.

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CHAPTER I

INTRODUCTION

Clinical and epidemiological studies have shown that oxidative stress causes a number of health issues such as cardiovascular diseases, cancer and neurological decline (Wootton-Beard and Ryan, 2011). Consumption of fruits and vegetables rich in antioxidant compounds may help to protect the body from oxidative stress (Ravichandran et al., 2012; Shahidi, 2004). Therefore, consumers and food industries have been interested in functional foods.

The United States Department of Agriculture defines functional food as foods or food ingredients designed to reduce the risk of chronic disease by providing additional physiological benefits beyond basic nutritional functions. It can be consumed as part of a regular diet, and it is similar in appearance to conservative food.

In recent years, red beetroot has attracted great attention as a health promoting functional food (Clifford et al., 2015). Beetroot extract contains a high level of antioxidant capacity in addition to many other health promoting compounds such as potassium, calcium, magnesium, sodium, folic acid, B_6, iron, zinc, phosphorus, niacin, biotin, and soluble fiber (Raupp et al., 2011; Wootton-Beard and Ryan, 2011).

Although beetroot products are a rich source of phenols and nitrate, most of these products are not meeting consumer demand for taste and texture. In this study, potato chips impregnated with beet root extract will offer to consumers the natural bioactive compounds of beetroot with similar taste and texture of most popular potato chip products. It is expected that this product will help to increase the consumption of phenol rich products particularly among children and young adults (Thakur and Gupta, 2006; Wootton-Beard and Ryan, 2011).

Potato chips are the most popular fried snacks in the US (Kita et al., 2015). In 2016, potato chips represented 25% of total sales of snacks in the US Market (Statista, 2017). Recently, many food industries have been looking for new techniques to make snacks healthier and richer with functional and antioxidant properties.

The vacuum impregnation technique has been used to enhance porous foods with liquid functional ingredients (Fito et al., 2001; Lin et al., 2006; Xie and Zhao, 2003). This is a useful technique to introduce antioxidant properties of beetroot extract directly into the porous structure of the potato slice matrix (Laurindo et al., 2007). This method changes the physical and chemical properties of the raw product. It is used to improve the product's nutritional value and the structure of some foods (Fito et al., 2001).

The vacuum impregnation treatment is a method of exchanging the internal gas and part or all of the native solution in the open pores of the food (vacuum step) with an external solution (impregnation step) (Sevimli and Moreira, 2013). This technique implies a fast introduction of an external liquid into a porous food material (Carciofi et al., 2012; Krasaekoopt and Suthanwong, 2008).

Vacuum frying is a technology for producing high quality snacks by preserving the original attributes of the texture, flavor, and taste (Da Silva and Moreira, 2008; Garayo and Moreira, 2002; Mariscal and Bouchon, 2008). It is a process of frying foods below atmospheric pressure and at lower oil temperature (Moreira et al., 2009; Teruel et al., 2014; Warning et al., 2012). This technology offers several advantages over atmospheric frying (traditional frying) such as preservation of natural color and flavors due to the low temperature and the absence of oxygen during the process (Teruel et al., 2014), enhanced organoleptic quality (Yagua and Moreira, 2011), lowering acrylamide formation (Granda et al., 2004), reducing oil content, and reducing adverse effects on oil quality (Garayo and Moreira, 2002). Furthermore, vacuum frying also preserves the nutritional components of the product (Da Silva and Moreira, 2008; Dueik et al., 2012; Teruel et al., 2014).

Potato chips impregnated with red beetroot extract will offer an opportunity for functional snack to be consumed by the general public and may participate positively to increase the consumption of phenol rich produces (Wootton-Beard and Ryan, 2011).

The aim of this research was to determine the feasibility of using a vacuum impregnation technology to enhance the functionality of the potato slices while preserving the original attributes of the potato chips by using vacuum frying technology.

The specific objectives of this study were:

1. To enrich potato slices with phenolic compounds of red beetroot solution by using vacuum impregnation technology.
2. To evaluate the effect of vacuum impregnated potato slices with different concentration of beetroot solutions on their impregnated phenolic compounds.
3. To identify the best vacuum impregnation pressure-restoration time combination to maintain the impregnated phenolic compound.

4. To perform kinetic studies of impregnated potato chips vacuum fried at different oil temperatures.
5. To compare the quality of impregnated potato chips fried under vacuum, dual stage, and traditional frying methods.
6. To characterize the final product quality attributes of impregnated potato chips fried at different frying methods such as moisture content, oil content, color, texture, bulk density, porosity, expansion, shrinkage, and impregnated phenolic compound retention.

CHAPTER II

LITERATURE REVIEW

2.1. Red beetroot

Red beetroot (Beta vulgaris rubra) is a rich source of carbohydrates (main sugar) and red pigment betalains. Betalains are used as additives in the food applications because of their natural colorant characteristics, high solubility in water, and absence of toxicity. Additionally, red beetroot contain health-promoting components such as phenolic (phenolic acids, phenolic acid esters, and flavonoids), nitrate, folic acid, potassium, magnesium, iron, zinc, calcium, phosphorus, sodium, niacin, biotin, B6 and soluble fiber (Raupp et al., 2011; Thakur and Gupta, 2006) (Figure 2.1).

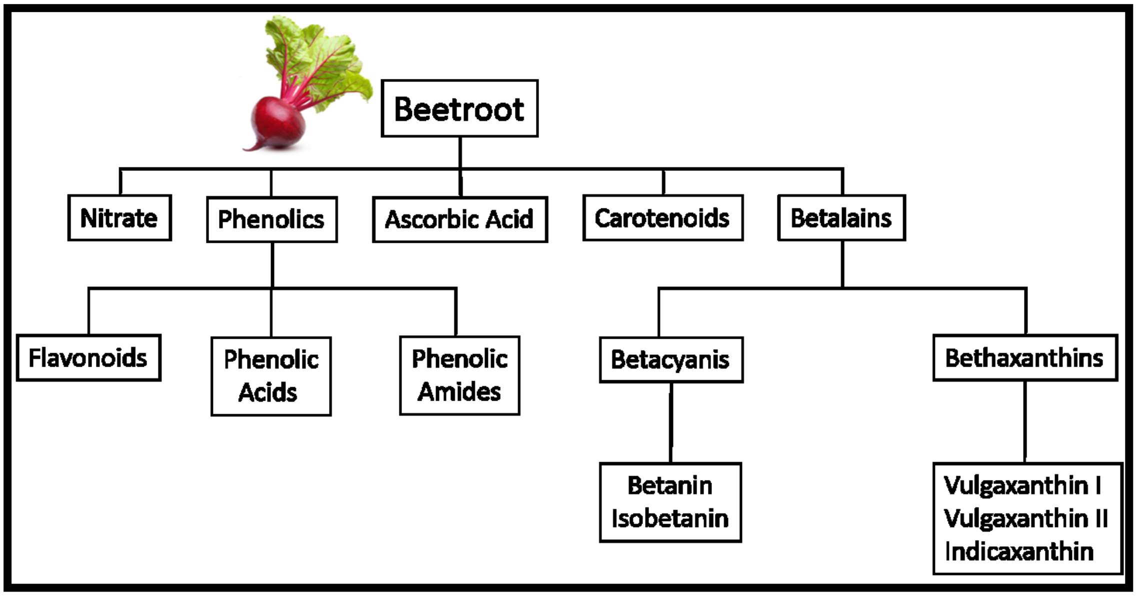

Figure 2.1. Overview of potentially bioactive compounds in beetroot (Adapted from Clifford et al., 2015)

Betalains are composed of two subclasses: red-violet pigments, which called betacyanins and yellow-orange pigments which named betaxanthins (Delgado-Vargas et al., 2000; Herbach et al., 2004). Betalains are mainly used for coloring food products (Cai et al., 2001). Some of the Betalains have antimicrobial and antiviral effects and it can prevent the cell growth of human tumor cells (Reddy et al., 2005; Strack et al., 2003).

The health benefits of well-documented diet rich in fruit and vegetable led to a growing interest in functional foods and their application in health and disease. In recent years, root beet has drawn great attention as a health promoting functional food. It is grown in many countries around the world, it consumes as a part of the normal diet, however, it mainly used in the food industry as a food coloring agent named E-162.

Beetroot is a rich source of number of phenolic compounds such as 4-hydroxy benzoic acid, cinnamic acid, vanillic, chlorogenic, trans ferulic acid, epicatechin, rutin and caffeic acid (Clifford et al., 2015; Georgiev et al., 2010; Ravichandran et al., 2012; Wootton-Beard and Ryan, 2011). The phenolic compositions of red beetroot have been studied in detail by (Kujala et al., 2002; Kujala, 2000). Shehata et al. (2014) found that the total phenolic content in red beetroot range from (236.21 to 333.50 mg GAE / 100g FW). Also, in another study found the total phenolic content of beetroots is (257.0 mg GAE/100g) (Ereifej et al., 2015).

Additionally, red beetroot is a naturally rich source of nitrate. Nitrate ions in beetroot range from several hundred to several thousand mg/kg of fresh weight, depending on the agricultural and environmental, storage, and processing conditions

(Walkowiak-Tomczak, 2012). Dietary nitrate has a beneficial effect on human health, including effect on the functioning of the brain in elderly people, reduction of blood pressure, and physical fitness enhancement (Bondonno et al., 2015; Walkowiak-Tomczak, 2012).

Based on clinical studies, increased nitrate levels have positive effects on muscle efficiency, fatigue resistance, and improvements in time-trial endurance tests of hobby athletes (Bailey et al., 2009; Cermak et al., 2012). Therefore, several beetroot products available on the market target mainly sportspersons, especially those in endurance sports. Beetroot juices and powders are advertised as performance-enhancing nutrition supplements. Moreover, nitrate has been recommended as a nutritional agent for the prevention and treatment of hypertension and cardiovascular diseases (Bailey et al., 2009; Kapil et al., 2015; Webb et al., 2008).

Red beet contains phenolic compounds that decrease oxidative damage of lipids and enhance antioxidant status in humans. Many studies have been reported that phenolic acids as antibacterial, antiviral, anti-carcinogenic, and anti-inflammatory (Duthie et al., 2000). Phenolic acids are known to be helpful in controlling inflammation, and improving the immune system and blood circulation, which produce significant anti-aging benefits. Phenolic acids can also be easily affected by oxidation and degradation, exposure to light, oxygen, heat, and food processing conditions (Han and Koh, 2011; Ravichandran et al., 2012).

2.2 Potatoes

Potatoes (*Solanum tuberosum*) are the fourth most important food crop in the world and the most important vegetable crop in the United States. The fifth largest producer of potatoes in the world is the United States (FAO, 2008). Almost 60 percent of the potato sales are to potato chips, French fries, dehydrated potatoes, and other potato products (NASS, 2013). In 2010, 81 plants processed potato chips only in the U.S (NASS, 2011).

Potatoes composition can be affected by several factors like growth location, maturity at harvest, and storage history. Potatoes are composed of two major components; water with an average of 77.5% and starch with an average of 19.4%. The major components of starch are amylopectin (79-85%) and amylose (15-21%) (Yagua Olivares, 2010). The average values of the major components of potatoes are shown in Table 2.1.

Table 2.1. Chemical composition of potato tubers (Adapted from Smith, 1977)

Component	Average Value [kg/kg potato]	Range [kg/kg potato]
Water	0.775	0.632-0.869
Total solids	0.225	0.131-0.368
Carbohydrate	0.194	0.133-0.305
Fiber	0.006	0.0017-0.0348
Protein	0.020	0.007-0.046
Fat	0.001	0.0002-0.0096
Ash	0.010	0.0044-0.019

Potato is a source of several bioactive compounds such as vitamins, minerals, amino acids, phenolic compounds, starch, and dietary fiber. Phenolic compounds in potato plant act as a protective response from fungi, viruses, bacteria, and insects. Many studies showed that potato compounds provide a health-improving effect in humans. However, the potato processing in the food industry exhibits it to different processing conditions that can change its phenolic content. (Akyol et al., 2016).

Although potatoes are lower in phenolic content than some of other plants, they may promote higher phenolic intake due to the higher consumption rates of potatoes than other plants. Potatoes contain a wide variety of phenolic compounds present in the peel and flesh; such as phenolic acids, stilbenes, lignans, and flavonoids including flavonols, flavanols, and anthocyanins.

Potatoes include a common phenolic acids such as caffeic acid, cinnamic acid, p-coumaric acid, ferulic acid, sinapic acid, and chlorogenic acid (Friedman, 1997). The dominant phenolic acid in potatoes is chlorogenic acid with 80% of the total (Brown, 2005).

In potato, the phenolic compounds are distributed between the peel and the flesh; but the peel presents the highest amounts (Akyol et al., 2016). Therefore, to compensate for the loss of phenols content during the peeling process to make potato chips, in this study, potato slices had been enriched with beetroot solution, which has a high amount of phenolic content.

2.3 Vacuum impregnation

Recently, the food industry is looking for new techniques to make snacks healthier and rich with functional and antioxidant properties. Vacuum impregnation (VI) is a useful technique that has been used to introduce external liquids rapidly in the porous structures in a controlled process (Fito et al., 2001; Lin et al., 2006; Xie and Zhao, 2003).

Although vacuum impregnation was introduced for the first time at least 20 years ago, it may be still considered as an emerging technique with high possible applications (Derossi et al., 2012). Many studies developed fruit and vegetables with functional properties by using vacuum impregnation treatment (Fito et al., 2001).

Some of the advantages of using VI are: fast process (usually in few minutes), low energy costs, performed at room temperature, and the external solution may be reused many times (Derossi et al., 2012). Therefore, in this study vacuum impregnation treatment was used to impregnate beetroot solution into the potato slices to take advantage of the total phenolic content of beetroot by maintaining the same quality attributes of traditional potato chips after frying.

During vacuum impregnation steps, three main phenomena happens: the evacuation of native liquid and gases from the pores, the introduce of external solution inside capillaries, and deformation– relaxation of the solid matrix. VI is a very complex treatment, several external and internal factors have been reported that affects the VI results. Factors such as the size and shape of samples, tissue structure (pores diameter and size distribution), the tortuosity of internal pathways, the presence of gas and/or liquid inside capillaries, viscoelastic property of the product (viscosity of the external solution and viscoelastic properties of biological tissues), and solution temperatures (Derossi et al., 2012; Sasireka and Ganapathy, 2016).

A study of the effect of two fruit sizes (3.5×2.5×1.0 and 1.2×1.2×0.8 cm3) of cantaloupe and apple and the effect of processing time (impregnation and relaxation times; both for 10 and 20 min) found that fruit size and processing time significantly affects the mass fraction of fruit occupied by impregnation liquid. The vacuum impregnation is affected by the surface area of the fruit and long processing times, which allowed for significant liquid impregnation into the fruit (Phianmongkol et al., 2015). Also, Gras et al. (2003) studied the utilization of VI to fortify carrot, eggplant and oyster mushroom with calcium salts. The authors found that due to the high porosity of eggplants and oyster mushroom, they were more suitable to VI than carrots.

Paes et al. (2008) studied the effect of vacuum impregnation temperature on the mechanical properties and osmotic dehydration parameters of apples. They found that by using temperatures in the range of 10 to 50 °C, and a sucrose solution of 50 Brix, the temperature had a significant effect on the water loss, which was much higher than for solids gain in apple samples.

VI has shown to be very effective in a number of applications in food processing such as dehydration (osmotic dehydration, acidification, brining of fish and meat products), pre-treatment methods (for drying, freezing, frying, and improving the quality of the final product). VI has been used to provide fresh fortified food (FFF), to enrich food with nutritional and/or functional ingredients, and to extend foods shelf life.

Furthermore, it used to reduce the freezing damage, oxidative reaction, and browning (Derossi et al., 2012).

Xie and Zhao (2003) evaluated the use of calcium and zinc to fortify fresh-cut apples using VI processing. Results show that 15-20% of the daily reference intake (DRI) of calcium and above 40% of the DRI of zinc could be obtained from 200 g of impregnated apple. According to them, vacuum impregnation has huge potential to modify the mineral contents in fresh fruits and vegetables. VI is an effective method to produce fruit or vegetable products with health-promoting properties as displayed in (Table 2.2).

Table 2.2. Examples of applications of vacuum impregnation to modify health-promoting properties of fruit and vegetable products (Adapted from Radziejewska-Kubzdela et al., 2014)

Raw Material	**Geometry**	**Composition of Vacuum Impregnation Solutions**	**Process Parameters**	**Effect**	**References**
Apple	Cylinder	Microorganisms Saccharomyces cerevisiae added to apple juice, Saccharomyces cerevisiae and Lactobacillus casei added to milk	p_1 5 kPa t_1 10 min t_2 10 min	Over 106 CFU/g Lactobacillus casei in air dried at 40 °C	(Gras et al., 2003)
Eggplant fruits and orange peel	Not mentioned	Calcium and iron	p_1 5 kPa t_1 15 min t_2 15 min	Fortified samples to 25% of (RDI)	(Fito et al., 2001)
iceberg lettuce leaves	Not mentioned	Calcium lactogluconate (5.4 g Ca/L of water) with sucrose aqueous solution of the same aw as lettuce leaves	p_1 50 kPa t_1 10 min t_2 10 min	Increased the total content of impregnated iceberg lettuce leaves to 169 mg Ca per 250 g	(Gras et al., 2011)

Table 2.2. Continued

Raw Material	**Geometry**	**Composition of Vacuum Impregnation Solutions**	**Process Parameters**	**Effect**	**References**
fresh-cut pears	Not mentioned	20% diluted wildflower honey	p_1 10 kPa t_1 15 min t_2 30 min	Vitamin E content increased 80 to 100 times	(Lin et al., 2006)
whole potatoes	whole	10% ascorbic acid solution	p_1 9.33 kPa t_1 0–60 min t_2 3 h	Ascorbic acid content of whole potatoes increased ten times (150 mg/100 g fresh weight)	(Hironaka et al., 2011)
endive, cauliflower, broccoli, carrots	Not mentioned	Aqueous sucrose solutions of the same a_W as each of the four raw materials; Aloe vera aqueous solution with an addition of 5 and 30 g/L of aloe vera powder	p_1 50 kPa t_1 10 min t_2 10 min	Enhance broccoli with up to 7 g of Aloe vera in 100 g (dry matter), 4 g in cauliflower and endive, and 3 g in carrots	(Sanzana et al., 2011)

p_1=vacuum pressure in the VI process, t_1=time in reduced pressure, t_2=time in atmospheric pressure.

2.4 Deep-fat frying

Deep-fat frying can be defined as a cooking method by submerging the foods in edible oil at above of boiling water temperature (Farkas, 1994). It is one of oldest cooking methods and it's still as one of the most common food processing methods, due to the unique flavor and texture combination that imparted to the food (Varela, 1988). Deep-fat frying can be performed using three different pressure conditions: atmospheric pressure (traditional frying), high pressure, and low pressure (vacuum frying) (Moreira et al., 1999).

Traditional frying, deep-fat frying under atmospheric pressure, is performed usually at temperatures between 150 and 190°C. The water at the food surface evaporates during frying due to the high temperatures of the frying oil. That led to absorbed the oil by the food to replace part of the evaporated water (Mariscal and Bouchon, 2008).

The high-pressure frying is performed when the pressure is increased in the frying vessel due to the vapor released from the food products inside a closed vessel (Erdogdu and Dejmek, 2010). High-pressure frying method is used especially in the fried chicken industries to reduce frying time, to uniform the product color, and maintain higher moisture content (Das et al., 2013).

A disadvantage of high-pressure frying method is that oil degradation is faster than the traditional frying method because the vapor released from the food remains inside the fryer vessel, thus increasing the buildup of free fatty acids (Garayo and Moreira, 2002).

2.4.1 Vacuum frying

Vacuum frying has been an alternative technology for producing snacks with preserved nutritional compounds and reduced oil content by using lower processing pressure and temperature (Da Silva and Moreira, 2008; Dueik et al., 2012; Teruel et al., 2014). Figure 2.2 shows a flow diagram of the vacuum frying process. Vacuum frying process consists of heating the food under reduced pressure with minimum exposure to oxygen in a closed system. That allows to reduce the boiling point of frying oil and the moisture evaporation point of the food.

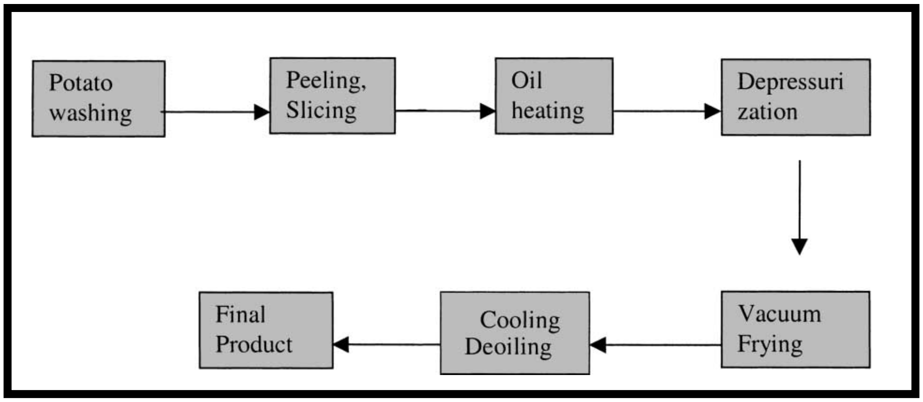

Figure 2.2. Flow diagram of the vacuum frying process (Adapted from Garayo and Moreira, 2002)

This technology offers more advantages over atmospheric frying such as preservation of natural color and flavors (Teruel et al., 2014), enhanced organoleptic quality (Yagua and Moreira, 2011), lowering acrylamide formation (Granda et al., 2004) and reducing adverse effects on oil quality (Garayo and Moreira, 2002).

Vacuum frying technology has been applied to process high-quality vegetables and fruit-based snacks (Table 2.3) show examples of applications of vacuum frying food products from 2011 to 2015. In number of studies this technology showed products with high-quality characteristics such as blue and sweet potatoes, green beans, and mangoes (Da Silva and Moreira, 2008), pineapples (Perez-Tinoco et al., 2008), carrot (Fan et al., 2005), and apples (Shyu and Hwang, 2001). Also, several of the Asian companies are already used vacuum frying processes for fruits, vegetables, fish, and shellfish (Moreira et al., 2009; Warning et al., 2012).

Nunes and Moreira (2009) developed high-quality mango chips using vacuum frying. Results showed that mango chips under vacuum frying had more carotenoid retention (up to 65%) than those under atmospheric frying (32%). In another study of the effects of vacuum frying in foods, potato chips showed better color and texture compared with potato chips under atmospheric pressure. Also, the potatoes under vacuum frying were lower on oil content compared with atmospheric ones (Garayo and Moreira, 2002). Furthermore, Granda et al. (2004) reported that vacuum frying reduced acrylamide formation in potato chips by 94% compared with traditional frying.

Table 2.3. Examples of applications of vacuum frying food products from 2011 to 2015 (Adapted from Diamante et al., 2015)

Product	**Temp. [^{o}C]**	**Time [min])**	**Pressure [kPa]**	**Centrifuged**	**Reference**
Apple	98	4.5	6.48	NO	(Dueik and Bouchon, 2011)
Apricot	100	72.5	2.3	NO	(Diamante et al., 2012b, 2012c)
Banana	89	90	2.66	5 minutes at 140 or 280 rpm	(Sothornvit, 2011)
Banana	110	20	8.0	Not mentioned	(Yamsaengsung et al., 2011)
Carrot	98	5	6.48	NO	(Dueik and Bouchon, 2011)
Chinese Purple Yam	100	15	90	5 minutes at 450 rpm	(Fang et al., 2011)
Grass Carp	100-110	15	80	2 minutes at 300 rpm	(Aachary et al., 2014)
Gold Kiwifruit	80	50	2.3	NO	(Diamante et al., 2011)
Gold Kiwifruit	72-76	35-65	2.3	NO	(Diamante et al., 2012a, 2013)
Mushrooms	90	12.5	4.25	10 minutes at 400 rpm	(Tarzi et al., 2011)
Potato	98	6.5	6.48	NO	(Dueik and Bouchon, 2011)
Sweet Potato	90	30	20	400 rpm, time not mentioned	(Yang et al., 2012)
Sweet Potato	130	2.33	1.33	Not mentioned	(Ravli et al., 2013)
Wheat-based Snack	141	4	33.21	NO	(Sobukola et al., 2013)

2.5 Product quality attributes (PQA)

2.5.1 Oil content

One of the most significant product quality parameters for fried foods is oil content. Reduce oil absorption while keeping the texture and color of fried foods is one of the main goals of fried foods studies and industries.

The total oil absorbed into fried foods are located in two main locations. The first one, called internal oil content, is located at the core of the food product. This oil is absorbed during frying period. The second location is at the product's surface, which absorbed into the product during the cooling period.

Moreira et al. (1997) measured the oil content of the tortilla chips in the core (internal oil) and the surface to determine the oil absorption during frying and cooling period. They observed that 20% of the total oil content was in the core (internal oil) during frying time and 80% was surface oil absorbed during the cooling period. Moreira et al. (2009) measured the oil content in the internal and surface of vacuum frying potato chips and found that 14% of the total oil content was absorbed during frying time and 86% was absorbed during cooling. They used a de-oiling system (centrifuging system) applied directly after frying and before the product its cool down to reduce oil absorption of fried foods.

Moreira et al. (2009); Ravli et al. (2013); Yagua and Moreira (2011) have used a de-oiling system after frying and before the pressurization step to produce low-fat snack foods. According to Moreira et al. (2009); Yagua and Moreira (2011), applying the de-oiled system before the pressurization step reduced the surface oil of potato chips up to

(87-90%). This indicates that the de-oiling method is important to produce high quality and healthiest snacks in vacuum frying system.

There are number of methods to determine oil content in fried foods; extraction, hydraulic press, refractometric, and NIR spectroscopy (Moreira et al., 1999). The most used methods to determine oil content is extraction methods. The Soxhlet method is considered a faster method for extracting oil from the foods using light petroleum ether (Granda, 2006).

The Soxhlet extractor works by placing the solid sample inside a thimble. Then boiling a solvent (petroleum ether). The solvent vapor moves up to a distillation arm, then floods into the chamber that has the thimble. That allows the oil to dissolve in the solvent. The thimble ensures that solvent does not transport any solid material to the collecting cup. This cycle allows repeating many times, over hours or days. The advantage of this system is recycling a small amount of solvent to dissolve a larger amount of material (Granda, 2006; Nunes and Moreira, 2009).

2.5.2 Degree of shrinkage and thickness expansion

The degree of diameter shrinkage and thickness expansion are used to measure the changes in food diameter and thickness during frying. Shrinkage and expansion are defined as the ratio between the dimension of the sample before and after drying (Yan et al., 2007). It affects the product appearance and the physical properties of food materials such as density and porosity (Taiwo et al., 2007).

Shrinkage of foods materials during frying takes place together with moisture diffusion, which can affect the rate of moisture removal. The shrinkage of foods materials is due to the loss of water and air-filled pores (Wang and Brennan, 1995). Garayo and Moreira (2002) observed that frying at higher temperatures resulted in a greater rate of volume change at the same frying period, but potato chips processed at higher oil temperature result in a lower final shrinkage in volume. This behavior is because the surface of the potato becomes rigid more rapidly at a higher temperature which producing increased resistance to volume change. They found that vacuum fried chips have less expansion and several small bubbles than atmospheric fried chips. The bubble formation at the surface of the fried chips depends on gas expansion inside the pores and the volume shrinkage results from water transfer within the product.

Moreira et al. (2009) found that as the time and temperature of frying increase, the diameter shrinkage increases by 10% at 120°C.

2.5.3 True density

True density is the weight of the material per unit of solid (kg/m^3), without counting the air volume of open and closed pores (Kawas and Moreira, 2001). True density is usually measured by a gas pycnometer. It uses gas displacement (usually helium) that is capable of penetrating all open pores up to the amount of the molecule of the gas used.

Several studies have shown that during traditional frying there is slightly increased in solid density for tortilla chips (Kawas and Moreira, 2001). On another hand, Moreira et al. (2009) found that during vacuum frying there is insignificantly decrease in the solid density of potato chips.

2.5.4 Bulk density

Bulk density is the mass per unit bulk volume (kg/m^3), so it considers both the solids and the pore space. Bulk density in foods is difficult to calculate by its own geometrical characteristics due to their irregular shapes (Kawas and Moreira, 2001). Bulk density of irregularly shaped materials can be determined by volumetric displacement of glass beads, and by using water-ethanol mixture displacement techniques or a liquid displacement techniques with toluene (Da Silva and Moreira, 2008; Nunes and Moreira, 2009).

Kawas and Moreira (2001) determined the bulk density in tortilla chips during frying using the liquid displacement technique with toluene. It was found that the chips become more porous by the end of frying due to the decrease in bulk density. The bulk density decreased from 880 to 580 kg/m^3 after 60 s of frying.

2.5.5 Color

Food color is the major food attribute that influences customer's acceptability. It is the first attribute to be evaluated by consumers (Fennema, 1996). The color of processed food products like potato chips can be affected by several factors, such as non-enzymatic browning reactions that is mainly caused by thermal treatments (Rodriguez-Saona and Wrolstad, 1997). The most important ones are the Maillard reaction that is caused by a reducing sugars and an amino acids, caramelization, and ascorbic acid browning processes (Fennema, 1996; Ibarz et al., 1999).

Marquez and Anon (1986) foud that reducing sugars and amino acids during potato frying participated in the color development. Also, frying temperature and thickness in fried foods can affect the color of the final product (Krokida et al., 2001).

Using vacuum frying, which uses lower temperatures with minimal exposure to oxygen, can decrease this effect. Garayo and Moreira (2002) found that vacuum frying potato chips is significantly lighter than potato chips fried under atmospheric pressure.

To determine color in chips there are several methods. Spectrocolorimeter has been the main method to measure potato chips (Segnini et al., 2004). Also, the color of potato chips can be determined by the subjective method as the Snack Food Association Potato Chip Color Chart the chips are rated on a scale of 1 to 5, which 1 being a light golden color, and 5 being very dark color (Sowokinos et al., 1987). Video Image Analysis has also been used to measure the color of potato chips (Granda, 2006; Scanlon et al., 1994; Segnini and Dejmek, 1999).

2.5.6 Texture

One of the most significant quality attributes in chips and in food products in general is texture because of its major impact to the overall quality and suitability (Granda et al., 2004; Kayacier and Singh, 2003). There are several factors that affect the texture of potato chips, such as type of raw material, thickness of the slices, pre-treatment technique, and frying temperature (Lisinska and Leszczynski, 1989).

Texture can be determined by using two methods: instrumental analysis and sensory evaluation (Steffe, 1996). Using instrumental analysis to determine texture is more accurate, easer to perform, simpler to reproduce, and less time consuming than sensory evaluation (McCormick, 1988).

To determine texture in chips, there are two qualities measured, hardness, and crispiness. Hardness is found on a texture profile curve which defined as the force at maximum compression during the first bite. Hardness can be described as soft, firm, hard and also it is called fracturability .Crispiness is the force which a sample cracks, fractures or crumbles and it is also called brittleness (Kayacier and Singh, 2003; Steffe, 1996).

For texture determination in chips, a number of instrumental set-ups have been developed because of their high variations. This high variation can be attributed to the air bubbles in chips, which make the surface of the chips un-uniform (Kayacier and Singh, 2003). A study distinguished changes in tortilla chips during frying by using a Texture Analyzer compression test: using 0.203 cm cylindrical probe and a cylindrical base with a hole of 19 mm and 25.5 cm of outside diameter in a bite compression test with a probe velocity of 10 mm/s (Moreira et al., 1997). Kawas-Escoto (2000) measured and compared fracturability (hardness) of the fried chips to baked tortilla and used a similar technique: a 1⁄4 inch ball probe moved at a downward velocity of 0.1 mm/s until it broke the sample; on an 18 mm diameter hollow cylindrical base the sample was placed. Fracturability, specified as the first peak of the force which fractured the tortilla versus distance, had a positive relationship with frying time where it increased until a point where the parameter significantly fell as the products became crispier.

Garayo and Moreira (2002); Granda et al. (2004) used Kawas-Escoto (2000) approach for potato chips. Garayo and Moreira (2002) determined the hardness of fried potato chips finding the maximum force at compression. Granda et al. (2004) compared the texture parameters of vacuum potato chips with traditionally fried potato chips.

Kasahara et al. (2002) studied the texture of pre-treated French fried potatoes with soaking solutions (20 % sugar,2% salt for 15 min, and 3% just salt for 50 min). A major improved in texture was found for the pre-treated samples. They used multiple puncture attachment with the Texture Analyzer to find maximum force (peak) to break the product. They found that pre-treating samples with 3% salt, during the frying time at 180°C, increased the work (hardness) to break the samples.

Da Silva and Moreira (2008) studied the texture of sweet and blue potatoes, green bean, and mango chips. They used the Texture Analyzer with a steel blade probe to measure the force required to break the chips. They found that when compare between samples fried under vacuum and atmospheric pressure, there is no significant different on the force required to break the products ($p < 0.05$).

CHAPTER III

MATERIALS AND METHODS

Vacuum impregnation and frying processes were conducted following the steps described in Figure 3.1.

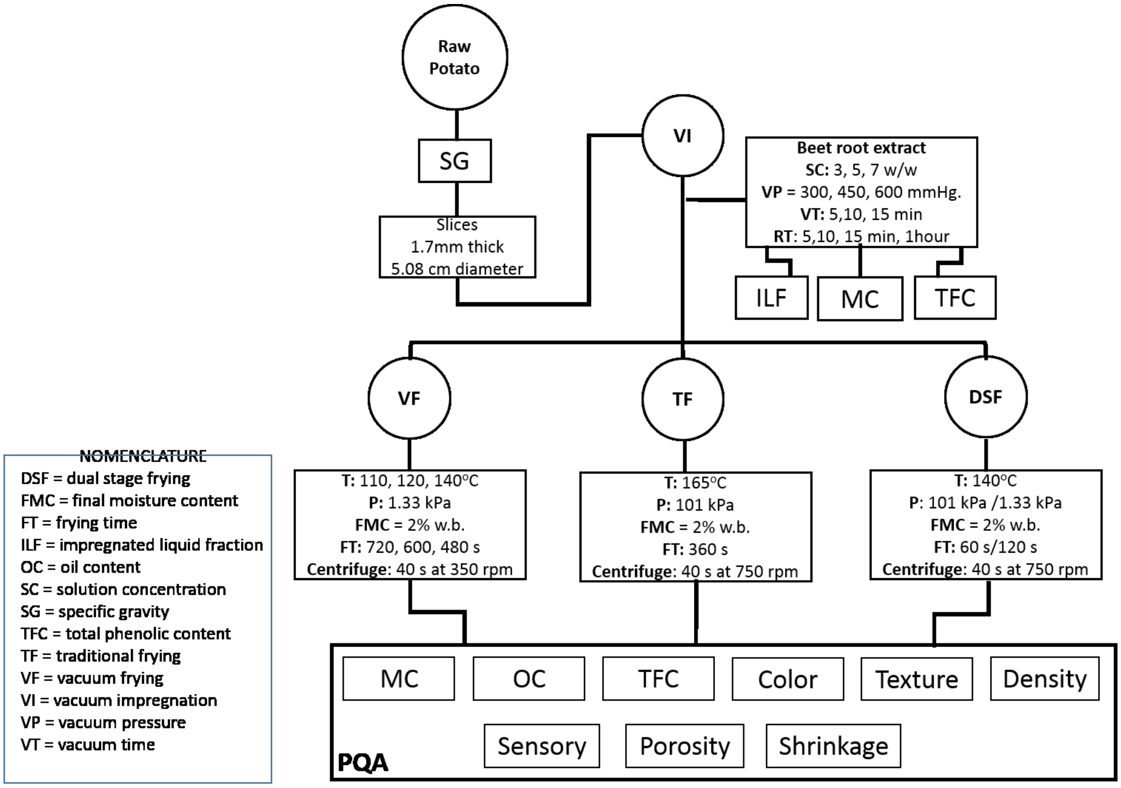

Figure 3.1. Experiment steps for vacuum impregnation and frying of potato slices.

3.1 Samples preparation

3.1.1 Raw potato

Potatoes were provided by Frito-Lay North America, Inc. (Plano, Texas) and CSS farms (Dalhart, TX). Potatoes were stored in a refrigerator at 10°C and 90% relative humidity. Before vacuum impregnation and frying experiments, they were left at room temperature for approximately 2-3 days to allow reconditioning by lowering the reducing sugar content before processing (Yagua Olivares, 2010).

3.1.2 Specific gravity

The specific gravity of raw potatoes was measured before processing using the weight in air and weight in water method. Specific gravity can be calculated using the following equation (Dean and Thornton, 1992):

$$SG=\frac{\text{Weight in air}}{(\text{Weight in air - Weight in water})} \qquad [3.1]$$

Each potato was weighed individually by placing it directly on a balance to record the potato weight in the air. To measure the potato weight in water, it was placed in a basket that was submerged into water. A string connected to the balance use attached to the basket. The test was conducted in triplicate at room temperature.

3.1.3 Potato sample preparation

Potatoes were peeled and then sliced using a mandolin (Matfer model 2000, France) to a thickness of 1.7±0.2 mm (Mitutoyo Thickness Gage, Japan). They were cut using a cylindrical metal cutter to a diameter of 5.08 cm. The potato slices were washed using distilled water to eliminate the surface starch. Before each experiment, the potato slices were blotted with paper towels. The samples were then placed in a glass jar with a lid to avoid any moisture loss before further processing (Yagua Olivares, 2010).

3.1.4 Raw potato physicochemical properties

3.1.4.1 Moisture content of raw potatoes

The moisture content of the raw potatoes was determined by drying 3 g of the product in a vacuum oven at 70°C until a constant weight was achieved (AOAC, 2000). The test was performed in triplicate. The weight of the samples was recorded before and after drying, and the moisture content, wet basis (MC $_{w.b}$), was calculated as follows (Granda, 2006):

$$\text{MC (w.b)}=\frac{\text{M(w.b)-M(d.b)}}{\text{M(w.b)}} \qquad [3.2]$$

The moisture content, dry basis (MC $_{d.b}$), was defined as:

$$\text{MC (d.b)}=\frac{\text{(M(w.b)-M(d.b)}}{\text{M(d.b)}} \qquad [3.3]$$

3.1.4.2 Extraction of phenolic content of raw potatoes

Raw potato slices were vacuum dried until a constant weight was achieved. The dried potato samples were ground to a fine powder and stored in plastic bags at room temperature until use. About 3.0 g of the ground sample were weighted and mixed with 50 mL of 70 mL/100 mL aqueous acetone (0.1 mL/100 mL acetic acid) using a food processor. The acetone extract was filtered on a Büchner funnel under the vacuum. The filter solution was placed on the Büchi rotavapor until all the residual acetone evaporated. The remaining aqueous extract was stored at 4°C until further analysis (Kita et al., 2015).

3.1.4.3 Determination of total phenolic content (TFC)

The total phenolic content of the sample extracts was evaluated using the Folin-Ciocalteu phenol reagent method (Singleton and Rossi, 1965). For the preparation of the calibration curve, a gallic acid solution was prepared in a 100-mL volumetric flask, where 0.5 g of dry gallic acid was dissolved in 10 mL of ethanol and then diluted to volume with water. Then 0, 0.1, 0.2, 0.3, 0.5, and 1 mL of the gallic acid solution was added to 10 mL volumetric flasks, and then diluted to volume with water. These solutions had phenol concentrations of 0, 50, 100, 150, 250, and 500 mg/L gallic acid, the effective range of the assay. From each calibration solution, 100 µL of the sample was pipetted into separate cuvettes, and 1.58 mL of distilled water was added to each. About 100 µL of the Folin-Ciocalteu reagent was added and mixed well. After 8 min, 300 µL of the sodium carbonate solution was added to the mixture and then shake to mix all components.

To make sodium carbonate, 20g of anhydrous sodium carbonate was added in 80 mL of water and it was brought to a boil. Few crystals of sodium carbonate were added after cooling, and after 24 hr, it was filtered and water was added to a volume of 100 mL. The solutions were left at 23°C for 2 hr. The absorbance of each solution was determined at 765 nm against the blank (the "0 mL" gallic acid solution) and then a plot of the absorbance vs. concentration values evaluated to obtain the calibration curve (Waterhouse, 2001).

3.2 Vacuum impregnation (VI)

3.2.1 Preparation of Impregnation Solution

Organic beet juice powder was purchased from the Synergy Company (Moab, Utah, United States). This powder is a pure juice highly concentrated with phenolic. About 3%, 5%, and 7% w/w solution concentrations were prepared by using beet powder mixed with distilled water. This beet solution was then used to impregnate the potatoes slides by the VI method.

3.2.2 Impregnation Procedure

A vacuum impregnation (VI) system composed of a vacuum pump (Emerson Motor Division, St. Louis, MO., USA) and a glass desiccator was used in this study (Figure 3.2). Sliced potatoes were immersed in the impregnation solution before vacuum was applied. During the vacuum step, different vacuum pressures (300 mm-Hg, 450 mm-Hg, and, 600 mm-Hg) were applied for different periods of times (5 min, 10 min and, 15 min) and then the atmospheric pressure was restored for various periods of times (5 min, 10 min, and 15 min) as shown in Table 3.1. Afterward, the excess of liquid in the surface of impregnated samples was removed with paper towel (Sevimli and Moreira, 2013). The impregnated liquid fraction, moisture content, and total phenolic content were evaluated and the best time/pressure/concentration combinations were determined. The temperature was maintained at ambient conditions (25 ± 2ºC).

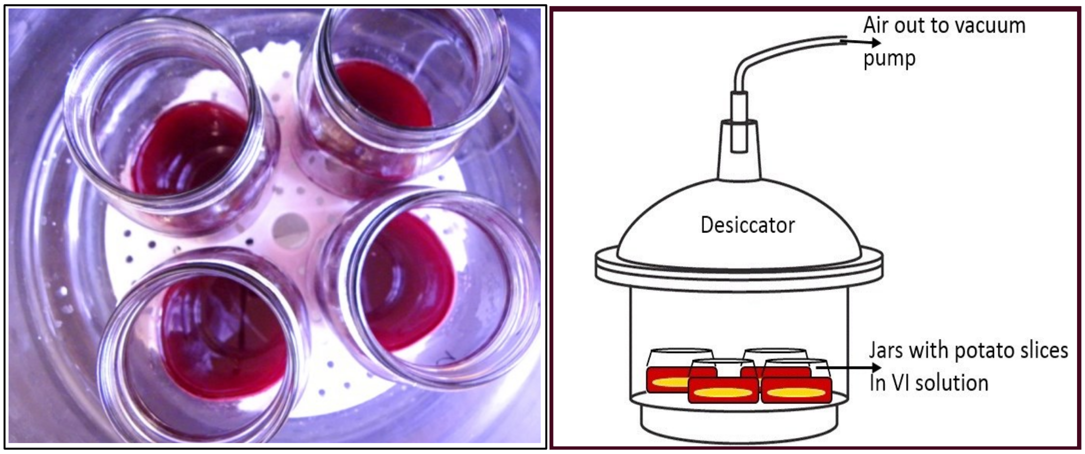

Figure 3.2. Schematic drawing of vacuum impregnation system (VI).

To improve the impregnation process, the best operating/process conditions were selected and a vacuum pressure of 600 mm Hg applied for 10 min, followed by atmospheric pressure restoration for 1 hour, while samples remained in the VI solution.

3.2.3 Physicochemical properties of vacuum impregnated potato slices

3.2.3.1 Water loss (WL) and solid gain (SG)

The percentage of WL during the VI process was calculated from the sample weight before and after each vacuum impregnated treatment. The calculated WL value for the potato slices represented the total external liquid that penetrated into the tissue.

Water loss (WL) was calculated using the following equation:

$$\mathrm{WL}[\%] = \frac{\mathrm{WS}_{o} \times \mathrm{MC}_{\text{o-db}} - \mathrm{WS}_{\mathrm{f}} \times \mathrm{MC}_{\text{f-db}}}{\mathrm{WP}_{\mathrm{o}}} \times 100 \qquad [3.4]$$

where WS_o is the weight of the solid in the product before impregnation [g], WS_f is the weight of solids in the sample after impregnation [g], WP_o is the weight of the product before impregnation.

The solid gain (SG) to or from the sample during impregnating was calculated as:

$$SG[\%] = \frac{WS_o - WS_f}{WP_o} \times 100 \qquad [3.5]$$

Table 3.1. Experimental design for each set of experiments (VP = vacuum pressure; VT = vacuum pressure time applied; RT = restoration time; SC= red beetroot solution concentrations).

Set #	Experiment #	Factor 1 SC [w/w]	Factor 2 VP [mmHg]	Factor 3 VT [min]	Factor 4 RT [min]
1	1	3%	300	5	5
	2	3%	300	10	10
	3	3%	300	15	15
	4	5%	300	5	5
	5	5%	300	10	10
	6	5%	300	15	15
	7	7%	300	5	5
	8	7%	300	10	10
	9	7%	300	15	15
2	10	3%	450	5	5
	11	3%	450	10	10
	12	3%	450	15	15
	13	5%	450	5	5
	14	5%	450	10	10
	15	5%	450	15	15
	16	7%	450	5	5
	17	7%	450	10	10
	18	7%	450	15	15
3	19	3%	600	5	5
	20	3%	600	10	10
	21	3%	600	15	15
	22	5%	600	5	5
	23	5%	600	10	10

Table 3.1. Continued

Set #	Experiment #	Factor 1 SC [w/w]	Factor 2 VP [mmHg]	Factor 3 VT [min]	Factor 4 RT [min]
3	24	5%	600	15	15
	25	7%	600	5	5
	26	7%	600	10	10
	27	7%	600	15	15
4	28	7%	600	10	60

3.2.3.2 Moisture content of vacuum impregnated potato sliced

The moisture content of VI potato slices was determined as described previously (section 2.1.4.1).

3.2.3.3 Total phenolic content of vacuum impregnated potato sliced

The total phenolic content of the vacuum impregnated potato sliced was determined as described previously (section 3.1.4.3 and 3.1.4.3).

3.3 Frying experiments

3.3.1 Vacuum frying (VF)

The frying experiments were performed by using a vacuum fryer available at the Food Engineering Laboratory, at the Department of Biological and Agricultural Engineering of Texas A&M University, College Station, Texas (Figure 3.3). The fryer consists of a cast aluminum vacuum vessel connected with an electrical heating system. The vessel contains a basket and a centrifuging system (de-oiling) with a maximum rotational speed of 750 rpm (63 g units). Vacuum is achieved in the vessel by connected a dual seal vacuum pump (model 1402 Welch Scientific Co., Skokie, IL) with a vacuum capacity of 1.33 kPa (Yagua Olivares, 2010).

The frying process was done by loading four potato slices (about 16 g) into the basket, closing the lid, and depressurizing the vessel. When the pressure in the vessel reached 1.33 kPa, the basket was submerged into the oil. Different oil temperatures (110°C, 120°C, and 140°C) were applied for different periods of time as show at (Teble.3.2). Fresh canola oil (Crisco, Ohio, USA) was used in all experiments. Potato chips were fried until 2% moisture content (w.b.) was achieved. The basket was then raised, and the centrifuging system was applied for 40 s at maximum speed 750 rpm (63 g units). Next, the vacuum was broken and the potato chips allowed to cool down at room temperature before storing the chips in polyethylene bags inside of a desiccator for further examination. The test was performed in triplicate (Yagua Olivares, 2010).

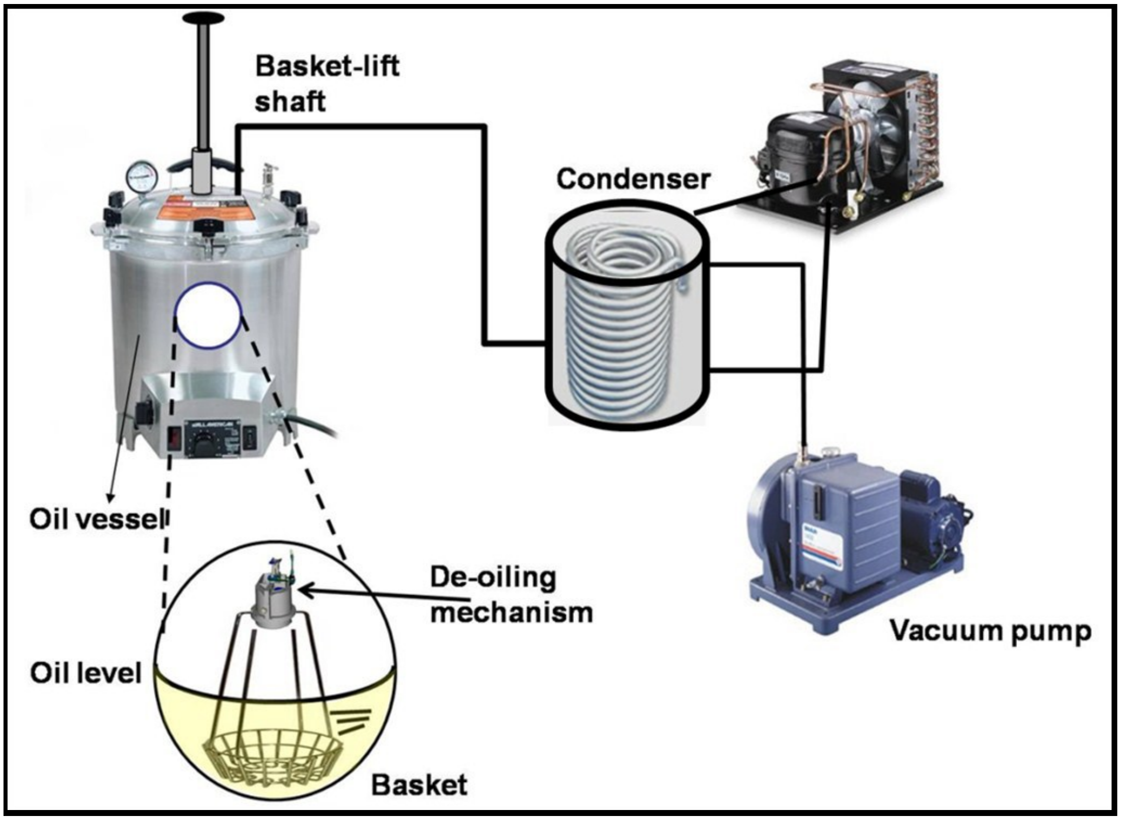

Figure 3.3. Schematic drawing of the vacuum frying system (Adapted from Da Silva and Moreira, 2008)

Table 3.2. Experimental design for vacuum frying study.

Set #	**Experiment #**	**Factor 1 Temperature [◦C]**	**Factor 2 Time [sec]**
1	1	110	0
	2		20
	3		40
	4		60
	5		80
	6		100
	7		120
	8		140
	9		180
	10		240
	11		300

Table 3.2. Continued

Set #	Experiment #	Factor 1 Temperature [◦C]	Factor 2 Time [sec]
1	12	110	360
	13		480
	14		600
	15		720
2	1	120	0
	2		20
	3		40
	4		60
	5		80
	6		120
	7		180
	8		240
	9		300
	10		360
	11		480
	12		600
3	1	140	0
	2		20
	3		40
	4		60
	5		80
	6		120
	7		180
	8		240
	9		300
	10		360
	11		480

3.3.2 Traditional frying (TF)

A commercial deep-fat fryer used to fry potato chips (George Foreman Spin Fryer – GSF026B, George Foreman's, Columbia, MO). The fryer with a capacity of 2.6 L of oil, and a centrifuge system. The centrifuge system consists of a basket, which can rotate at two different speeds. The basket can rotate (loaded with potatoes and sample holder) at 350 ± 1 and 457 ± 1 rpm. The relative centrifugal force (RCF), commonly referred to as “g-force” or “times g” values, are 8.1 and 13.8 for 350 and 457 rpm, respectively. Four potato slices (about 16 g) were fried at 165°C oil temperature for 300 s and then centrifuged at a maximum rotational speed of 457 rpm (13.8 g units). The tests were performed in triplicate.

3.3.3 Dual-stage frying (DSF)

A two-stage frying process (atmospheric and vacuum frying) was performed using the vacuum frying equipment. First, four potato slices (about 16 g) were loaded into the frying basket. The basket was then submerged into the oil under atmospheric pressure (1st-stage at 140°C). Once the potato slices were partially cooked (60 sec), the vessel was depressurized until a pressure of 1.33 kPa was reached (2nd-stage). The product was fried at 140°C until 2% final moisture content is achieved (120 sec). The basket was raised after completed the frying, and the potato slices were centrifuged at 750 rpm for 40s. Next, the vessel was pressurized, and the fried potato chips were allowed to cool down at ambient temperature. All frying experiments were done by using a fresh canola oil, and the test was performed in triplicate (Ravli et al., 2013).

The experimental design for the different frying methods is shown in Table 3.3. Product quality attributes (PQA), such as, moisture content, oil content, texture, color, bulk density, porosity, shrinkage and expansion, of the raw potato slices and the fried chips were measured to compare the effects of the different frying methods on the final product quality.

Table 3.3. Experimental design for the different frying method experiments.

Set #	Experiment #	Factor 1 Frying time [s]	Factor 2 Temperature [^{o}C]	Factor 3 Frying Pressure [kPa]
1	1	0	0	0
	2	120	140	1.33
2	1	0	0	0
	2	300	165	101
3	1	0	0	0
	2	60/120	140	101/1.33

3.4 Product quality attributes (PQA)

3.4.1 Moisture content

The moisture content of the potato chips was determined as described in section 3.1.4.1.

3.4.2 Oil content

The oil content of the samples was determined by using the Soxtec System HT extraction unit (Pertorp, Inc., Silver Spring, MD, USA) with petroleum ether solvent (AACC, 1986). About 3 g of ground potato chips was placed on cellulose thimbles (model 2800256, Whatman, England). Before measuring the weight of the empty aluminum cups, the cups were dried for 15 min in a convection oven at 105ºC and cooled down in a desiccator for 25 min.

The oil extraction process is made up of three steps. First, the thimbles contain potato chips samples were submerged into boiling petroleum ether inside the cups for 40 min. Then, the thimbles were raised up to be rinsing by washing them with recirculating petroleum ether while oil was collected in the cups. The final step consists of collecting the oil after evaporated the petroleum ether from cups. To ensure that all the petroleum ether was evaporated from the oil, the cups were placed in a convection oven for 15 min at 105ºC. Then, the cups were cooled for 20 min in a desiccator. The cups with the oil were weighted and the oil content of each sample were determined in dried basis (d.b.) using the following equation.

$$\text{OC (d.b)}=\frac{W_1-W_2}{W_i} \qquad [3.8]$$

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

3.4.3 Color

The color of the potato chips was determined using a LabScan XE colorimeter (Hunter Lab, Inc, VA., USA). Color measurements were taken for eight chips of each condition. The colorimeter was calibrated utilizing a standard black plate and white plate (Y = 94.00, x = 0.3158, y = 0.3322). Three readings of L^* (lightness), a^* (red-green), b^*(yellow-blue) values were measured for each group of samples (Garayo and Moreira, 2002; Sevimli and Moreira, 2013).

3.4.4 Texture

Texture analyses was performed on the fried potato chips obtained from different frying methods using the Brookfield CT3 Texture Analyzer (Brookfield, Middleboro, MA, United States). The test was performed by placing a single potato chip on a 2-point support (TA-DEC pot) base. A spherical stainless steel probe type (TA18) with diameter of 12.7 mm was used to break the chip.

The speed at which the probe approached the sample was 1.00 mm/s. The force applied was 0.04 N, and the probe travelled 2mm after touching and fracturing the potato chip. The tests were performed using eight chips per frying method. For good experimental practice, all tests were run on the same day the chips were fried. The highest peak on the force/time curve was assumed as a hardness value.

Kawas-Escoto (2000) used a similar procedure to measure the texture of tortilla chips: a probe of 1⁄4-inch ball traveled at speed of 0.1 mm/s until it broke the sample; the sample was located on an 18-mm diameter hollow cylindrical base.

3.4.5 Determination of total phenolic content of potato chips

The total phenolic content of vacuum fried potato chips was determined as described previously in sections 3.1.4.2 and 3.1.4.3.

3.4.6 True density

The true volume is the volume of solid matter. About 1 g of ground fried potato chips was measured by using a compressed helium gas multi-pycnometer (Quantachrome & Trade, NY, USA). The solid volume was determined by using pycnometer to read the two pressure. The volume of a reference (Vr) and the sample cell (Vc), and the solid volume (Vt) was calculated by:

$$V_t = V_c - V_r \cdot \left(\frac{P_1}{P_2} - 1\right) \qquad [3.9]$$

where P1 is an initial pressure and P2 is a final pressure which was given by the pycnometer, respectively. The reference cell and the volumes of the sample are constants collected at a previous calibration of the equipment; the values of Vc and Vr used in this study are 13.045 and 7.379, respectively. True density, ρt, was calculated using the following equation:

$$\rho_t = \frac{M_s}{V_t} \qquad [3.10]$$

where M_s is the weight of the de-oiled sample (g) and V_t is the solid volume (m^3). The weight of the without oil samples were calculated from the original weight of the potato chips and the oil content data. The test was done in triplicate.

3.4.7 Bulk density

Liquid displacement technique with ethanol used to measure the bulk volume (Da Silva and Moreira, 2008; Nunes and Moreira, 2009) The volume in the equipment was recorded with, and without the sample, the sample weight was determined of five potato chips. The bulk density was calculated by dividing the weight of the chips without oil by its bulk volume. The weight of a de-oiled chip was calculated from the original weight of the chip and the oil content data. Bulk density, ρb, was calculated using the following equation:

$$\rho_b = \frac{M_s}{V_b} \qquad [3.11]$$

where M_s and V_b are the weight of the de-oiled sample (g) and bulk volume (m^3), respectively. The test was performed in triplicate.

3.4.8 Porosity

The porosity, ϕ, of the potato chips was calculated as:

$$\phi = 1 - \frac{\rho_b}{\rho_s} \qquad [3.12]$$

where ρ_b is bulk density and ρ_s is solid (true) density.

3.4.9 Diameter shrinkage and thickness expansion

The diameter and thickness of raw and fried potato slices were included using a steel caliper (MG Tool Co., New York, NY, USA). For each frying method, four slices and four readings per slice were recorded.

The degree of shrinkage diameter, *D*, was calculated by:

$$D=\frac{d_o-d(t)}{d_o}\times 100 \qquad [3.13]$$

where d_o is the initial diameter of the raw sample (m) and $d\ (t)$ is the diameter of the sample at frying time t (m).

The degree of expansion thickness, *L*, was calculated by:

$$L=\frac{l_o-l(t)}{l_o}\times 100 \qquad [3.14]$$

where l_o is the initial thickness of the raw sample (m) and l (t)is the thickness of the sample at frying time t (m).

3.4.10 Sensory evaluation

Sensory analysis is a method to evaluate consumer acceptability for new food products. Sensory evaluation of phenol-enriched potato chips was done by using different frying methods (vacuum at 140°C, dual steps at 140°C, and traditional at 165°C). The samples were presented on white plates labeled to each participant at once. The pleats were coded with 3 random digits to identify the frying methods. A consumer test was carried out among 30 participants (students, faculty, and staff at Texas A&M University).

A nine-point hedonic scale was used, with a score of 1 to 9 where 9 the most liked and1 was the most disliked attribute. Scores equal or higher than 5 were considered acceptable based on the nine-point hedonic scale used by Carr et al. (1999).

The quality rating test (QRT) was on a 5- point numerical scale (1= very bad, 5= very good). The measured attributes of the QRT were color (dark yellow, dark red), texture including hardness (soft, hard), and crispness (not crispy, very crispy), and oiliness (oily, not oily), flavor and overall quality (1= very bad, 5= very good) (Troncoso et al., 2009).

3.5 Statistical analysis

The data was analyzed using SPSS software (version 20.0 for Windows). Statistical differences between variables were analyzed for significance by one-way ANOVA using Tukey's multiple range tests. Statistical significance was expressed at the $P < 0.05$ levels.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Vacuum Impregnation (VI)

Preliminary studies were performed to determine the best vacuum impregnation (VI) conditions (pressure, vacuum and restoration times, and impregnation solution concentration) to enrich potato slices with red beetroot solution, as a pre-treatment before frying. The specific gravity of the potatoes used in these experiments was 1.084 ± 0.004.

4.1.1 Effect of red beetroot impregnation on product quality attributes (PQA)

4.1.1.1 Impregnated liquid and moisture content of potato slices

The first VI experiments showed that the potato slices gained weight due to the process. The samples absorbed the impregnated liquid as shown in Table 4.1 (water loss values have a negative sign, indicating the water was gained). Martinez-Valencia et al. (2011) also reported increased water loss in VI cantaloupe pieces with increased immersion times.

As the solution concentration increased, the WL values decreased. The viscosity of the solution increased (not shown) with increased solute concentration, what could have resulted in less solution transfer into the potato slices. Additionally, the solution Brix increased (Table 4.2), due to the amount of sugar in the beetroot solution, thus causing some of the water to leach out from the potato slices.

Solid gain (sugar from the beet solution) values (Table 4.1) were negative for all treatments, indicating that the samples lost solids during the VI process. However, these results are inconclusive due to the large variation of the results. The differences in potato batches and storage conditions may have affected these results.

Table 4.1. Effect of solution concentration and vacuum pressure on the impregnated liquid fraction of potato slices.

SC [w/w]	**VP [mmHg]**	**VT/RT [min]**	**WL [%]**	**SG [%]**
3%	300	5	-11.19 ± 1.48	-6.04 ± 1.83
		10	-11.08 ± 1.73	-5.57 ± 0.90
		15	-6.39 ± 4.71	-1.47 ± 3.33
	450	5	-5.71 ± 1.68	-0.40 ± 1.73
		10	-9.65 ± 1.03	-1.43 ± 0.08
		15	-5.87 ± 2.97	2.41 ± 0.95
	600	5	-11.21 ± 1.91	-6.45 ± 1.26
		10	-11.93 ± 1.06	-6.40 ± 1.11
		15	-5.09 ± 1.42	0.48 ± 2.41
5%	300	5	-10.52 ± 0.54	-10.52 ± 0.54
		10	-12.78 ± 1.21	-12.78 ± 1.21
		15	-5.04 ± 3.08	-5.04 ± 3.08
	450	5	-3.75 ± 0.38	-3.75 ± 0.38
		10	-3.32 ± 1.27	-3.32 ± 1.27
		15	-8.70 ± 2.05	-8.70 ± 2.05
	600	5	-10.53 ± 1.22	-10.53 ± 1.22
		10	-11.31 ± 0.70	-11.31 ± 0.70
		15	-2.62 ± 3.69	2.91 ± 0.42
7%	300	5	-6.82 ± 0.79	-5.37 ± 0.49
		10	-4.13 ± 1.53	-3.69 ± 0.83
		15	0.21 ± 1.41	0.48 ± 2.34
	450	5	-3.21 ± 0.60	-0.92 ± 1.02
		10	-1.00 ± 0.82	1.76 ± 1.74
		15	0.88 ± 1.93	3.48 ± 2.00
	600	5	-7.87 ± 1.36	-5.97 ± 0.55
		10	-5.37 ± 0.50	-4.76 ± 0.78
		15	0.36 ± 1.81	-1.66 ± 0.53

SC= solution concentration; VP= vacuum pressure; WL = water loss; SG = solid gain

Table 4.2. Degree Brix of raw potato (RP) and red beet solution concentrations (SC).

Material	**°Brix [g sucrose/100 g solution]**
RP	5.1 ± 0.06
SC 3%	3.0 ± 0.06
SC 5%	4.9 ± 0.06
SC 7%	6.8 ± 0.12

During VI process, the vacuum pressure causes the gases/liquid inside the tissue to expand and flow out of the extracellular spaces. When the pressure is restored, the residual gas is compressed and the external liquid flows into the product pores (Fito et al., 2001).

The differences in impregnated samples solution content are due to the differences in tissue deformation between samples, irreversible tissue deformation, or reduced tissue rigidity of potato slices by the deformation-relaxation phenomenon. The degree of tissue impregnation is associated to a considerable extent with porosity, the size, and shape of the pores as well as mechanical properties. Thus, the tissue deformation may have reduced the free space for the solution transfer to the potato (Fito et al., 1996; Radziejewska-Kubzdela et al., 2014).

The change in water content changes after impregnation were calculated by measuring the moisture content of potato slices before and after VI (Table 4.3). There is a variation of potatoes initial moisture contents between batches, which makes moisture content transfer values different. The impregnation liquid content and amount of moisture content transferred were not associated with enriching the potato slices with total phenolic component values as will be discussed later.

Table 4.3. Effect of solution concentration, vacuum pressure and vacuum and restoration times on moisture contents of potato slices.

SC **[w/w]**	**VP** **[mm Hg]**	**VT** **[m]**	**MC_i** **[w.b.]**	**MC_f** **[w.b]**
3%	300	5	0.73 ± 0.00	0.80 ± 0.03
3%	300	10	0.72 ± 0.01	0.79 ± 0.02
3%	300	15	0.79 ± 0.03	0.79 ± 0.06
3%	450	5	0.79 ± 0.04	0.81 ± 0.03
3%	450	10	0.79 ± 0.04	0.83 ± 0.02
3%	450	15	0.79 ± 0.02	0.78 ± 0.02
3%	600	5	0.73 ± 0.00	0.80 ± 0.03
3%	600	10	0.72 ± 0.01	0.80 ± 0.02
3%	600	15	0.79 ± 0.03	0.80 ± 0.02
5%	300	5	0.73 ± 0.01	0.81 ± 0.02
5%	300	10	0.71 ± 0.04	0.81 ± 0.03
5%	300	15	0.79 ± 0.02	0.77 ± 0.03
5%	450	5	0.79 ± 0.02	0.78 ± 0.02
5%	450	10	0.79 ± 0.02	0.78 ± 0.01
5%	450	15	0.77 ± 0.01	0.79 ± 0.01
5%	600	5	0.73 ± 0.01	0.81 ± 0.03
5%	600	10	0.71 ± 0.04	0.80 ± 0.02
5%	600	15	0.79 ± 0.02	0.78 ± 0.02
7%	300	5	0.72 ± 0.01	0.78 ± 0.02
7%	300	10	0.74 ± 0.01	0.78 ± 0.05
7%	300	15	0.77 ± 0.02	0.77 ± 0.02
7%	450	5	0.78 ± 0.02	0.79 ± 0.02
7%	450	10	0.78 ± 0.02	0.77 ± 0.02
7%	450	15	0.79 ± 0.02	0.76 ± 0.03
7%	600	5	0.72 ± 0.01	0.78 ± 0.02
7%	600	10	0.74 ± 0.01	0.79 ± 0.02
7%	600	15	0.77 ± 0.02	0.78 ± 0.02

Means with different letter are significantly different ($p<0.05$). SC= solution concentration, VP= vacuum pressure, VT= vacuum and restoration time, MC_i= initial moisture content, MC_f= final moisture content, and MC = the percentage of transfer moisture content

4.1.1.2 Total phenolic content of potato slices

Figures 4.1 to 4.3 show that there was no specific trend in total phenolic content values versus vacuum impregnation conditions (pressure, vacuum and restoration times, and impregnation solution concentration). There was a large variation in TPC (19 – 63 mgGAE/100 g) in the potatoes used in this investigation. A different variety (see Table 4.7) showed much higher TPC values (116 – 139 mgGAE/100g DW). These potatoes had a much higher quality than the potatoes used at the beginning of this study. The specify gravity of these potatoes was 1.072 ± 0.004. Madiwale et al. (2011) reported that the total phenolic content of different potato cultivars can range from 26 to 269 mg GAE/100g DW.

Figures 4.1 to 4.3 show that, in general, vacuum impregnated potato slices with longer vacuum and restoration time (15 min) were the least enriched with total phenolic component than the other treatments. The higher the impregnation solution concentration, the lower the impregnation causing the water in the potato to diffuse out due to the difference in concentrations between the water in the potato and the solution.

Plant tissue cells placed in different solution concentrations react differently. A higher external concentration solution than the product internal cell membrane (hypertonic solution) will cause higher water loss from the product (Sasireka and Ganapathy, 2016). Shi et al. (1995) reported that a high-water loss could be obtained from low-pressure systems. However, there is only slightly differs in the solid gain between the vacuum and atmospheric pressure processes. The microstructural characterization of the plant tissues is the main factor influencing the solid gain. The higher the vacuum, the greater the volume of impregnated solution. The property of the raw material and the vacuum level are affecting the sample deformation and the amount of solutes impregnated into samples (Fito et al., 1996).

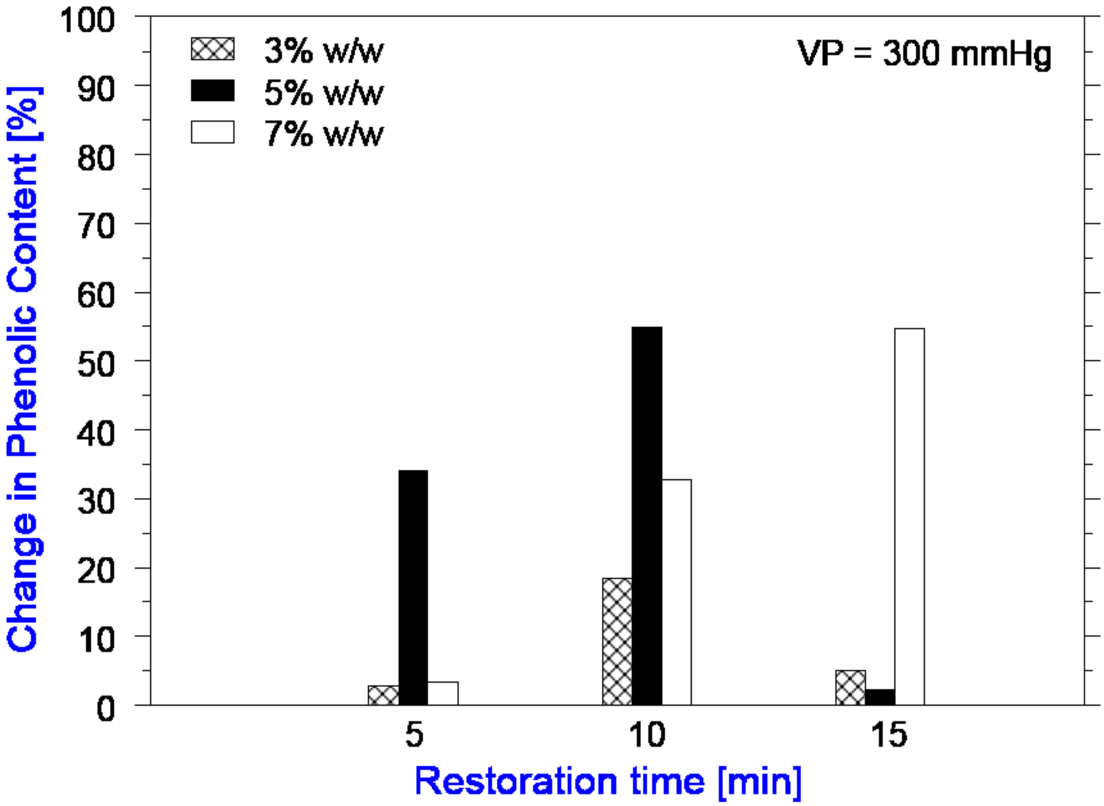

Figure 4.1. Effect of solution concentration, and vacuum and restoration time at 300 mmHg vacuum pressure on total phenolic component of potato slices.

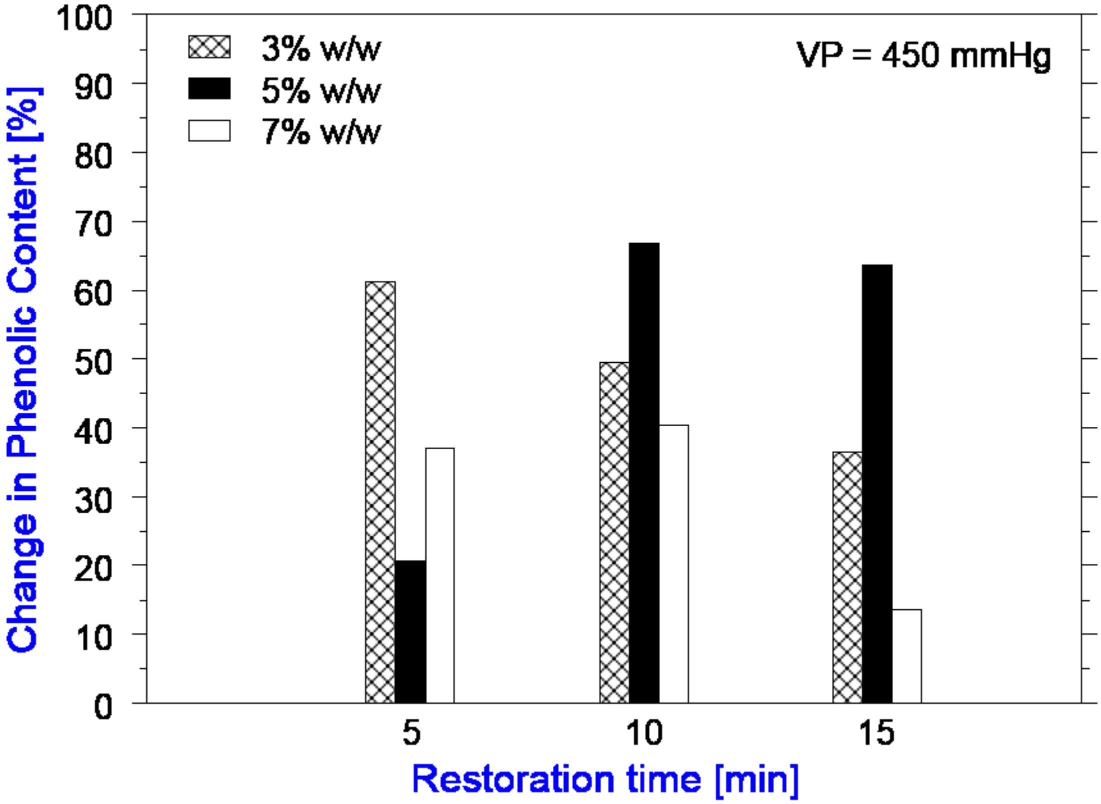

Figure 4.2. Effect of solution concentration, and vacuum and restoration time at 450 mmHg vacuum pressure on total phenolic component of potato slices.

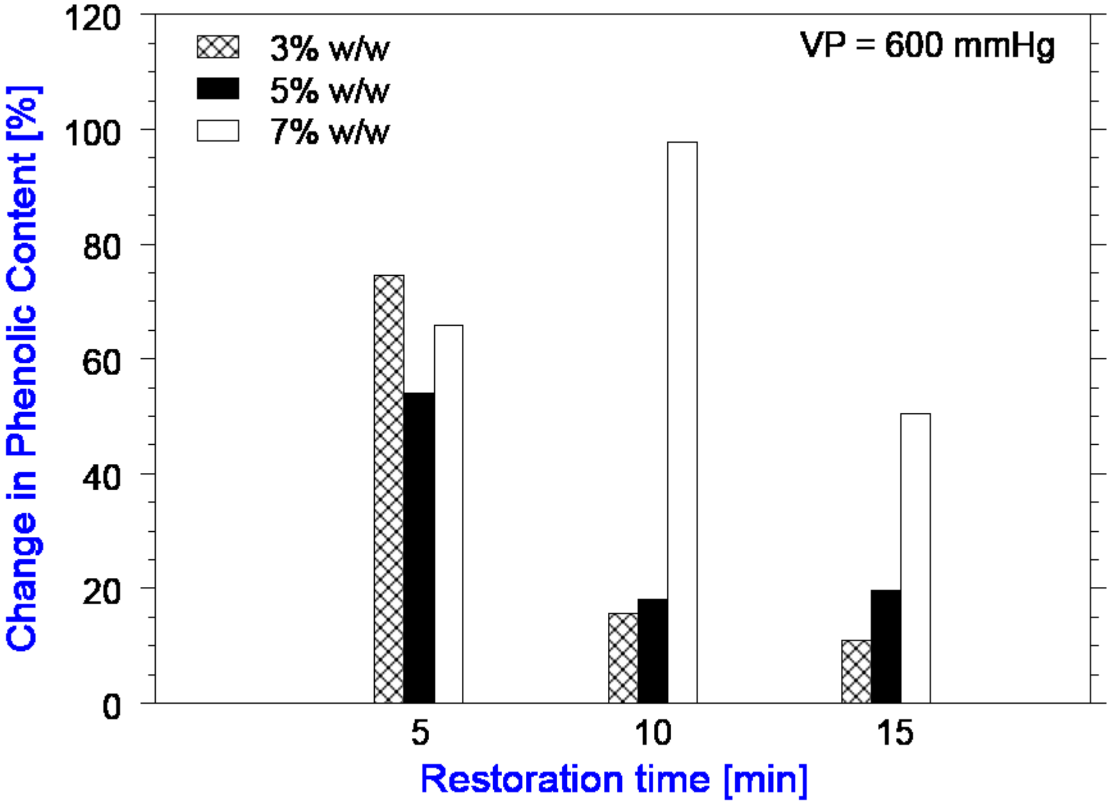

Figure 4.3. Effect of solution concentration, and vacuum and restoration time at 600 mmHg vacuum pressure on total phenolic component of potato slices

The best vacuum impregnation conditions to enrich the potato slices were with a solution of 7% (w/w) at 600 mmHg pressure, and 10 minutes of vacuum pressure and 10 minutes restoration time (Table 4.4).

Fito and Pastor (1994) observed that the intercellular space determines the occupied volume of the external liquid in the product tissue during VI processing. In the case, the intercellular air space of potato is very small (1%) (Hironaka et al., 2011) compared with the intercellular space of apple (25%), peach (15%) and, mushroom (37–

45%) (Alzamora et al., 2005).

Table 4.4. Effect of solution concentration, vacuum pressure and vacuum and restoration times on total phenolic component of potato slices.

SC [w/w]	**VP [mm Hg]**	**VT or RT [m]**	**TPC_i [mgGAE/100g DW]**	**TPC_f [mgGAE/100g DW]**	**ΔTPC [%]**
3%	300	5	19.00 ± 0.62	19.55 ± 1.68	2.93
3%	300	10	54.16 ± 2.40	64.15 ± 4.12	18.44
3%	300	15	63.78 ± 4.29	67.07 ± 10.55	5.15
3%	450	5	37.92 ± 11.6	61.16 ± 8.67	61.3
3%	450	10	37.92 ± 11.6	56.71 ± 9.81	49.57
3%	450	15	21.33 ± 1.30	29.77 ± 4.99	36.55
3%	600	5	19.00 ± 0.62	33.16 ± 1.04	74.57
3%	600	10	54.16 ± 2.40	62.66 ± 2.25	15.68
3%	600	15	66.1 ± 6.87	70.82 ± 13.27	11.04
5%	300	5	19.00 ± 0.62	25.47 ± 1.87	34.1
5%	300	10	21.33 ± 1.30	33.05 ± 7.48	54.91
5%	300	15	50.38 ± 7.65	51.52 ± 8.41	2.26
5%	450	5	21.60 ± 3.63	26.0 ± 6.15	20.58
5%	450	10	21.60 ± 3.63	36.1 ± 3.07	66.89
5%	450	15	23.40 ± 4.40	38.3 ± 4.01	63.64
5%	600	5	19.00 ± 0.62	29.27 ± 2.53	54.10
5%	600	10	58.24 ± 4.96	68.78 ± 1.63	18.10
5%	600	15	50.38 ± 7.65	60.32 ± 12.5	19.73
7%	300	5	19.00 ± 0.62	19.65 ± 1.18	3.46
7%	300	10	19.95 ± 1.01	26.48 ± 2.98	32.69
7%	300	15	36.51 ± 1.50	56.46 ± 8.73	54.65
7%	450	5	45.16 ± 7.16	61.93 ± 11.2	37.12
7%	450	10	45.16 ± 7.16	63.40 ± 3.31	40.38
7%	450	15	38.37 ± 4.49	43.6 ± 5.65	13.62
7%	600	5	19.00 ± 0.62	31.53 ± 3.24	65.96
7%	600	10	19.95 ± 1.01	39.47 ± 1.34	97.83
7%	600	15	36.51 ± 1.50	54.93 ± 5.25	50.43

Means with different letter are significantly different ($p<0.05$). SC= solution concentration, VP= vacuum pressure, VT= vacuum and restoration time, TPCi= initial total phenolic component, TPC_f= final total phenolic component, and TPC= the percentage of transfer total phenolic component

Hironaka et al. (2011) impregnated a whole potato with ascorbic acid (10% SC) for 1 hour at vacuum pressure of 700 mmHg and 3 hours restoration time. The VI treatment resulted in a 10 times increase in ascorbic acid content of whole potatoes (150 mg/100 g). Authors observed that the impregnation occurred almost at the central pith and the areas between the vascular ring and the periderm.

For the potato variety (better storability characteristics) used in the frying experiments, longer restoration time (1 hour) was applied to impregnate the potato slices with 7% SC at 600 mm Hg VP for 10 min. A set of 9 experiments, each with three replications (Table 4.5). The product lost water during the VI treatment (15.06% ± 2.26); however, the SG values varied greatly showing little solid change.

Table 4.5. Water loss (WL) and solid gain (SG) for potato slice impregnated with 7% w/w SC and 600 mm Hg for 10 min and 1-hour restoration time.

	WL [%]	**SG [%]**
Exp1	16.45 ± 0.85	1.35 ± 0.26
Exp2	15.57 ± 0.79	0.76 ± 0.25
Exp3	15.30 ± 0.71	0.29 ± 0.23
Exp4	13.85 ± 0.62	-1.20 ± 0.17
Exp5	18.89 ± 0.84	3.24 ± 0.24
Exp6	17.40 ± 0.85	2.03 ± 0.27
Exp7	12.72 ± 0.84	-3.25 ± 0.21
Exp8	12.45 ± 0.97	-2.90 ± 0.22
Exp9	12.94 ± 1.03	-2.86 ± 0.23

4.2 Effect of oil temperature and frying time on product quality attributes (PQA)

4.2.1 Kinetics of moisture loss during vacuum frying

Figure 4.4 shows the drying behavior of potato slices fried using a vacuum fryer at different oil temperatures (110, 120, and 140°C). These curves show the typical dehydration behavior for fried food products in accordance to previous observations (Gamble et al., 1987; Garayo, 2001; Shyu and Hwang, 2001).

According to Van Arsdel et al. (1973) and Garayo and Moreira (2002), three distinct periods can be noticed in a typical dehydration curve. The first is an initial warm-up period of the food product in which heat is absorbs by the wet material from the surrounding media (frying oil). The second period is known as the constant rate phase where the water in the product reaches the evaporation temperature of 100°C (1 atm) and the moisture begins to evaporate from the food's surface continuously (at constant P and T) as long as the surface contains water. In the last phase, the falling-rate period, the moisture content of the product is lost by diffusion, as the moisture is lost exponentially until the moisture content equilibrium is reached (Table 4.6).

Table 4.6. Initial and equilibrium moisture content of potato chips fried under vacuum at different oil temperatures.

T_{Oil} [°C]	FT [s]	IMC [%w.b.]	EMC [%w.b.]
110	0 - 720	75.80 ± 0.74^a	1.04 ± 0.11^c
120	0 - 600	77.58 ± 1.33^a	0.73 ± 0.03^b
140	0 - 480	81.17 ± 0.86^b	0.51 ± 0.04^a

The test was performed in triplicate. Means within the column with the same letter are not significantly different ($p<0.05$). Toil= oil temperature, FT= frying time, IMC= initial moisture content, and EMC=the equilibrium moisture content

In vacuum frying, the first period, warm-up and constant-rate periods are very short and may last no more than one to five seconds because the boiling point of water is much lower (11.2°C at 1.33 kPa) than at atmospheric pressure (Garayo, 2001). At the time the raw material is in contact with the oil, water starts to evaporate. During the first 60-100 seconds of the process, the drying rate is very fast and afterward slows down as the product reaches equilibrium moisture content (Figure 4.4).

Different oil temperatures influence the moisture loss of potato slices during vacuum frying. The chips fried at 120°C and 140°C lost moisture at a faster rate than the chips fried at 110°C (Fig. 4.4).

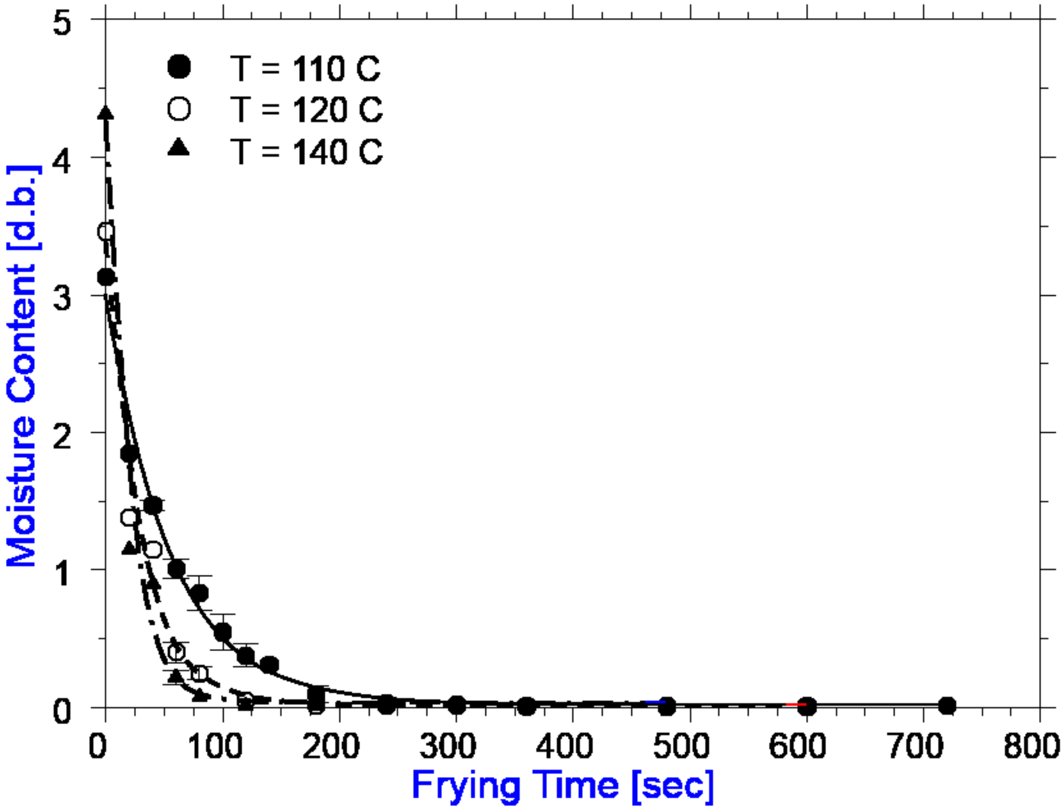

Figure 4.4. Moisture loss of potato chips during vacuum frying at different oil temperatures.

4.2.2 Kinetics of oil absorption during vacuum frying of potato chips

Oil absorption is a complex phenomenon that occurs mainly during the cooling stage when the product is removed from the fryer (Sun and Moreira, 1994).

Figure 4.5 shows the oil absorption curves for vacuum frying of potato slices at various oil temperatures. It can be noted that the chips' oil content increased as frying time increased within the first 80 seconds at 140°C and 120 seconds at 120°C frying temperatures and then decreases as frying time increased. This behavior was not observed at 110ºC frying temperature.

Garayo and Moreira (2002) explained the oil absorption phenomena in vacuum frying can be divided into 3 steps, during vacuum, pressurization, and cooling. As frying time increases and the free moisture in the potato reaches a critical level (at the 80 s at 140ºC), the oil absorption during the pressurization process decreases. The air diffuses into the pore spaces faster than the oil, hence blocking the oil to flow into the product. Therefore, most of the oil is absorbed during cooling. During the initial period of frying, the higher the oil temperature, the highest is the oil content of the chips. That due to the availability of the free water in the product during the initial period of the frying. Therefore, the lowest oil content is achieved when the chips are fried as close as to the equilibrium moisture content at the end of frying.

Frying potato slices at 140°C resulted in chips with the highest oil content compared to the chips fried at 120ºC, and 110ºC (Table 4.7). It seems that VI does have an effect on the surface structure/wettability of the chips increasing the oil absorption during the de-oiling process.

Table 4.7. Oil content for potato chips fried under vacuum at different oil temperatures.

T_{oil} [°C]	FT [s]	OCi [%d.b.]	OCe [%d.b.]	OC_M [%d.b.]
110	20 - 720	$5.87 \pm 0.71^{a,x}$	$0.35^{a,y} \pm 9.31$	$0.92^{a,y} \pm 10.90$
120	20 - 600	$8.94 \pm 0.73^{b,x}$	$11.96 \pm 0.78^{b,y}$	$12.58 \pm 1.21^{a,y}$
140	20 - 480	$12.99 \pm 0.66^{c,x}$	$12.12 \pm 0.81^{b,x}$	$15.80 \pm 0.51^{b,y}$

The test was performed in triplicate. Means within column with the same letter (a, d, c) or within row with the same letter (x, y, z) are not significantly different ($p<0.05$). T_{oil}= oil temperature, FT= frying time, OCi =Initial oil content at 20s of frying time, OCe =Equilibrium oil content (final oil content), and OC_M= maximum oil content value.

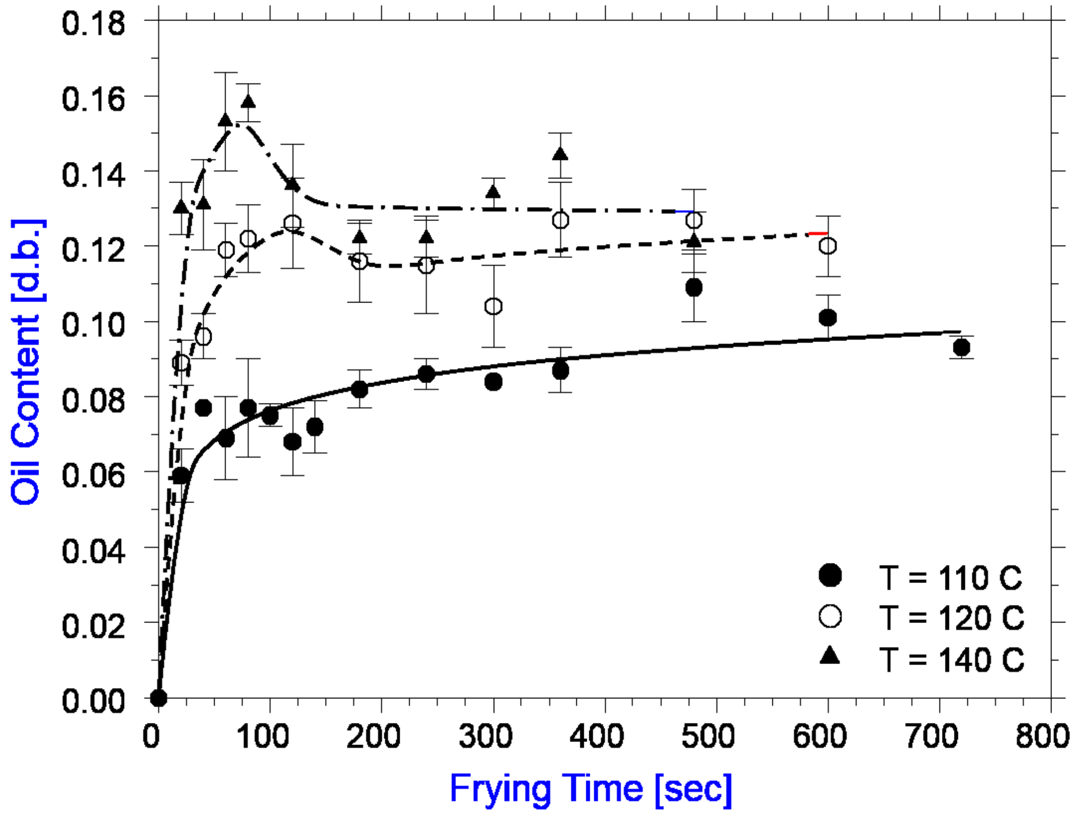

Figure 4.5. Oil absorption of potato chips during vacuum frying at different oil temperatures.

4.2.3 Kinetics of TPC during vacuum frying of potato chips

Table 4.8 shows that the maximum TPC was 27% higher than the initial TPC of the vacuum impregnated potato slices fried at 140°C. The vacuum impregnated potato slices fried at 120°C and 110°C had the maximum TPC only 20% and 11% higher than the initial TPC values, respectively. This indicates that the higher the frying temperature the higher TPC released during frying.

Table 4.8.Total phenolic content of potato chips fried under vacuum at different oil temperatures

T_{oil} [°C]	FT [(s]	TPC_{RP} [mg GAE/100g DW]	TPC_{AVI} [mg GAE/100g DW]	TPC_f [mg GAE/100g DW]	TPC_M [mgGAE/100g DW]
110	0-720	$116.42 \pm 14.71^{a,x}$	$137.87 \pm 8.52^{a,x,y}$	$117.89 \pm 0.96^{a,x}$	$2.70^{a,y} \pm 152.70$
120	0-600	$139.41 \pm 20.67^{a,x}$	$173.52 \pm 26.36^{a,b,x,y}$	$128.02 \pm 16.68^{a,x}$	$207.46 \pm 16.81^{b,y}$
140	0-480	$132.44 \pm 3.10^{a,x}$	$201.31 \pm 12.27^{b,y}$	$174.91 \pm 13.00^{b,y}$	$255.81 \pm 10.00^{c,z}$

The test was performed in triplicate. Means within column with the same letter (a, d, c) or within row with the same letter (x, y, z) are not significantly different ($p<0.05$). T_{oil} = oil temperature, FT= frying time, TPC_{RP} =Initial total phenolic of raw potato slices before VI, TPC_{AVI} =Initial total phenolic before frying after VI, TPC_f = final total phenolic content after frying and TPC_M= maximum total phenolic content during frying.

The TPC changed non-linearly during the frying process for all frying temperatures (Figure 4.6). The results show that the final TPC values of the chips after frying were lower than the vacuum impregnated potato slices for all frying temperatures. Vacuum impregnated potatoes fried at 120°C had 26% reduction in TPC after frying compared to the samples fried at 110°C (15%) and 140°C (13%). It was observed that the oil became reddish during the frying process due to the transfer of impregnated liquid from the samples.

Potato chips fried at 110°C had the same TPC of the raw potato slices, while those fried at 120°C had 15% less TPC than the raw potatoes, but those values were not significantly different ($p > 0.05$). Frying vacuum impregnated potato slices at 140°C produced potato chips with 33% more TPC than the raw potatoes. In conclusion, the VI treatment with red beet extract improved the process by making potato chips with the same or higher TPC than the raw material. The higher the temperature, the best TPC in VI fried chips.

Padda and Picha (2008) discussed that heating may disrupt the intracellular separation of the phenolic acids and oxidative enzymes (polyphenoloxidases), resulting in degradation of the phenolic acids in heated treated sweet potato. DeWanto et al. (2002) commented that thermal processing might release more bound phenolic acids from the breakdown of cellular constituents in sweet corn.

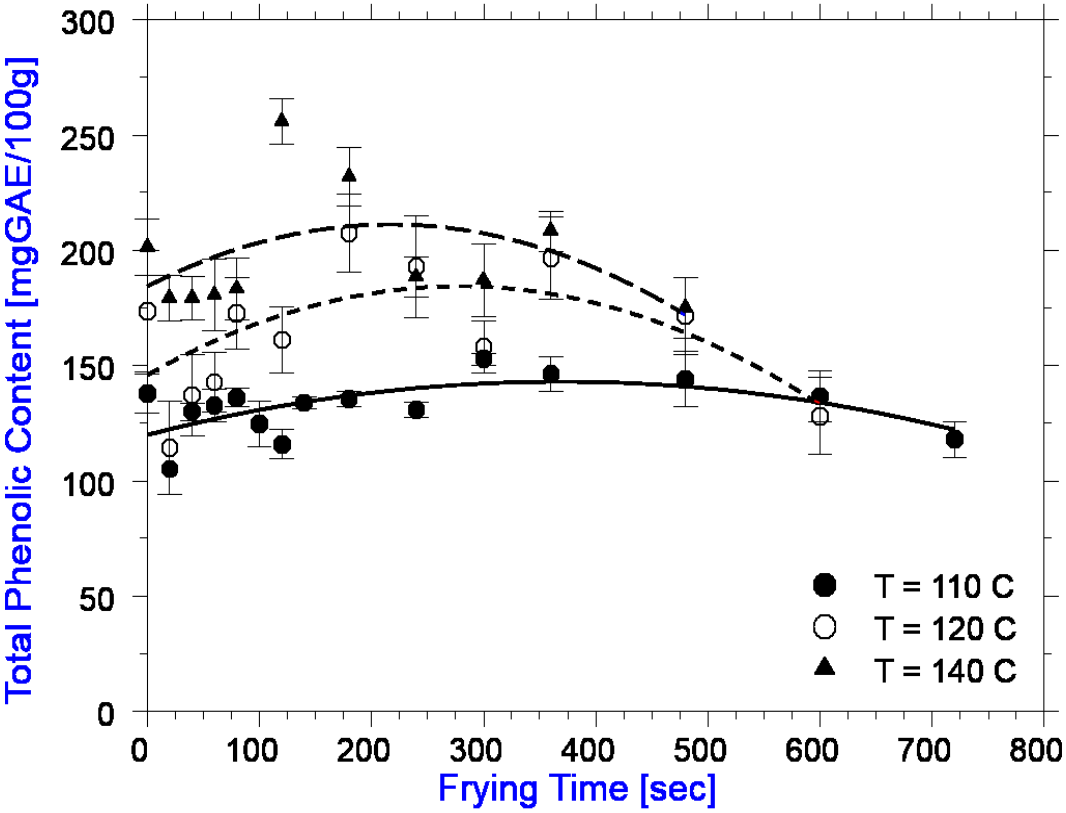

Figure 4.6. TPC of potato chips fried at different temperatures.

Different heating processes (boiling, frying, roasting) can liberate the phenolic compound in biological materials. The results in this study indicated that phenolic compounds in potato chips was either released by the cleaving of the esterified and glycosylated link or by the production of Maillard reaction are responsible for the increase in total phenolic content after heating (Maillard et al., 1996). Lee et al. (2003) commented that simple heating cannot cleave covalently bound phenolic compounds and showed that far-infrared (FIR) was able to liberate and activate covalently bound phenolic compounds in rice hull.

High temperature used during heating processes could also destroy the hydroxyl groups of phenolics (Barros et al., 2007) or modify phenolics with high antioxidant activity into different phenolics with low antioxidant activity (Jacobo-Velzquez and Cisneros-Zevallos, 2009), which cause a decrease in their antioxidant activity.

The phenolic compounds in the potato plant act as a protection response from bacteria, fungi, viruses, and insects. The total phenolic content of potatoes is higher than other fruits and vegetables like carrots, onions, or tomatoes; it is good sources of phenolic compounds (Chun et al., 2005).

The most abundant phenolic compounds in potatoes are phenolic acids. Chlorogenic acid constitutes 90% of the phenolic compounds in potato peels and exists in the form of three main isomers, chlorogenic acid, neochlorogenic acid, and cryptochlorogenic acid. Also, caffeic acid is quantified at 25–72 mg/100 g in potatoes by many studies (Akyol et al., 2016).

One of the factors responsible for the decline of phenols is the selective leaching of phenols from potato tubers. Unlike drying process, boiling process may show less destruction of compounds due to the thermal capacity of water. Optimized cooking techniques with low cooking temperatures and/or short processing times have been shown to improve the availability of different phenolic compounds in potatoes during the cooking process (Barba et al., 2008).

The characteristics of the particular potato cultivar, growing location, stage of potatoes tested, matrix compound (fat, protein, sugar), and treatments before cooking may have serious effects on the results of different cooking processes (Blessington et al., 2010). Additionally, a study showed that young potatoes have greater phenolic content than mature potatoes (Navarre et al., 2010)

4.3 Effect of different frying methods on (PQA) of the potato chips

4.3.1 Effect of frying method on moisture content of potato chips

Table 4.9 shows the moisture loss of potato slices fried by different methods and oil temperatures. Different frying methods and oil temperatures affected frying time and therefore the frying rate. It took 120 sec at 140°C in the VF, 180 sec at 140°C in the DSF, and 300 sec at 165°C in the TF to produce potato chips with the same characteristics in terms of color and texture.

When comparing potato slices fried under vacuum and atmospheric frying, the drying rate did not depend only on the temperature but also on the frying method. Potato slices fried under vacuum at 140°C had dried faster (Figure 4.7) than potato slices fried under atmospheric conditions at 165°C. The drying rate was calculated based on 16 g of potato slices.

Table 4.9. Initial moisture content of impregnated potato slices and moisture content after frying for potato chips fried under different methods.

FM	Toil [^{0}C]	FT[s]	P [kPa]	MC$_i$ [%w.b.]	MC$_f$ [%w.b.]
VF	140	120	1.33	77.97 $\pm$ 0.01^a	1.87 $\pm$ 0.01^a
DSF	140	60+120	101/1.33	77.97$\pm$ 0.01^a	1.69 $\pm$ 0.02^a
TF	165	300	101	77.97$\pm$ 0.01^a	1.59 $\pm$ 0.02^a

Test were performed in triplicate. Means with the same letter are not significantly different ($p<0.05$). FM= Frying methods; VF = Vacuum frying, DSF = dual-stage frying, TF= traditional frying. Toil= oil temperature, FT= frying time, P= frying pressure, MC$_i$ = initial moisture content, MC$_f$ = final moisture content

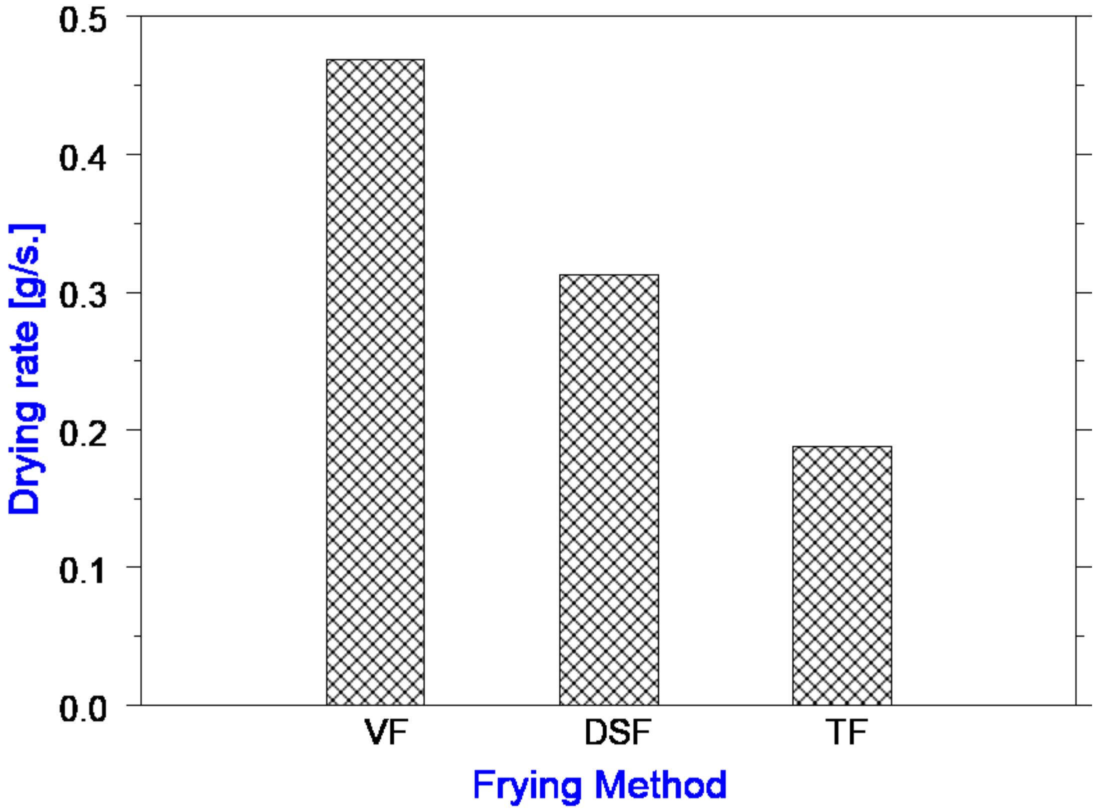

Figure 4.7. Drying rate of impregnated potato chips fried under different frying methods.

4.3.2 Effect of frying method on oil content of potato chips

One of the most important product quality factors for fried foods is oil content, and one of the main goals of fried foods studies and industries is to reduce the oil content while keeping the texture and color of fried foods.

Moreira et al. (2009) found that 14% of the total oil content was absorbed during frying and 86% was absorbed during cooling for tortilla chips fried at 190°C for 60 s. Therefore, the de-oiling system was used in this study to reduce oil absorption of fried chips. According to Ravli et al. (2013), the use of the de-oiling system removed up to

52% of the surface oil content of sweet potato chips fried under vacuum at different temperatures (120, 130, 140ºC) for 140s.

The oil content for the chips fried under vacuum at 140ºC (15.10% d.b.) was significantly lower ($p < 0.05$) than the oil content of potato chips fried under DS at 140ºC and atmospheric conditions at 165ºC (17.63% d.b.) and (32.32% d.b.), respectively (Figure 4.8 and Table 4.10).

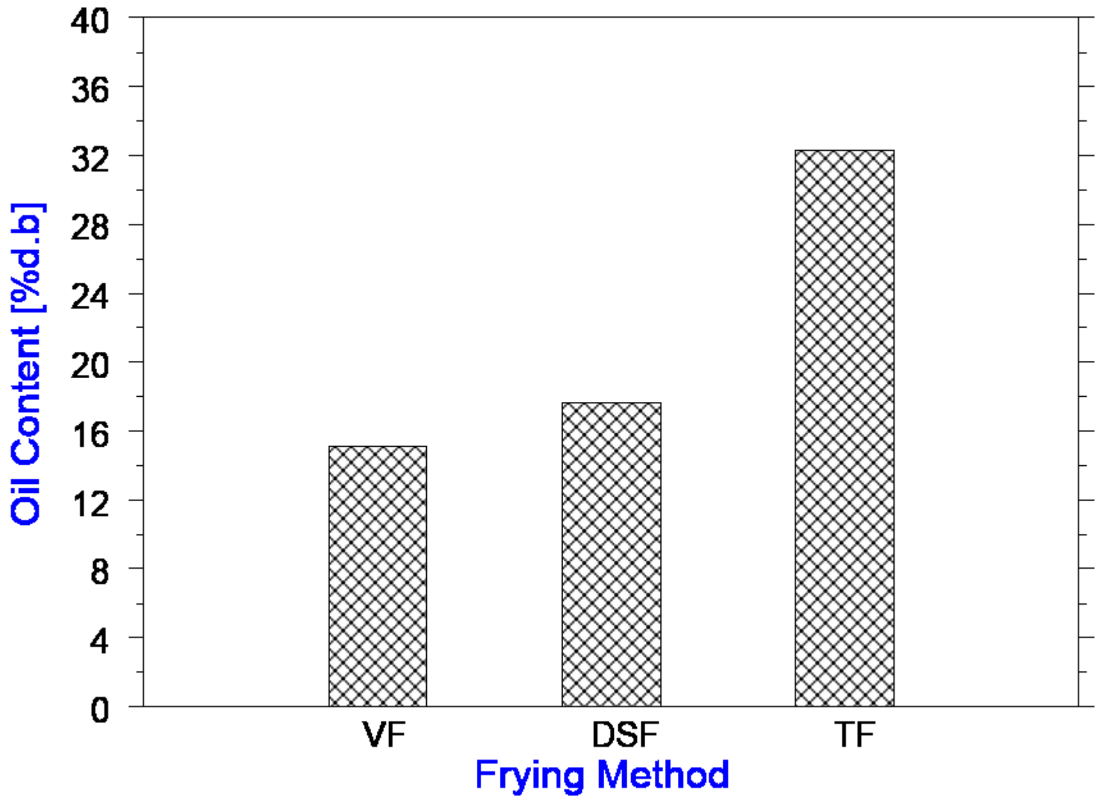

Figure 4.8. Oil content for potato chips fried under different frying methods.

Table 4.10. Oil content for potato chips fried under different frying methods.

FM	Toil [ºC]	FT [s]	P [kPa]	OC [%d.b.]
VF	140	120	1.33	15.10 ± 0.08^{a}
DSF	140	60+120	101/1.33	17.63 ± 0.04^{b}
TF	165	300	101	32.32 ± 0.10^{c}

Test were performed in triplicate. Means with different letter are significantly different ($p<0.05$).
FM= Frying methods; VF= Vacuum frying, DSF=dual stage frying, TF= traditional frying. Toil= oil temperature, FT= frying time, P= frying pressure, OC= oil content.

Baumann and Escher (1995) found out that higher oil temperatures caused a rapid progress of a solid crust and consequently surface properties that are good for oil absorption of chips fried under atmospheric pressure. Vacuum frying reduced oil content by using lower processing pressure and temperature (Da Silva and Moreira, 2008; Dueik et al., 2012; Garayo and Moreira, 2002; Teruel et al., 2014).

The total oil content of the dual-stage fried chips (17.63% d.b.) was significantly higher ($p < 0.05$) than the vacuum fried ones (15.10% d.b.). Potato chips fried under the DS method stayed longer in the oil and had more blisters than the vacuum fried chips that were formed during the atmospheric frying stage.

4.3.3 Effect of frying method on TPC of potato chips

Figure 4.9 shows that the total phenolic content in potato chips varied among chips fried under the different methods. The chips fried under atmospheric condition had a 19% reduction TPC after frying, while potato chips fried under vacuum and in dual-stage frying method had a 38% and 23% increase in TPC after frying, respectively (Table 4.11).

The significant diversity of phenolic compounds present in potatoes explained the diversification in phenols stability in fried potato chips. Phenolic acids are primarily found in bound form, linked to cell-wall structural components. Many types of food processing contributes to the release of these bounded phenolic acids, such as thermal processing, pasteurization, fermentation, and freezing (DeWanto et al., 2002; Ravichandran et al., 2012). The total phenols released from the potato during VF and DSF might have been more stable due the lower temperature, pressure, and frying times compared to the TF method.

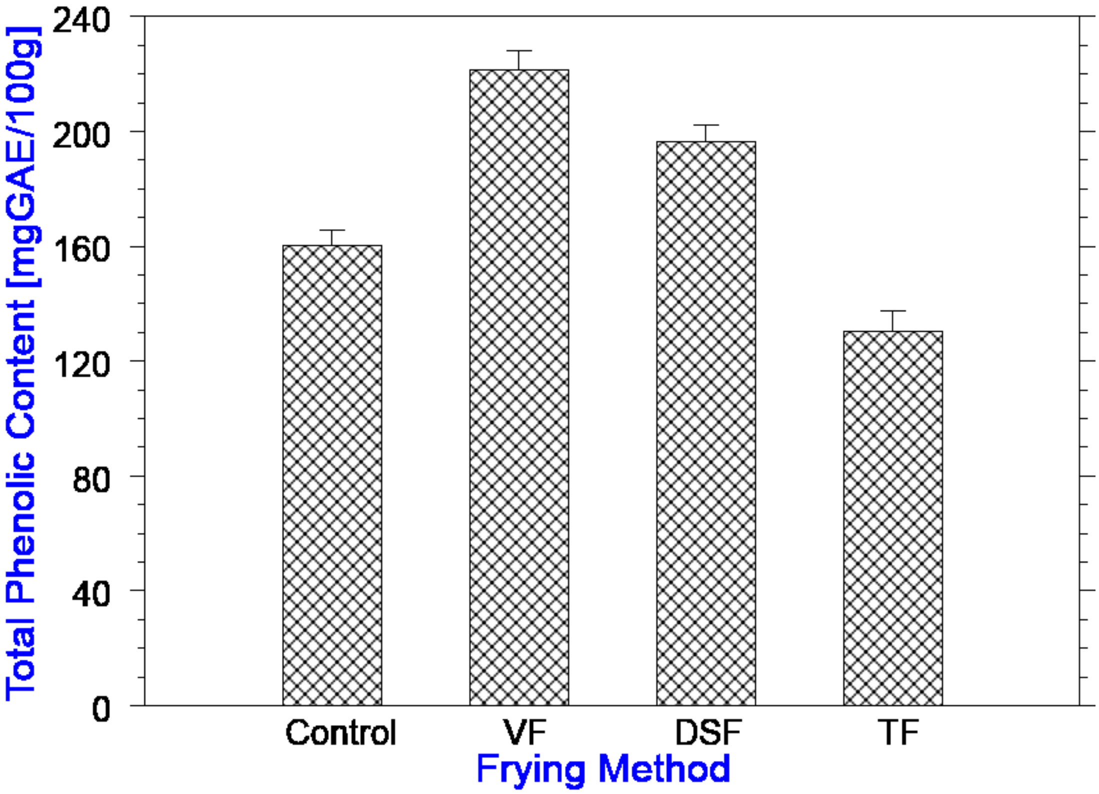

Figure 4.9. Total phenolic content (TPC) of frying potato chips at different methods vacuum frying (VF), dual-stage frying (DSF), and traditional frying (TF). Error represent standard deviation (± SD).

Table 4.11. Total phenolic content for vacuum impregnated potato slices (control) and potato chips fried under different frying methods.

FM	Toil [ºC]	FT (s)	Frying Pressure [kPa]	TPC [mgGAE/100g DW]
Control	-	-	-	160.27 $\pm$ 5.34^{b}
VF	140	120	1.33	221.65 $\pm$ 6.67^{d}
DSF	140	60+120	101/1.33	196.55 $\pm$ 5.61^{c}
TF	165	300	101	130.50 $\pm$ 7.55^{a}

Test were performed in triplicate. Means with different letter are significantly different ($p<0.05$). FM= Frying methods; VF= Vacuum frying, DSF= Dual stage frying, TF= Traditional frying. Toil= oil temperature, FT= frying time, P= frying pressure, TPC= Total phenolic content. Control is the VI potato slices before frying.

According to (Raupp et al., 2011), during hot air drying of beetroots, phenols degradation did not always result in the same outcomes. The differences between treatments, in terms of antioxidant potential, may happen from the phenomena of enzymatic action and/or physicochemical action, which are greatly dependent on temperature as well as on levels of water, oxygen, and natural compounds such as the phenolic constituents.

According to Nur Arina and Azrina (2015), TPC values were higher in the fried Jackfruit, Breadfruit, and Cempedak, compared to the fresh samples. Phenolic content of foodstuff can be easily affect by temperature and the polyphenol compounds that exist in the oil used for frying (Ruiz-Rodriguez et al., 2007). According to Sultana et al. (2008), TPC of the peas, and spinach significantly increased ($P < 0.05$) with microwave cooking. Also, TPC of the carrot increased with the cooking treatments (boiling, frying and microwave cooking). The study explained that the cooking treatments were the reason of that increase, which may have caused to the extractability and bioavailability of antioxidants from the vegetables. TPC may increase after some food processing due to softening or disruption of plant cell walls and the destruction of complex phenolics (Bernhardt and Schlich, 2005). In another hand, some phenols are more sensitive to degradation than other phenols, especially with longer time exposure to high temperature. That explain the degradation in phenolic content of potato chips fried under atmospheric condition, due to the higher oil temperature (165°C), longer frying time (300s), and oxygen exposure. Perla et al. (2012) tested some cooking methods on potato such as boiling, baking, and microwaving on phenolic compounds of five different cultivars. They found that the level of phenolic compounds was reduced by the three cooking methods, but boiling minimized those losses. The quantity and stability of phenolic compounds are dependent on several factors such as agriculture environment, harvest and post-harvest manipulations, storage conditions, and processing and cooking methods.

According to Crozier et al. (1997), cooking may have a major influence on the phenolic acid degradation. For instance, between 75% and 80% of the initial quercetin content is lost in onions and tomatoes after boiling for 15 min, 65% after cooking in microwave oven, and 30% after frying. Other study shows that atmospheric frying process caused a degradation of total phenolic compounds in potato chips with losses below 20% in chips obtained from red flesh potatoes and up to 60% of chips gotten from purple fleshed potatoes (Kita et al., 2015).

4.3.4 Effect of frying method on the bulk and true density, and porosity of potato chips

Table 4.12 shows the bulk density, true density, and porosity of fried potato chips at three different frying methods (VF, DSF, and TF).

The bulk density of DS and atmospheric fried chips were lower than vacuum fried chips. This indicates that vacuum fried chips were more compacted than the DS and atmosphere fried chips. Also observed by Ravli et al. (2013), the bulk density of the DS fried sweet potato chips was lower by 82% compared to the chips fried under vacuum. The porosity of the vacuum fried chips was much lower than the dual-stage fried chips (Figure 4.10) as was noted by Ravli et a. (2013).

Table 4.12. Bulk density (ρ_b), true density (ρ_t), and porosity (ϕ) values for potato chips fried at different methods.

FM	Toil (°C)	Time [s]	P [kPa]	ρ_b [kg/m^3]	ρ_t [kg/m^3]	ϕ
VF	140	120	1.33	537 ± 31^a	1408 ± 2^a	0.62
DSF	140	60+120	101/1.33	348 ± 13^b	1400 ± 3^a	0.75
TF	165	300	101	462 ± 46^c	1404 ± 2^a	0.67

Tests were performed in triplicate. Means within column with the same letter are not significantly different ($p<0.05$). FM= Frying methods; VF= Vacuum frying, 2SF=Two stage frying, ATM= atmospheric frying. ρ_b =bulk density, ρ_t = true density, and ϕ= porosity.

The surface of the potato chips fried under vacuum frying contained several small, uniformly distributed bubbles, while the potato chips fried under atmospheric and dual stage pressure had less, but larger bubbles. Under vacuum frying and during the evacuation process, water vapor in the chip's pores expands with little resistance because the crust has not yet been formed (Garayo and Moreira, 2002). On the other hand, the gelatinized starch and then the crust formation during traditional frying form a barrier for the saturated vapor to escape, thus resulting in the formation of large but few bubbles during frying (Kawas and Moreira, 2001).

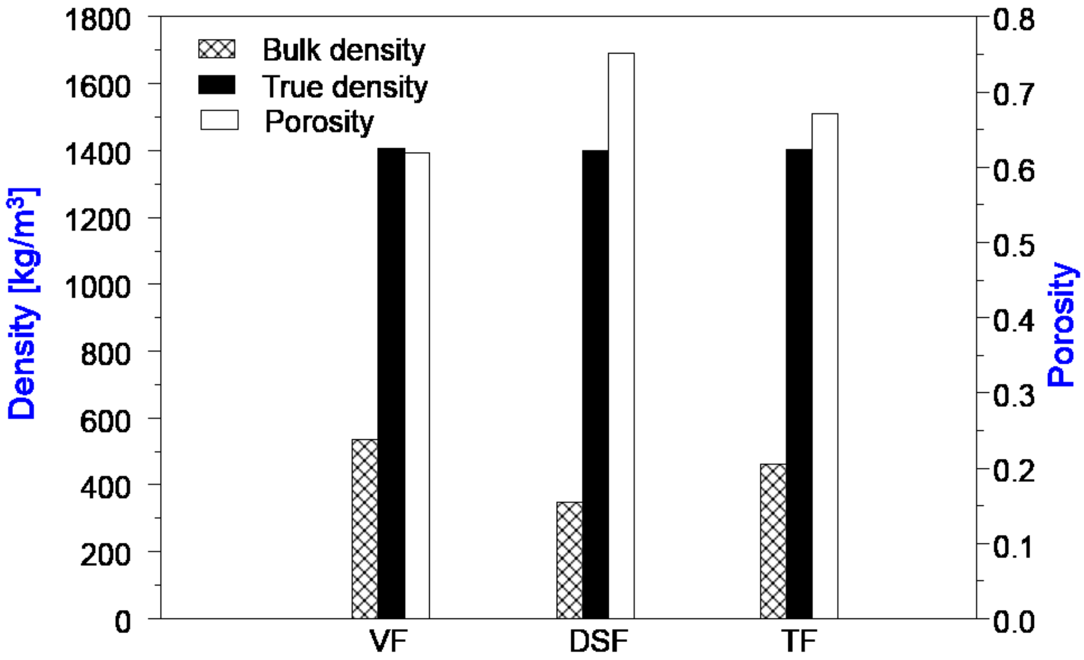

Figure 4.10. Bulk density (ρ_b) values for potato chips fried at different methods.

4.3.5 Effect of frying method on changing chips dimensions

Figure 4.11 and Table 4.13 represent a comparison of the degree of shrinkage in diameter for potato chips fried under different frying methods. Potato chips fried under vacuum pressure had higher diameter shrinkage (13.07%) than potato chips fried under dual stage frying (12.53%) and atmospheric pressure (10.31%). However, the volume shrinkage of the three frying methods are not significantly different ($p < 0.05$).

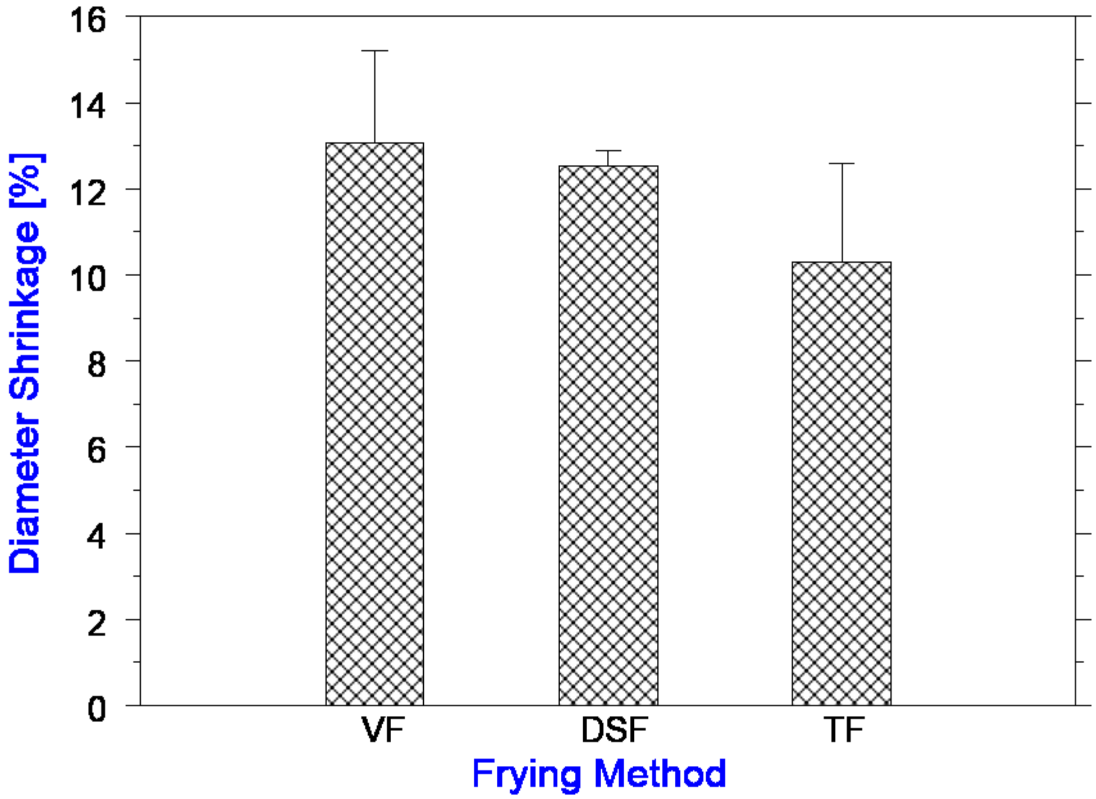

Figure 4.11. Degree of shrinkage in diameter (D) of frying potato chips at different methods; vacuum frying (VF), two stage frying (2SF), and atmospheric frying (ATM). Error represent standard deviation (± SD).

Table 4.13. Shrinking in diameter (D), and expanding in thickness (L) values for potato chips fried at different methods.

FM	D [%]	L [%]
VF	13.07 ± 2.16^a	19.46 ± 0.60^a
DSF	12.53 ± 0.37^a	40.59 ± 4.71^b
ATM	10.31 ± 2.29^a	55.10 ± 2.36^c

Means within column with the same letter are not significantly different ($p<0.05$).
FM= Frying methods; VF= Vacuum frying, DSF= dual stage frying, TF= traditional frying. D = shrinking in diameter, and L = expanding in thickness

Garayo and Moreira (2002) studied the degree of shrinkage in volume for potato chips fried under vacuum and atmospheric conditions. Potato chips fried under vacuum showed a higher degree of volume change than potato chips fried at atmospheric conditions. They had explained that this behavior is due to the fact the product becomes more rigid rapidly at a higher temperature, when fried under atmospheric frying, than when fried under vacuum frying which producing increased resistance to volume change.

Potato chips fried at different frying methods had higher thickness than the initial thickness (1.60 mm) of the raw slice. Figure 4.12 and Table 4.13 show that thickness expansion of potato chips fried under dual-stage and atmospheric pressure were significantly higher ($p < 0.05$) than potato chips fried under vacuum pressure.

Garayo and Moreira (2002) studied the thickness expansion between potato chips fried using vacuum frying and at atmospheric frying and found that chips fried under vacuum have less thickness expansion and several small bubbles then the atmospheric ones. Ravli et al. (2013) found that thickness expansion for dual-stage fried chips was higher than chips fried under the vacuum.

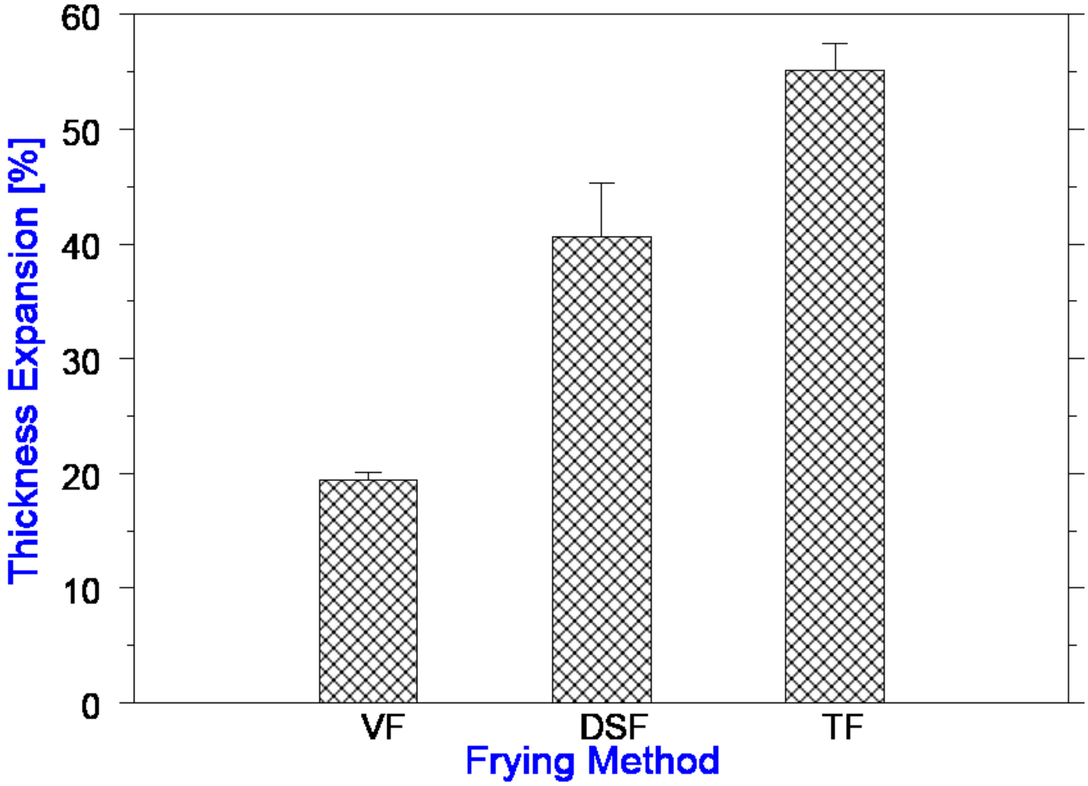

Figure 4.12. Degree of expansion in thickness (L) of frying potato chips at different methods; vacuum frying (VF), two stage frying (2SF), and atmospheric frying (ATM). Error represent standard deviation (± SD).

4.3.6 Effect of frying method on the color of potato chips

Figures 4.13 shows the differences in the color parameters (L*, a*, and b*) for the vacuum impregnated potato slices (VI) and potato chips fried at three different frying methods.

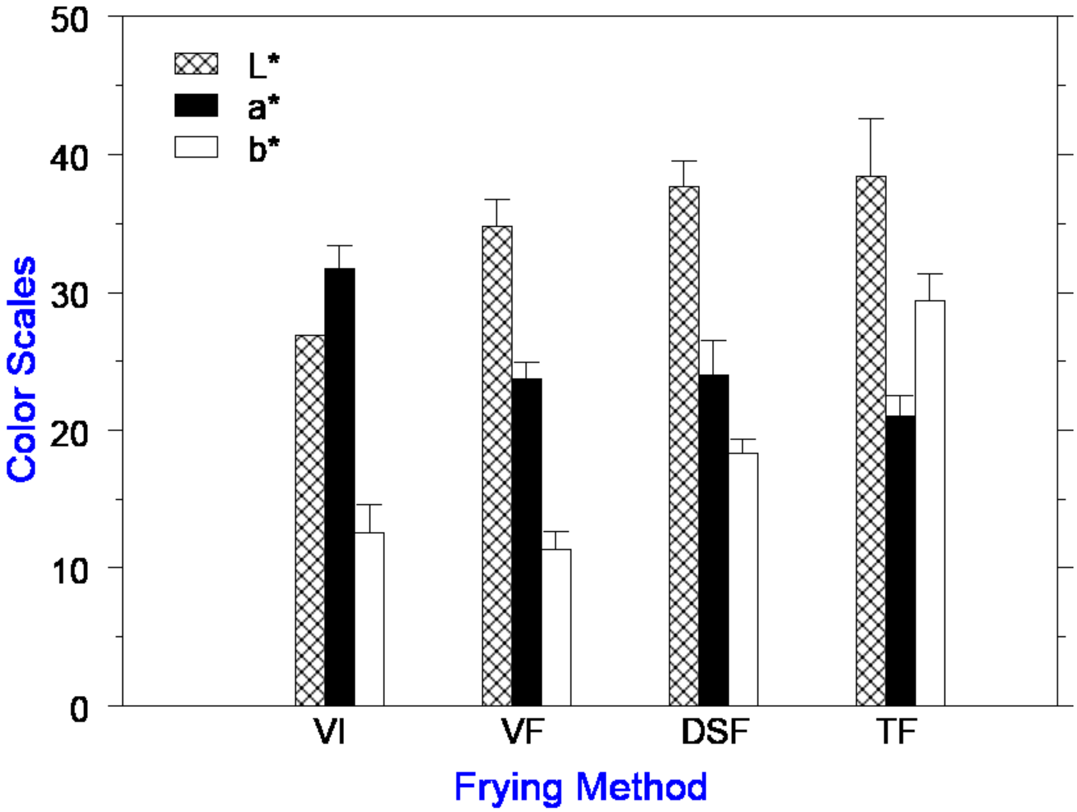

Figure 4.13. Comparison of color of vacuum impregnated potato slices (VI) and frying potato chips at different frying methods; vacuum frying (VF), two stage frying (2SF), and atmospheric frying (ATM). Error represent standard deviation (± SD). Values are given as mean (n= 9).

The L* value points to lightness with ranges from 0 to 100 (from black to white). Table 4.14 shows that the VI potato slices chips were darker (L* values 26.89 ± 0.31) than the potato chips fried under different frying methods. The vacuum impregnated potato slices showed a significant difference ($p < 0.05$) value of L* than the potato chips fried under different frying methods. The atmospheric frying method improved the color of the impregnated potato chips in terms of lightness, due to the number of large pores in the potato chips surface.

The a* value indicates the redness, the a* value for potato chips fried under atmospheric frying was lower than the vacuum impregnated potato slices, and potato chips fried under the other frying methods (Table 4.14). The potato chips fried under atmospheric pressure lost the red pigment of the impregnated red beetroot solution, while chips fried by the vacuum frying and dual-stage methods maintained the red color of the red beetroot solution in the potato chips.

For the b* values of potato chips fried under the dual-stage and traditional frying methods were significantly higher ($p < 0.05$) than chips fried under vacuum frying (Table 4.14). The change in color, yellowness, in fried potato chips is due to Maillard reaction also known as non- oxidative browning. Maillard reaction is a chemical reaction between amino acids and reducing sugars that gives brown color (Garayo and Moreira, 2002).

Table 4.14. Color values of vacuum impregnated potato slices and potato chips fried under different frying methods.

Color values	**L***	**a***	**b***
VI	26.89 ± 0.31^{a}	31.78 ± 1.65^{x}	12.54 ± 2.02^{a}
VF	34.77 ± 1.92^{b}	23.77 ± 1.16^{x}	11.31 ± 1.31^{a}
DSF	37.66 ± 1.87^{b}	23.97 ± 2.52^{x}	18.29 ± 1.08^{b}
TF	38.45 ± 4.10^{b}	20.98 ± 1.51^{y}	29.38 ± 1.95^{c}

Means within column with different letter are significantly different ($p<0.05$). VI= vacuum impregnated potato slices; VF= Vacuum frying, 2SF=Two stage frying, ATM= atmospheric frying. L*= color values (black to white) points to lightness, a*= color value (green-red chromaticity), b*= color value (blue-yellow chromaticity)

4.3.7 Effect of frying method on texture of potato chips

The effect of frying method on the potato chips texture is shown in Figure 4.14. Table 4.15 shows the texture results of potato chips fried under different frying methods. The maximum force to break the chips was found when using the traditional frying method. However, this value was not significantly different ($p > 0.05$) from those fried under vacuum frying and dual-stage methods.

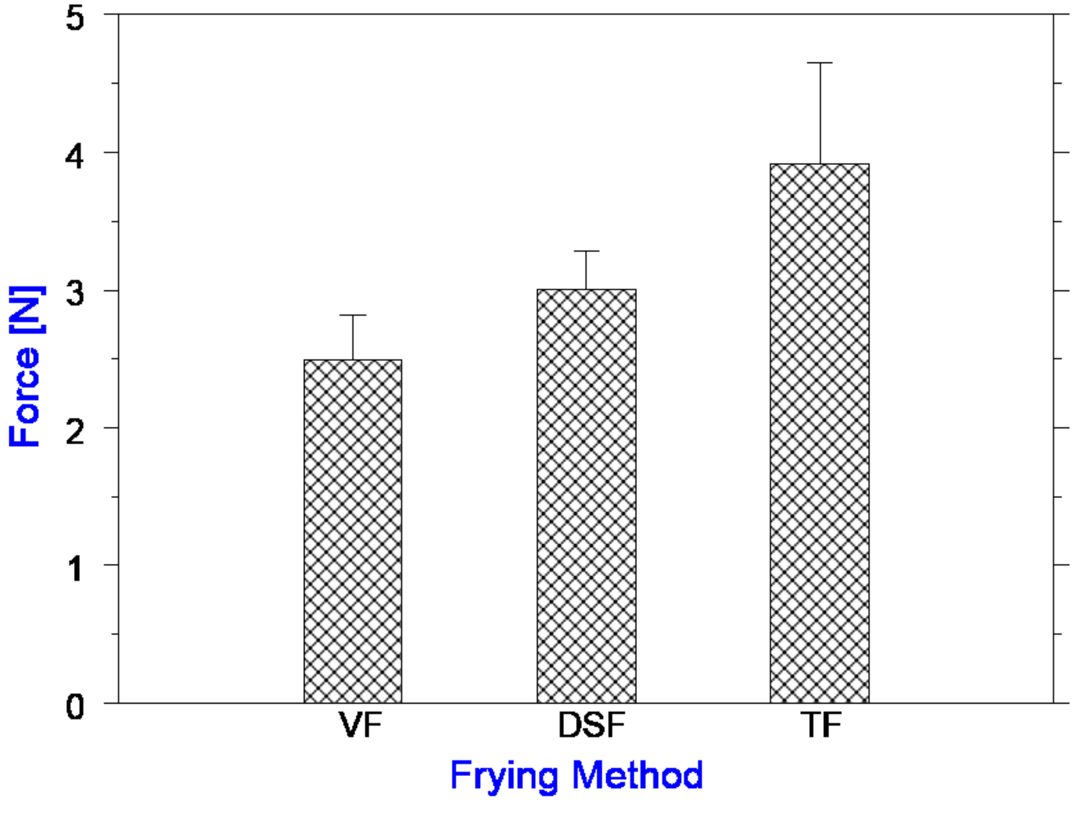

Figure 4.14. The effect of frying method on the potato chips texture; vacuum frying (VF), two stage frying (2SF), and atmospheric frying (ATM). Error bars represent standard deviation (± SD). Values are given as mean.

Table 4.15. Texture of potato chips fried under different frying methods.

FM	Toil [^{0}C]	FT [s]	P [kPa]	F [N]
VF	140	120	1.33	2.49 ± 0.33^{a}
DSF	140	60+120	101/1.33	3.01 ± 0.27^{a}
TF	165	300	101.33	3.92 ± 0.73^{a}

Means with different letter are significantly different ($p < 0.05$). FM= Frying methods; VF= Vacuum frying, DSF= dual stage frying, TF= traditional frying. Toil= oil temperature, FT= frying time, P= frying pressure, F = force.

Granda (2006) found that there were no significant textural differences (P>0.05) among potato chips fried under vacuum or traditional methods. Also, Da Silva and Moreira (2008) measured the texture of blue and sweet potato, green bean and mango chips. They found no significant different on the force required to break the samples (P>0.05) when frying under vacuum and atmospheric pressure.

The variation in texture data is due to numerous reasons, including the shape of the samples (some samples were a little not uniform), unnoticed cracks, and the degree of puffiness. The surface of the potato chips fried under vacuum frying method had several small bubbles, which make the surface of the chips uniform. In the other hand, the potato chips fried under traditional and dual-stage frying methods were not uniform as also observed by Garayo and Moreira (2002).

4.3.8 Effect of frying method on sensory quality of potato chips

Figure 4.15 shows the scores of sensory evaluations of that potato chips fried under the different frying methods. Scores equal or higher than 5 were considered acceptable, based on the nine-point hedonic scale (Carr et al., 1999) The potato chips fried under the three different frying methods obtained scores above 5 (acceptable) in every category offered to the panelists in terms of appearance, color, odor, texture, flavor, and overall quality. The potato chips fried under atmospheric pressure obtained the lowest scores for the flavor category, because those chips tasted as overcooked by the panelists.

Potato chips fried under vacuum and dual-stage frying methods were significantly more acceptable ($p > 0.05$), in terms of flavor and overall quality than the potato chips fried under atmospheric pressure (Table 4.16). The texture scores among the different frying methods show no significant different ($p > 0.05$).

In summary, all potato chips fried under different frying methods were acceptable by the consumer panelists. However, potato chips fries under vacuum and dual-stage frying were more acceptable than the potato chips fried under atmospheric pressure.

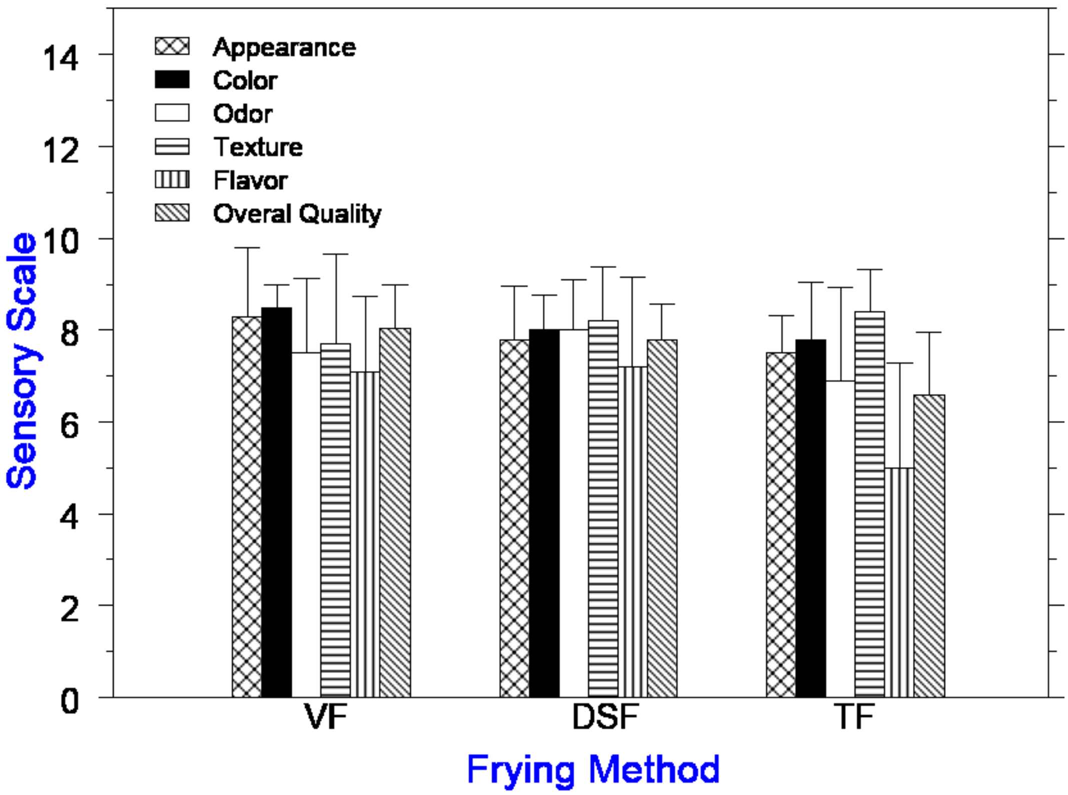

Figure 4.15. Sensory evaluation for potato chips fried under different frying methods; vacuum frying (VF), two stage frying (2SF), and atmospheric frying (ATM). Error represent standard deviation (± SD). Values are given as mean (n= 30).

Table 4.16. Sensory evaluation for potato chips fried under different frying methods.

FM	Appearance	Color	Odor	Texture	Flavor	Overall quality
VF	8.30 ± 1.49^{b}	8.50 ± 0.50^{b}	7.50 ± 1.63^{a,b}	7.70 ± 1.95^{a}	7.10 ± 1.64^{b}	8.03 ± 0.95^{b}
DSF	7.80 ± 1.17^{a,b}	8.00 ± 0.77^{a,b}	8.00 ± 1.10^{b}	8.20 ± 1.17^{a}	7.20 ± 1.94^{b}	7.80 ± 0.75^{b}
TF	7.50 ± 0.81^{a}	7.80 ± 1.25^{a}	6.90 ± 2.02^{a}	8.40 ± 0.92^{a}	5.00 ± 2.28^{a}	6.60 ± 1.36^{a}

Means within a column with different letter are significantly different ($p < 0.05$). FM= Frying methods; VF= Vacuum frying, DSF=dual-stage frying, TF= traditional frying.

Figure 4.16 shows the images of different potato samples, raw and fried at different frying methods. Figure 4.16a displays the deep red color of the vacuum impregnated potato slices. Figures 4.16b and 4.16c show that vacuum frying and dual-stage methods maintained the red color of the red beetroot solution in the potato chips. However, for potato chips fried under atmospheric frying (Figure 4.16d), they have an orange like color caused by oxidation during the frying process.

The surface of the potato chips fried under vacuum frying pressure (Figure 4.16b) shows less expansion and several small bubbles. The potato chips fried under atmospheric pressure (Figure 4.16d) and under dual-stage pressure (Figure 4.16c) have less, but larger bubbles. The bubble formation at the surface of the fried chips depends on gas expansion inside the pores and the volume shrinkage results from water transfer within the product.

These results agree with the sensory evaluation results, which show that potato chips fried under vacuum and dual-stage frying methods were significantly more acceptable ($p < 0.05$), in terms of overall quality than the potato chips fried under atmospheric pressure.

Figure 4.16. Color differences among raw potato slices and potato chips. (a) Vacuum impregnated potato slices (VI); (b) vacuum fried potato chips (VF), (c) dual-stage fried potato chips (DSF), and (d) traditional fried potato chips (TF).

CHAPTER V

CONCLUSIONS

This study focused on evaluating the feasibility of using vacuum impregnation technique to enrich potato chips with a phenolic component of red beetroot as a pretreatment to frying processes.

The vacuum impregnation variables such as impregnation solution concentration, vacuum and restoration times, and pressure were evaluated to find the best pre-treatment to obtain high-quality fried potato chips.

The effect of vacuum frying temperature and time on potato chips were evaluated based on product characteristics such as moisture loss, oil absorption, and total phenolic content to find the best vacuum frying temperature and time to obtain high-quality of potato chips.

Three different vacuum frying methods, vacuum, dual-stage, and traditional frying, were used to evaluate potato chips quality attributes and sensory analysis.

These parameters were important to determine the best quality of potato chips. A de-oiling system was used to remove the oil at the surface of the chips before cooling.

The main results obtained in the study were:

- Solution absorption during VI decreased as the solution concentration increased.
- The solution Brix increased as the solution concentration increased, thus causing some of the water to leach out from the potato slices.

- The best pre-treatment to enrich the potato slices with phenolic content of red beetroot solution were 7% of impregnation solution concentration at 600 mmHg pressure and 10 minutes of vacuum pressure and 10 minutes atmospheric restoration.
    - The best restoration time was 60 min. The product lost, in average, 15.06% + 2.26 of its water during the VI treatment, however, the SG values varied greatly showing little solid gains or solid losses
- The oil temperatures influence the moisture content of potato slices during vacuum frying differently.
    - The chips fried at 120 and 140°C lost moisture faster than the chips fried at 110°C.
- The chips' oil content increased as frying time increased within the first 80 seconds for 140°C and 120°C temperatures
    - Frying at 140°C made the chips to absorbed more oil with maximum value of 16% d.b.
- The TPC of the potato chips fried under vacuum increased as frying time increased until reached the maximum TPC by half way during frying.
    - Frying vacuum impregnated potato slices at 140°C produced potato chips with 33% more TPC than the raw potatoes.
    - Potato chips fried at 140°C were showing more increase in TPC than chips fried at 120°C and 110°C.

    - The TPC in chips process with longer exposure to heat, decrease for all different frying temperatures.
- Different frying methods and oil temperatures affected the frying rate; it took 120 sec at 140°C during VF, 180 sec at 140°C during DSF, and 300 sec at 165°C during TF to produce potato chips with the same characteristics in terms of color and texture.
- Frying methods affected ($p < 0.05$) the oil content in fried potato chips.
    - The oil content for the chips fried under vacuum at 140°C (15.10% d.b.) was significantly lower ($p < 0.05$) than the oil content of potato chips fried under DS at 140°C and atmospheric conditions at 165°C (17.63% d.b.) and (32.32% d.b.), respectively.
- The TPC of chips fried under traditional method was the lower in comparison with other methods (130.50 ± 7.55 mg GAE/100g DM).
    - Potato chips fried under vacuum presser show higher total phenolic content (221.65 ± 6.67 mg GAE/100g) than the vacuum impregnated potato slices (160.27 ± 5.33 mg GAE/100g DM).
    - The potato chips fried under dual stage frying method shows lower total phenolic content (196.55 ± 5.61 mg GAE/100g DM) compared with the chips fried under vacuum pressure, however it shows higher total phenolic content than the vacuum impregnated potato slices.
- The bulk density of dual stage and traditional fried chips were lower than the vacuum fried chips.

  - The dual stage and traditional fried samples were more porous than vacuum fried samples, which resulted in a lighter color.
  - The porosity in potato slices increased as the bulk density decreased.
- Potato chips fried under vacuum pressure had higher diameter shrinkage (13.07%) than potato chips fried under dual stage frying (12.53%) and atmospheric pressure (10.31%).
- Potato chips fried at different methods had higher thickness than the initial thickness (1.60 mm) of the raw slice.
  - That thickness expansion of potato chips fried under dual stage and traditional pressure were significantly higher ($p < 0.05$) than potato chips fried under vacuum pressure.
- Color a* (redness) significantly decreased ($p < 0.05$) and the color b* (yellowness) significantly increased ($p < 0.05$) in potato chips fried at traditional method comparing with the control and other frying methods.
- Texture (the maximum force to break the chips) was 3.92 ± 0.73 N for chips fried under traditional frying method.
  - There was no significantly different ($p > 0.05$) in texture between the different frying methods.
- Potato chips fried under the three different frying methods obtained scores above 5 (acceptable) in every category offered to the panelists.

  - Potato chips fried under vacuum and dual-stage frying methods were significantly more acceptable ($p < 0.05$), in terms of flavor and overall quality, than the potato chips fried under traditional method.
  - The texture scores among the different frying methods show no significant differences ($p > 0.05$).
- Overall, the best technique of enriched potato chips is when using 7% concentration of beetroot solution at 600 mmHg vacuum pressure for 10 min, and 60 min restoration time as a pre-treatment

The best fryer technique was frying VI potato slices at 1.33 kPa for 120 sec at 140°C to improve total phenolic content, color, flavor, and, and reduce the oil content in the final product.

CHAPTER VI

RECOMMENDATIONS FOR FURTHER STUDY

Recommendations for future research on enriched frying of vegetable-based chips include:

- Study the possibility of reuse the beetroot solution many times to impregnate the potato chips to lower preparation costs.
- Study the raw material characteristics such as porosity, size, and shape to improve vacuum impregnation technique.
- Provide a broader study in vacuum impregnation area, considering the factors affecting the tissue material such as the differences in porosity and rigidity.
- Evaluate the effect of potato variety on pre-treatment (vacuum impregnation) and frying parameters and the product quality attributes.
- Study the effect of vacuum impregnation and vacuum frying in other vegetables and fruits.
- Determine the phenolic content of enriched potato chips by using HPLC analysis method.
- Study the bioavailability of phenolic compounds and antioxidant effects of enriched potato chips.
- Determine the nitrate content of enriched potato chips.
- Study the effect of the total phenol content present in the oil used for frying.

- Provide more research studies in dual-stage frying method

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APPENDIX A

Sensory Evaluation

Instruction: Please evaluate each sample for each quality parameter and use the number scale below to mark the box which you feel best describes how you like the sample.

An honest expression of your personal feelings will help us. Thank you.

Like extremely	Like very much	Like moderately	Like slightly	Neither like nor dislike	Dislike slightly	Dislike moderately	Dislike very much	Dislike extremely
9	8	7	6	5	4	3	2	1

	Appearance	Color	Odor	Texture (Crispness)	flavor	Overall Quality
Sample # 708						
Sample # 756						
Sample # 864						

Comments: ……………………………………………………………………

APPENDIX B

Effect of frying time and oil temperature on the moisture content, oil content, and total phenolic content of impregnated potato chips fried under vacuum at 110 °C

Toil [^{o}C]	**FT[s]**	**MC% [%w.b.]**	**OC [%d.b.]**	**TPC [mgGAE/100g DW]**
110	720	1.04 ± 0.12	9.31 ± 0.34	117.89 ± 7.96
	600	1.10 ± 0.07	10.08 ± 0.55	136.78 ± 11.01
	480	1.30 ± 0.20	10.90 ± 0.92	144.06 ± 11.94
	360	1.72 ± 0.15	8.65 ± 0.63	146.27 ± 7.46
	300	2.12 ± 0.10	8.39 ± 0.11	152.73 ± 2.70
	240	2.72 ± 0.20	8.59 ± 0.40	130.77 ± 3.42
	180	9.01 ± 2.73	8.24 ± 0.46	135.41 ± 3.25
	140	23.62 ± 2.38	7.24 ± 0.65	133.82 ± 2.62
	120	27.47 ± 7.90	6.82 ± 0.91	115.81 ± 6.31
	100	35.46 ± 9.90	7.50 ± 0.34	124.58 ± 9.83
	80	45.45 ± 8.96	7.68 ± 1.33	136.08 ± 4.04
	60	50.19 ± 6.51	6.93 ± 1.09	132.77 ± 6.91
	40	59.51 ± 3.87	7.68 ± 0.14	130.03 ± 3.76
	20	64.91 ± 2.85	5.87 ± 0.71	105.24 ± 0.18
	0	75.80 ± 0.74	-	137.88 ± 8.52

Toil= oil temperature, FT= frying time, MC = moisture content, OC= oil content, TPC= Total phenolic content.

Effect of frying time and oil temperature on the moisture content, oil content, and total phenolic content of impregnated potato chips fried under vacuum at 120 °C

Toil [^{0}C]	**FT[s]**	**MC% [%w.b.]**	**OC [%d.b.]**	**TPC [mgGAE/100g DW]**
120	600	0.73 ± 0.03	11.96 ± 0.78	128.03 ± 16.68
	480	0.71 ± 0.14	12.72 ± 0.84	171.52 ± 16.76
	360	1.01 ± 0.18	12.68 ± 1.05	196.75 ± 17.93
	300	1.10 ± 0.13	10.40 ± 1.15	158.02 ± 11.32
	240	1.20 ± 0.14	11.50 ± 1.29	192.78 ± 22.20
	180	1.88 ± 0.30	11.63 ± 1.09	207.47 ± 16.81
	120	5.08 ± 1.22	12.58 ± 1.21	161.18 ± 14.43
	80	19.76 ± 4.43	12.22 ± 0.93	172.63 ± 15.53
	60	28.72 ± 6.78	11.88 ± 0.67	142.72 ± 13.01
	40	53.52 ± 0.65	9.63 ± 0.65	137.09 ± 17.46
	20	58.03 ± 3.21	8.94 ± 0.63	114.53 ± 20.18
	0	77.58 ± 1.33	-	173.52 ± 26.36

Toil= oil temperature, FT= frying time, MC = moisture content, OC= oil content, TPC= Total phenolic content.

Effect of frying time and oil temperature on the moisture content, oil content, and total phenolic content of impregnated potato chips fried under vacuum at 140 °C

Toil [^{0}C]	**FT[s]**	**MC% [%w.b.]**	**OC [%d.b.]**	**TPC [mgGAE/100g DW]**
140	480	0.51 ± 0.04	12.12 ± 0.81	174.91 ± 13.01
	360	0.66 ± 0.06	14.41 ± 0.56	208.30 ± 8.65
	300	0.84 ± 0.09	13.42 ± 0.40	187.05 ± 15.69
	240	0.90 ± 0.05	12.16 ± 0.50	188.35 ± 8.76
	180	1.12 ± 0.06	12.21 ± 0.42	231.89 ± 12.57
	120	1.37 ± 0.05	13.61 ± 1.15	255.81 ± 10.00
	80	6.82 ± 0.35	15.80 ± 0.51	183.25 ± 13.55
	60	17.77 ± 4.75	15.33 ± 1.28	180.52 ± 15.43
	40	47.21 ± 3.14	13.14 ± 1.51	179.02 ± 9.44
	20	53.47 ± 1.21	12.99 ± 0.67	179.01 ± 9.76
	0	81.18 ± 0.86	-	201.31 ± 12.27

Toil= oil temperature, FT= frying time, MC = moisture content, OC= oil content, TPC= Total phenolic content.