DEVELOPING HEALTHY SNACK CHIPS BY CONTINUOUS VACUUM BELT DRYING

by

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(Under the Direction of William L. Kerr)

ABSTRACT

Low-fat tortilla chips and sweet potato chips were developed by a continuous vacuum belt drying (CVD) method and compared to those made by deep fat frying (DFF). Quality factors of the products were investigated including oil content, texture attributes, color, sensory properties, shrinkage and nutrient retention. Drying characteristics such as drying time, diffusivity, and drying models were studied in this research.

A continuous vacuum drying method was used to develop low-fat tortilla chips and sweet potato chips with good sensory properties. The CVD chips developed an expanded structure and contained 1.57-1.82 g oil/100 g, depending on initial thickness, compared to 33.37-34.80 g oil/100g for DFF chips. Three levels of chip thickness and three levels of plate heating temperature were studied to show how the drying conditions affected the quality of tortilla chips and the amount of energy consumed.

Several drying models were investigated to test their applicability to CVD tortilla chips. The models can be used to predict drying times and optimize drying processes, and provide insight into the mechanisms of drying and the importance of product properties. Model was developed from the drying rate curves that incorporated a characteristic drying coefficient [k(t)] that varied with time. All models had good agreement between experimental data and predicted

data, with r2>0.98. With consideration of other goodness-of-fit indicators (SSE and $\chi 2$), results showed that the model that incorporated k(t) gave the best fit.

The color, texture, microstructure, and β-carotene content of CVD sweet potato chips were studied and compared to DFF chips. The results showed that continuous vacuum belt drying gives good color and nutrient retention in the sweet potato chips, and that CVD chips had similar texture attributes to those prepared by deep fat frying. Low temperature (100°C) vacuum dried products had the most similar color values (L* C* H*) to fresh sweet potatoes. Chips dried at a sequence of temperatures (T-mix=140/120/100°C) had the lowest hardness and highest fracturability, and were most similar to DFF chips.

INDEX WORDS: Continuous vacuum belt drying, Low-fat, Corn chips, Tortilla chips, Sweet potato chips, Texture, Deep-fat frying, Acoustic analysis, Drying models, Diffusivity, Drying time, Microstructure, Beta-carotene

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DEDICATION

Dedicated to my parents, Weisen Xu and Yilian Xu

Husband, Jinjun Xia

My sons, Jerry Xia and Ethan Xia

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CHAPTER 1

INTRODUCTION

1.1 Justification of the research

1.1.1 Problems

Obesity has been a growing problem in the United States for the last few decades. Among American adults, some 68.0% are overweight or obese (Flegal, Carroll, Kit, & Ogden, 2012). Obesity is also correlated with diseases such as diabetes, heart disease, high blood pressure, joint disease and cancer (Mokdad, Marks, Stroup, & Gerberding, 2004). Obesity related diseases cause approximately 400,000 deaths per year in the US, and are associated with $150 billion in medical costs. Hospital costs associated with childhood obesity were estimated at $127 million during 1997-1999, up from 35 million during 1979-1981. The total cost of obesity in the US was estimated to be $117 billion in the year 2000 (Flegal et al., 2012).

Obesity can be associated with many factors including sociological issues, behavioral patterns, government policy, and available food choices**.** Increasing the availability of healthy choices in the food supply may play an important role in combating obesity. Many consumers blame the food industry for contributing to the obesity problem. In particular, “fast” foods, sugary sodas and beverages, and high-fat snacks are most commonly accused as culprits that lead to overconsumption of calories that provide little nutrition. While this is an overly simplistic viewpoint as to the causes of obesity, there is clearly a market demand for, and benefits to be had in creating nutrient dense and low-fat savory foods. For snack chips in particular, these are commonly prepared by deep-fat frying, and this leads to relatively high fat content in the finished

product. Researchers have shown that consuming too much fat is a contributor to obesity and other related chronic diseases. Excess lipid consumption, especially of saturated fats, increases the risk of coronary heart disease, diabetes, hypertension, and cancer (Saguy & Dana, 2003).

1.1.2 Market requirement

A Mintel Survey (2011) shows that 80% of the population is trying to limit the amount of "junk food" they eat, and 83% of overweight people monitor what they eat in order to lose weight. When people are watching their diet, 69% purchase low-fat foods and 50% purchase fat-free/not-fat foods. However, there is one underdeveloped area, the role of food processing in developing new or reformulated healthy foods that are tasty and acceptable to consumers, meet cultural demands, and provide nutrition with low-fat and low calorie content. In particular, there is a big market for snack chips. In 2005, potato chips generated revenues of $ 16.4 billion and accounted for 35.5% of the total savory snacks market (Anonym, 2010). Sixty-one percent of customers viewed "low-fat" as an important attribute of snack foods, and this opinion increased by 14% from 2007 to 2009. Based on a survey conducted by the Snack Food Association in 2009 (Wyatt, 2009), 88% of customers think that "good value" is the key driver of snack selection and 79% of consumers are trying "to eat healthier". The survey also showed that "healthier" snack sales grew 3.9% (2007 vs. 2008) Therefore, the demand for low-fat or fat- free snack chips provides an important opportunity for developing new snack items with a healthier profile.

1.1.3 Current situations and efforts:

Deep-fat frying is a common technique for processing snack foods. However, the products made by fry processing have very high fat content. For example: fried potato chips have 39.8% of fat (w.b), corn chips have 36.6% fat and tortilla chips have 25.2% fat (Moreira, Castell-

Perez, & Barrufet, 1999). It is well known that excess fat consumption especially saturated fat contribute to obesity and related chronic diseases (Saguy & Dana, 2003).

The impact that individual consumers have on successful product launches is especially important. On one hand, consumers consider nutritional information, low-fat or reduced-fat claims, and other health-related aspects when making food choices (Philipson, 2005). Their purchase decisions are more directly influenced by taste, quality, convenience, and price of the food (Lando, Labiner, & Williams, 2004). Making new and healthier products for kids can be even more difficult. Although people want to eat healthier foods, consumers have their own preferences for texture, flavor, novelty, shapes, and colors, especially for young kids (Pszczola, 2010).

Therefore, it is important and meaningful to create new low-fat products that retain maximum nutrition and desirable sensory properties.

1.2 Hypotheses and objectives

1.2.1 Hypotheses:

To produce crisp snacks without deep-fat frying is a challenge for snack chip industry. Any competing process needs to be able to remove most of the water from the food, while creating a porous structure that fractures in multiple spots and creates the sounds associated with crisp foods. One alternative to frying is continuous vacuum belt drying. Under a specific condition, the product dried by continuous vacuum drying equipment may develop a puffed structure. In addition, the saturation temperature of water is lower than 100°C when it is under the vacuum conditions. The water is boiled inside the food even at room temperature. When the temperature is higher than the saturation temperature of water at low pressure, the flashing of steam causes the product to puff. This phenomenon is similar to the deep-fat frying processing. Therefore,

vacuum drying could be an effective way to make crispy chips. The process for making vacuum-dried chips does not involve oil, so the products contain extremely low-fat content per serving. Because the processing is under high vacuum and low temperature, nutrient, color, and flavor compounds in the product can be highly retained.

1.2.2 Objectives:

The objectives of this research are as follows: to compare the properties of snack chip products (tortilla chips) prepared by vacuum-belt drying to those made by deep-fat frying; (2) to understand the heat and mass transfer during the continuous vacuum belt drying processing; (3) to understand how processing parameters affect the quality of the final product and energy consumption; and (4) to study the properties of sweet potato chips by vacuum belt drying.

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CHAPTER 2

LITERATURE REVIEW

2.1 Obesity

2.1.1 Obesity

Health issues related to overweight and obesity have been a growing concern in the United States. The proportion of the population that can be classified as obese has increased significantly in the last few decades (Katherine M. Flegal, Carroll, Kit, & Ogden, 2012). Increasing obesity amongst children is of special concern, as the numbers of obese children has increased threefold in the last 30 years (Ikenson, 2004). Studies show that between 1980 and 2008, the number of obese children between the ages of 6 and 12 increased from 6.5% to 19.6%, and obese children over 12 increased from 5.0% to 18.1% (Ogden, Carroll, Curtin, Lamb, & Flegal, 2010). The prevalence of obesity in all adults (20 years or older), was 68.0%, with 72.3% amongst men and 64.1% amongst women in 2007-2008 (K. M. Flegal, Carroll, Ogden, & Curtin, 2010). In addition, obesity can be a systemic problem as 50-77% of youth will become obese adults. Hospital costs associated with obesity are nearly $150 billion per year in the US and childhood obesity related medical costs were estimated at $127 million during 1997-1999, up from 35 million during 1979-1981.

2.1.2 Efforts targeting obesity

Successfully combating obesity will involve a multifaceted approach. The recent “Let's Move!” Childhood Obesity Program initiative outlines several strategies including “providing healthier food in schools, ensuring access to healthy affordable food, increasing opportunities for physical activity, empowering parents and caregivers with better information about making

healthy choices, and giving children a healthy start in life" (Anonym, 2011). Recent initiatives have called on the food industries to make healthier foods (Pszczola, 2010). Extensive studies are underway examining societal factors, nutritional strategies, and policy effects on the obesity epidemic. People also want to live a healthy life, and to eat more healthy food. A Mintel survey (2007) showed that 73% of people perceived saturated fats and trans fats to be harmful. A more recent Mintel Survey (2011) showed that 80% of people try to limit the amount of "junk food" they eat and 83% of overweight people watch what they eat to try to lose weight. When people are watching their diet, 69% purchased low-fat food, and 50% purchased fat-free/not-fat food.

2.1.3 Low-fat foods

Creating lower fat/lower calorie products is an important way in which the food industry can contribute to reducing obesity. By recognizing the demand for healthy and low calorie foods, they also realize the constraints under which successful new food products can be produced.

Several researchers have studied technologies for developing low-fat foods (Colmenero, 1996; Mendoza, García, Casas, & Selgas, 2001) and the sensory characteristics of low-fat food products (Jimenez-Colmenero et al., 2010). Low-fat and skim milk, low-fat cheese, low-fat sausage, low-fat bakery products, and low-fat and fat free cookies and crackers were among the most active new food product categories (Oreopoulou, 2006). Several researchers have begun to target deep-fat fried snacks. For example, vacuum frying has been introduced to reduce fat content in fried chips, which often have up to 40% fat (Moreira, Castell-Perez, & Barrufet, 1999). Garayo and Moreira (2002) studied the feasibility of vacuum frying to make low-fat potato chips. They found that the oil content of vacuum fried product was significantly lower than those fried without vacuum, and concluded that vacuum frying could be a feasible alternative for producing low-fat potato chips with desirable texture and color. However,

Troncoso, Pedreschi and Zuniga(2009) found that vacuum frying increased the oil content of potato slices and diminished the color and texture. Baking has also been investigated for the production of low-fat potato and tortilla chips (Kayacier & Singh, 2003). Pretreatments such as blanching and impingement drying (Lujan-Acosta & Moreira, 1997) have also been studied as a way to reduce the fat content of deep-fat fried products.

Consumers do consider nutritional information, low-fat or reduced fat claims, or other health-related aspects when making food choices (Philipson, 2005). However, taste, quality, convenience and price may more directly influence sales (Lando, Labiner, & Williams, 2004). Although people want to eat more healthy foods, consumers have their own preferences for texture, flavor, novelty, shapes, and colors (Pszczola, 2010).

Reducing fat in foods also changes the properties of the product. Because of the unique physical and functional properties of lipids, reducing the fat in food can alter flavor, appearance, texture, mouth-feel, handling, preparation and storage stability (Brown, 2000). Reduced fat or low-fat products are often perceived by consumers as lacking in taste (Akoh, 2008). Fat substitutes with little or no calories have also been used to replace conventional fats. However, the ideal fat substitute does not exist, as substitutes only partially recover the properties of conventional fats. For example, some fat substitutes have mouth feel and physical properties approximating those of lipid but are not suitable for frying because they can be denatured or caramelized (Akoh, 2008). As fat substitutes are not usually adequate for deep-fat frying, it is difficult to replace the fat in many fried snacks.

2.2 Deep fat frying

Deep-fat frying is a process of cooking and drying through contact with hot oil. It involves simultaneous heat and mass transfer. During the deep fat frying, the food is soaked in

hot oil which serves as a heating medium. The common fried products in the US are snack chips, French fries, doughnuts, extruded snacks, fish sticks and fried chicken products (Heldman & Lund, 1992). Deep fat frying uses large volumes of lipid, at a temperature well above the boiling point of free water. The evaporation of free water occurs at the saturation temperature, and the evaporation rate is roughly proportional to the temperature difference between the oil temperature and saturation temperature of water (Nawel Achir, 2009).

During deep fat frying, products evaporate water and absorb oil. The oil content of fried products is normally very high. Snack chips that are processed by deep fat frying have an oil content ranging from 25.5 to 39.8% (Moreira et al., 1999). There are multiple health issues that may be related to fried foods. High fat content and high caloric value is the primary concern with fried products. Poorly maintained frying oil will increase the oil absorption. For example, cake doughnuts are often fried in highly abused oil, and the fat content can be as high as 60%. Several studies have shown that highly oxidized and heated oils may have carcinogenic properties because of toxic substances formed during extended heating (Tyagi & Vasishtha, 1996). Other studies have shown that cholesterol, saturated fats and trans fats, that are normally high in deep fat fried foods, have adverse affects on health. Many degradation products from the frying oil may potentially cause mutations of gastrointestinal irritations (Clark & Serbia, 1991). Badly abused frying oils are even more harmful to health.

2.3 Snack chips

2.3.1 Histories of snack chips

George Crum was the first one to invent the Saratoga chip (potato chip) in 1853 in New York, after a customer complained the potato was too soggy. In 1895, William Tappendon (Ohio) began selling potato chips in grocery stores instead of only in restaurants. Later, potato

chips moved from being a kitchen-cooked product to full-scale production in factories. The first potato chips sealed in packages were introduced by Laura Scudder in the 1920s. In 1929, the continuous fryer was invented, which allowed for a further increase in production. In 1932, Charles Elmer Doolin started his corn chip business by purchasing a corn chip recipe for $100 (Frito Co.) In 1933, Herman Lay founded Lay's in Nashville, Tennessee and then opened a factory in Atlanta, Georgia (Lay's). In 1965, Lay's Potato Chips merged with the Frito Co. to form a nation-wide potato chip brand (Burhans, 2008). Tortilla chips were invented by EI Zarape, a tortilla factory in the 1940s in Los Angeles. Originally, tortilla chips were cut into triangle shapes and fried from the malformed tortillas that came out of the automated tortilla machine.

2.3.2 Varieties of salty snack

The total U.S. retail sale of salty snacks was $18,809 million in 2010. These include potato chips, tortilla chips, snack nuts and seeds, pretzel, multi-grain chips, sweet potato chips, and banana chips (Mintel, 2011). Figure 2.1 shows the two biggest market shares of salty snack market are potato chips and tortilla chips.

There are two kinds of potato based chips. Most potato chips are made from raw potatoes. These are sliced into thin pieces (1.27-1.78 mm), and fried in a continuous flyer for 3-5 minutes, at temperatures ranging from 177 to 190°C. Another kind of potato chip, called fabricated chips, is made from dough containing dehydrated potatoes and other ingredients. The dough is sheeted, cut to shape, placed between two molds and then deep fat fried.

Two major chips that are made from corn are corn chips and tortilla chips. The differences between these two chips are tortilla chips are baked before deep fat frying and corn chips are fired without being baked. However, they both are made from alkaline-cooked corn.

2.4 Corn flour (masa)

Corn, also known as maize, is a major grain for human's consumption. It constitutes a staple food in many regions of the world. Masa is the main ingredient for tortillas and many other dishes of Mexican origin. Corn is the largest grown crop in the North America. In the US, the usage of corn include livestock feed, ethanol production, exports, and human consumption (Goreham, 2008).

The procedure that transforms corn into masa is called nixtamalization. Figure 2.2 shows the procedure of nixtamalization. Typically, whole corn is added to an alkaline solution, cooked to its boiling point, and then steeped for a period of time. The alkaline liquid is discarded, and the kernels are washed, and this prepared grain is called nixtamal (Orthoefer & Eastman, 2004). After grinding, it becomes masa. The fresh, wet masa is usually used to make tortillas or other Mexican food, while dying masa is used for "instant masa". In the industry, tortilla chips are made from the raw corn.

The nutritional content of corn (yellow) is shown in Table 2.1 (USDA data). Yellow corn flour is a main carbohydrate source, and it contains 76.85g of carbohydrate per 100 g of corn flour. It also has a high fiber content of 7.3 g per 100g, and provides 29% of the daily value for fiber. Yellow corn flour is particularly rich in potassium and magnesium with 100g providing 315 mg (9% DV) of potassium and 93 mg (23% DV) of magnesium. Both of these minerals are necessary for healthy muscle function (Rouzier, 2011). Carotenoids are also relatively abundant in yellow corn flour, especially the water soluble carotenoids, lutein and zeaxanthin. One hundred grams of yellow corn flour provides 1355 µg of lutein and zeaxanthin.

2.5 Sweet potato

Sweet potatoes (*Ipomoea batatas*) are one of the world's leading food crops. The world produced 106.5 million tons of sweet potatoes in 2010, while the US produced 1.08 million tons (FAO, 2012). Sweet potatoes are an economical and health-friendly food. Besides being a carbohydrate source for human and animals, sweet potatoes have become an attractive food source because of its high nutritive value. They contain high amounts of beta-carotene, vitamin C and minerals. The nutritional content of sweet potatoes is listed in Table 2.2 (USDA database).

When prepared properly, a serving of sweet potato has about four times the amount of the recommended daily intake of beta-carotene. Beta-carotene is a vitamin A precursor and can be converted to active vitamin A in the body. Sweet potatoes are also a good source of vitamin C and provide 33% of daily recommended amount per 100g serving. Sweet potatoes are rich in fiber containing 3.3 grams of fiber per 100 g. Sweet potatoes are high in antioxidants such as beta-carotene.

Sweet potatoes can be produced in tropical regions, where storage is particularly difficult because of its high moisture content. Sweet potatoes are normally consumed as fresh and prepared by boiling or steaming (J. A. Woolfe, 2008). Dehydrated sweet potato "root flakes" have been produced in many areas of the world as an effective means of storage. Pureeing, canning, and freezing are also practiced as post harvest processing (J. A. Woolfe, 2008). Utilizing sweet potatoes as a value-added material has been studied by several researchers (Akpapunam & Abiante, 1991; Dansby & Bovell-Benjamin, 2003; Walter, Truong, & Espinel, 1999). Sweet potato chips have been marketed in several countries including the US, China, and Japan for years. Sweet potato chips are normally prepared by deep fat frying. The process of preparing sweet potato chips is shown in US in Figure 2.3 (J. A. Woolfe, 2008).

However, commercial sweet potato chips have been limited due to problems with final product quality and a continued raw material supply. Common problems that sweet potato chip producers encounter include: phenolic oxidation resulting in a darkening of uncooked slices, excessive browning caused by Maillard reaction during frying, oiliness, excessive chip hardness, and lack of crispness. If the product is subjected to moisture and excessive oxygen post-process, it can become leathery and develops rancid off-flavors (J. A. Woolfe, 2008). Dipping in 1 % (w/v) ascorbic acid solution before frying can improve the crispness of the final product. In recent years, sweet potato chips as snacks have garnered more attention because of the high nutrition profile. Sweet potato snacks are a rich source of vitamin A, and can be an important means to battle vitamin A deficiency (Graham & Rosser, 2000; Jennifer A. Woolfe, 1992). Some research has been done to improve the quality of sweet potato chips. Fontes, Oliveira, & Collares-Queiroz (2011) studied the optimization of the deep–fat frying process of sweet potato chips in palm olein or stearin. Da Silva and Moreira (2008) studied sweet potato chips made by vacuum frying. Taiwo and Baik (2007) studied the effects of pre-treatment on fried sweet potato chips.

2.6 Carotenoids

2.6.1 Carotenoids in food

Carotenoids are pigments that have an important nutritional role. Some of the carotenoid groups are precursors of vitamin A, which is involved in protein metabolism, synthesis of epithelial tissue, vision, and night vision. Carotenoids are antioxidants that may provide beneficial health effects. Carotenoids include carotenes (e.g. beta-carotene), which are more non-polar and xanthophylls (e.g. lutein), which are more polar (Christen & Smith, 2000). Vegetables and fruits that are rich in carotenoids normally have yellow-orange or dark green

color. Sweet potatoes, kale, carrot, cantaloupe, pumpkin, are rich in carotene and corn, orange pepper, green bean, broccoli, and kiwi are rich in lutein and zeaxanthin. Tomatoes, pink grapefruit, and watermelon are sources of lycopene (Lessin & Schwartz, 1997; Sommerburg, Keunen, Bird, & van Kuijk, 1998). Carotenoid concentration in fruits and vegetables varies with plant variety, degree of ripeness, harvest time, growing conditions, and storage conditions (Lessin & Schwartz, 1997). In some cases, carotenoid pigments are combined with proteins and show bluish-green color. Heat denatures the protein and breaks down the complex and reveals the red color (Christen & Smith, 2000).

The role of carotenoids as precursors of Vitamin A can be traced to the unsubstituted β -ionone ring they possess. The structure of beta carotene and vitamin A are shown in figure 2.4. Beta-carotene contains 11 conjugated double bonds and has λ_{max} of 450 nm (yellow-orange color). Beta carotene is cleaved into two molecules of retinal (vitamin A) by a carotenoid cleavage enzyme when required by the body (Bauernfeind, 1972).

2.6.2 Carotenoid oxidation

Oxidation is a degradative reaction that affects the quality of food. Carotenoid containing foods can be bleached colorless by oxidization, and the subsequent fission reactions can yield volatile carbonyls, such as beta-ionone, that are responsible for typical oxidation flavors. Vitamin A activity will be lost with oxidation. Dehydrated foods are particularly susceptible to oxidations; therefore the package is made with oxygen impermeable materials and flushed with nitrogen before sealing. Lipoxygenase will accelerate carotenoid destruction, because the free radicals that are generated by the breakdown of lipid hydroperoxides that will react with carotenoids (Christen & Smith, 2000). Light, elevated temperature, the nature of solvent, the presence of unsaturated fatty acids and other factors affect the decomposition of the carotene

molecule (Yanishlieva, Aitzetmuller, & Raneva, 1998). Madhavi, Singhal & Kulkarni (1996) demonstrated the temperature susceptibility of beta-carotene by exposing the sample to air, dark environment and holding it at two different temperatures. The UV-VIS absorption at the maximum wave length decreased 25% in 6 weeks for sample storage at 20°C, and was found almost completely destroyed after 6 weeks for sample that storage at 45° C. Beta carotene is stable in pentane, hexane and decane solutions with 0.02% butylated hydroxyanisole(BHA) (or the same amount of ethyl, propyl, or cetyl gallate). When properly protected, there was no change in absorption spectra for up to 6 months (Yanishlieva et al., 1998).

2.6.3 Carotenoids as antioxidants

The antioxidant activity of carotenoids such as beta-carotene has been widely studied (Paiva & Russell, 1999). The antioxidant activity is a biological mechanism of carotenoids and is based on their singlet oxygen-quenching properties and ability to trap peroxyl radicals (Paiva & Russell, 1999). The number of conjugated double bonds and end group of the molecule mainly decide the quenching activity of a carotenoid. Lycopene is the one of most efficient singlet oxygen quenchers in the carotenoid family (Krinsky, 1998). Beta-carotenes are scavengers of peroxyl radicals, especially at low oxygen tension (Burton & Ingold, 1984). Compared to unsaturated acyl chains, carotenoids react more rapidly with peroxyl radicals, but destroy themselves to work as antioxidants (Woodall, Britton, & Jackson, 1997). Beta carotene and other carotenoids are often used to prevent lipid oxidation. In association with other antioxidants, such as vitamin E, carotenoids can increase their activity against lipid oxidation (Yanishlieva et al., 1998). There are controversial results about the relationship of carotenoids intake and cancers and cardiovascular disease. Paiva and Russell (1999) suggest that the dietary level of carotenoid consumption can promote health, but high doses of beta-carotene supplements may have adverse

effect on health, especially for people who smoke or are exposed to asbestos. Contradictory results also have been found for the role of beta carotene in prevention of lipid oxidation. Carotenoids can work as antioxidants and can shift to pro-oxidant activity. The role of beta carotene as an antioxidant or pro-oxidant depends on the environment, oxygen concentration, and presence of other antioxidants (Paiva & Russell, 1999; Yanishlieva et al., 1998).

2.6.4 Carotenoid changes in sweet potato during storage and processing

There is some variability in the total carotenoid content of sweet potatoes. The major factor that affects total carotenoids (mainly beta carotene) content is the cultivar. The mean beta-carotene content of fresh American sweet potato ranges from 2.55 to 6.73mg/100g (fwb) (J. A. Woolfe, 2008). The region in which the sweet potatoes are grown also affect the total carotenoids content. For the same cultivar, the differences in carotenes due to location range from 62%-95%. Other factors such as weather conditions and cultural practices also affect the content of beta-carotene (K'Osambo, Carey, Misra, Wilkes, & Hagenimana, 1998; J. A. Woolfe, 2008). In general, the carotenes and total carotenoids of sweet potatoes increase during storage. The degree of change may be different for different cultivars and storage conditions. (Priyadarshani, Jansz, & Peiris, 2007) studied the beta-carotene change of orange-yellow fleshed sweet potatoes (*lpomoea batatas*) under two storage conditions, namely (a) in the open air and (b) inside a Jute hessian (gunny) bag at ambient temperature for 12 days. They concluded that all carotenoid content was increased during open storage including beta-carotene. The beta-carotene content increased 115.36 % at day 12 and increased 127.6% in the Jute hessian bag storage. Yamamoto and Tomita (1958) suggested that catotenoids are synthesized and degraded at the same time during storage. The decrease or increase of the catotenoids depends on the rate of enzymatically controlled synthesis (Yamamoto & Tomita, 1958). The effects of post-harvest

processing on total carotenoids was studied by (Vimala, Nambisan, & Hariprakash, 2011). The highest retention was observed in oven drying (total carotenoids 90%-91% and beta-carotene 89%-96%) followed by boiling (total carotenoids 85%-90% and beta-carotene 84%-90%), and frying (total carotenoids 77%-85% and beta-carotene 72%-86%). The lowest retention of total carotenoids (63%-73%) and beta-carotene (63%-73%) was recorded for the sun drying method. The effect of drying and the subsequent storage of the orange-flashed sweet potato on the total carotenoid has also been studied. Bechoff et al. (2010) found that the loss of total carotenoids in sweet potatoes during sun drying were relatively small compared to those stored for 4 months, with losses of 15% and 70%, respectively. Different cultivars have different levels of change in total carotenoids during drying and storage. The use of opaque or transparent package had no effect on the rate of carotenoid loss. Cinar (2004) found that storage under light or dark conditions did not significantly affect the decrease of carotenoid pigments. K'Osambo et. al., (1998) found that boiling sweet potatoes for 30 minutes significantly decreased the total beta-carotene content, but no further decrease occurred after boiling for 60 minutes.

2.6.5 Quantitative measurement by spectroscopy

The concentration of analyte in a given sample solution can be determined by the quantitative absorption of light from a reference beam as it pass through the sample solution (Penner, 2010). The relation between concentration and absorbance is given by Beer's Law:

$$A=\varepsilon lc \qquad (2.1)$$

where

A=absorbance (no units, $A=\log_{10}(P_0/P)$), measured by spectrophotometer

l= path length of the sample (cm)

c= concentration of the compound in solution (mol/L)

ε = the molar extinction coefficient or molar extinction absorbtivity of the substance (L/ mol*cm). The molar absorptivity ε is unique for each compound. For beta-carotene in hexane, ε at 450nm is 138,730 L/ mol*cm (Anonym, 2012; Zechmeister & Polgar, 1943).

2.7 Food dehydration

2.7.1 Food drying

Food drying or food dehydration is a method of removing water from food. The main reasons for dehydrating food are to preserve food, to decrease the weight and bulk, or to make convenience products. The process of food drying involves simultaneous heat and mass transfer. The drying conditions affect the rate of heat and mass transfer and the dried food quality (Potter & Hotchkiss, 1995) . Humidity, temperature, air velocity and pressure are the main environmental factors that influence drying rates and final product moisture. Normally, lower humidity, higher temperature and higher air velocity increases the drying rate. Drying at low pressure, as in vacuum drying, decreases the boiling point of water. At a constant product temperature, lower pressure can speed up the evaporation rate of water, thereby reducing the drying time. Vacuum drying and freeze drying are two typical applications of low pressure drying. In the case of heat-sensitive food drying, lowing temperature and shorter drying time is important for quality and nutrition retention (Potter & Hotchkiss, 1995).

Food properties also affect the drying rate and dried product quality. These properties include the product size, solute concentrations, initial water content, cellular structure, surface hardening, thermo-plasticity, porosity, and any chemical changes that during drying.

Several physical and chemical changes can occur during food drying. The food often shrinks during the dehydration process. Food does not have a perfect elastic structure and can

form a concave shape as water is removed. Surface hardening can happen during baking or drying. The high surface temperatures cause the outer layers to dry quickly and form a hard skin layer, which severely decreases the drying rate. Case hardening is desirable for baking because it keeps a moist inner product. However, this phenomenon is not good for drying because it increases the drying time. Drying may cause some degree of porosity depending on the drying method used. Escaping water vapor tends to cause expansion of the product, which can result in a porous and puffy structure, especially for low pressure processes such as freeze and vacuum drying (Potter & Hotchkiss, 1995).

Enzymatic oxidation of polyphenols may occur during dehydration if the enzymes are not inactivated. Some pretreatments, such as blanching, are recommended to minimize this problem. Excessive heat can cause caramelization of sugars and scorching of other materials. Maillard browning is formed by the reaction of a reducing sugar and an amino group of protein at elevated temperature. Researchers have found that Maillard browning generally proceeds most rapidly at a moisture range of 15-20%. If the product proceeds quickly through the 15-20% moisture range, Maillard browning may be minimized (BeMiller, 2007).

2.7.2 Continuous vacuum belt drying

Vacuum drying is a food process using reduced air pressure and mild temperature to dehydrate food. Lowering the pressure will lower the boiling point of the water, which allows the product to stay at low temperature. Normally vacuum drying maintains high quality in the final products. Currently, vacuum drying applications include vacuum shelf drying, continuous vacuum belt drying, freeze drying, and most recently, vacuum microwave drying (Sagar & Kumar, 2010).

The continuous vacuum belt drier has been commercially used for dehydrating high quality citrus crystals, instant tea, and pharmaceutical drugs (Potter & Hotchkiss, 1995). There are some application studies of continuous vacuum belt drying on ginseng and banana paste (Liu, Qiu, Wang, & Chen, 2011; Wang, Li, Chen, Bao, & Yang, 2007). Sagar and Kumar (2010) reviewed some of the most recently drying methods for fruit and vegetable and concluded that vacuum drying, along with freeze drying and spray drying, has higher energy consumption compared to other traditional drying methods. However, the product quality of these low-temperature methods can be much higher than that realized from hot-air or solar drying. Wang et. al. (2007) compared the energy consumption of a continuous vacuum belt drier, a spay drier, and a vacuum shelf drier and found that the energy consumption of the continuous vacuum belt drier was much less than others for drying pharmaceutical products. Energy use was 58, 38, and 11kWh/kg for spray drier, vacuum shelf drier, and continuous vacuum belt drier, respectively. Compared to freeze drying, the operation time of vacuum belt drying is one-fifth of freeze drying, with similar product quality (Wang, Chen, et al., 2007). The phenolics content and antioxidant activity was not significantly different for grape pomace products when comparing vacuum belt dried and freeze dried product, but continuous vacuum belt drying has significantly shorter drying time and lower energy consumption than freeze drying (Vashisth, Singh, & Pegg, 2011).

It has been reported that a puffed structure can be achieved by continuous vacuum belt drying equipment (Potter & Hotchkiss, 1995). However, there is no literature, based on our best knowledge, about the utilization of the continuous vacuum belt drier to make high value products having a puffed structure such as snack chips.

2.8 Quality measurements of snack chips

In general, the overall quality of snack chips include moisture content, color, oil content, flavor, texture, nutrition, yield, and shelf life stability. Consumers may only focus on texture, flavor, color, oil content, and nutrition, but yield and shelf life stability are also important for food manufacturers (Moreira et al., 1999).

2.8.1 Moisture

Moisture content of food is usually expressed on a percentage basis as follow equations:

$$MC\% \text{ (wet basis)} = 100 \times (\text{mass of water})/\text{mass of wet product} \quad (2.3)$$

$$MC\% \text{ (dry basis)} = 100 \times (\text{mass of water})/\text{mass of dry product} \quad (2.4)$$

For offline products, an air-oven method is standard for moisture content determination (Moreira et al., 1999). Near infrared techniques are used to determine the moisture content of online products (Brescia & Moreira, 1997).

2.8.2 Oil

Oil content is an important attribute for fried products and usually expressed as:

$$OC\% \text{ (wet basis)} = 100 \times (\text{mass of fat})/\text{mass of product} \quad (2.5)$$

Methods for determining food oil content include extraction methods, refractometric methods, hydraulic press, and NIR spectroscopy (Moreira et al., 1999). Extraction in ether using a Soxhlet apparatus is one of the AACC standard methods for crude oil extraction (AACC) Supercritical fluid extraction, which uses CO_2 as extract solvent, is an official oil extraction method of the American Oil Chemists' Society (AOCS). The near infrared (NIR) technique is an online fat content measurement technique for tortilla chips and other snack food production (Brescia & Moreira, 1997).

2.8.3 Color

Color is a major factor that affects consumer's acceptability for snack chip products. Panel sensory evaluation and instrumental evaluation are the two common methods for measurement of food color(Moreira et al., 1999).

A colorimeter is often used for instrumental color evaluation of snack chips. Color scale systems such Hunter L, a, b scale, CIELAB scale, and Munsell color system has been applied in food color measurement. CIE LAB (L*, a*, b*) scale and Hunter L, a, b color scale are similar but they have different formula calculations. The CIE LAB scale is used more than Hunter in industry since CIE's release in 1976. Figure 2.5 shows the CIE LAB color system. The L axis runs from top to bottom, and the value is from zero to 100. The L* value of zero represents black and the value of 100 represents white color. The a* and b* axes have no specific numerical limits. Positive a* represents red, negative a* represents green, positive b* represents yellow, and negative b* represents blue (Anonym, 2008). The Munsell color systems consist of three dimensions: Value, Hue and Chroma. Value is the lightness of a color. Value ranges from black (value 0) at the bottom, to white (value 10) at the top. Hue is the name of a color. There are five principal hues: Red, Yellow, Green, Blue, and Purple, along with 5 intermediate hues halfway between adjacent principal hues. Chroma is the strength of a color, measured radially from the center of each slice (Munsell & Farnum, 2004). In some cases, a color can be measured as L*, a*, b*, and then converted to the Lightness, Hue and chroma system using follow equations:

$$L = L^* \tag{2.6}$$

$$\text{Hue} = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{2.7}$$

$$\text{Chroma} = \sqrt{(a^*)^2 + (b^*)^2} \tag{2.8}$$

2.8.4 Flavor

Flavor is a combination of taste and odor (Potter & Hotchkiss, 1995). Taste is the perception of specific compounds on the tongue. Basic taste includes salty, sweet, bitter, and sour, which associate to different chemical compounds. Umami and astringency also have been suggested as tastes by some researchers (Christen & Smith, 2000). Odor, which is perceived in the olfactory center in the nose by chemical stimuli, is even more complex than taste. Under normal conditions, we only detect volatile chemicals that can reach the olfactory epithelium (Dodd, 1992).

Human sensory evaluation of flavor still is used as the gold standard in the food industry. However, combining sensory measurements with instrumental evaluation may provide a more complete picture of products (Carolyn, 2009). Analytical chemistry techniques are employed to determine the chemical components of products that contribute to taste and odor. High-pressure liquid chromatography (HPLC) is used to separate non-volatile compound such as sugars or organic acids and Gas chromatography (GC) is used to analyze volatile compounds such as aroma (Marsili, 2007). Electronic noses and tongues are widely applied for instrumental sensory evaluation.

2.8.5 Texture

Crispness and crunchiness are critical texture attributes of snack chips. Bourne(1975) described crisp or crunchy food as " characterized by having a rigid, non-deformable, stiff structure that suddenly collapses with a brittle fracture and a rapid decay of the force after fracture, very low shear strength, break up under simple compression between the teeth with little or no grinding tearing, rapid breakdown into small pieces, small number of chews per piece, not chewy, low work content required for mastication, sound effects associated with brittle fracture often desirable, structure usually comprised of cellular aggregate." Vicker and Bourne

(1976) suggested that crispness in fried foods, such as snack chips, depends upon the amount of deformation the food undergoes at the initial bite before breaking.

Sensory panel evaluation is used to determine the crispness of foods and still is the primary method used in the food industry. How sensory evaluation relates to instrumental evaluation has been extensively studied (Carolyn, 2009).

Instrumental methods used to measure food texture have been classified into three categories: fundamental, empirical, and imitative. Fundamental tests simply measure the physical parameters such as strain, and elasticity, but they have poor correlation with sensory properties. Empirical tests have poor definition but high relation with texture properties and have been used mostly in food industry. Imitative tests are methods that mimic the conditions of food be eaten (Moreira et al., 1999).

Bend deformation to fracture and stiffness are two basic instrumental approaches used to assess crispness. Crispness is regarded as a combination of force-deformation sensation and acoustic sensation. The Instron and Texture Analyzer are two typical instruments used for force-deformation studies. Vickers (1987) studied 5 kind of commercial chips on the sensory, acoustical and force-deformation measurements of potato crispness. They found out the crispness of product is the combination of the three parameters, namely, the number of peak sounds, the mean height of peaks, and the force peak/slope of force-deformation curve, which had r=0.99 correlation coefficient. As a single factor, the number of sounds produced during biting best correlates with the oral sensory crispiness (r=0.92).

Seymour and Hamann (1988) studied the texture properties of 5 commercial snack foods such as chips, crunch twists, and crackers. They found that crispness and crunchiness are two closely related sensory interpretations of food texture. These two texture terms can be quantified

by the combination of mechanical force and acoustic perception. Comparing the sensory evaluation of crispness to the instrumental measurement, a combination of the mechanical and airborne acoustic response to a fractured food product has the best correlation. They reported that the mechanical response gives the best sensory interpretation and the acoustic response further refines it.

The sounds of chewing or biting certain food reflect the texture of that food. Numerous studies have examined acoustical measurements of food quality attributes and their relationship with food texture, especially for crispness/crunchy products. Acoustical analysis of the sound emitted when a force is allied to a food product, is used to study crispness or gather qualitative information regarding crispness. Vickers (1983) found that the number of sound bursts provided the most useful indication of crispness. Vickers and Bourne (Z. Vickers & Bourne) found that the amplitude and the number of sounds produced from biting wet and dry foods varied with the crispness of the samples. The louder crushing sounds had a higher positive correlation with the perceived crispness. Chen et.al (2005) studied the texture of biscuits by combination of force/displacement measurement with the acoustic detection of food materials. In this study, an acoustic envelope detector was attached to the texture analyzer. During the tests, the force and displacement was measured simultaneously with the sound record. The acoustic signal was expressed in term of maximum sound pressure and the number of sound acoustic events. They found that the sound event that emitted during the crash match to the force peak.

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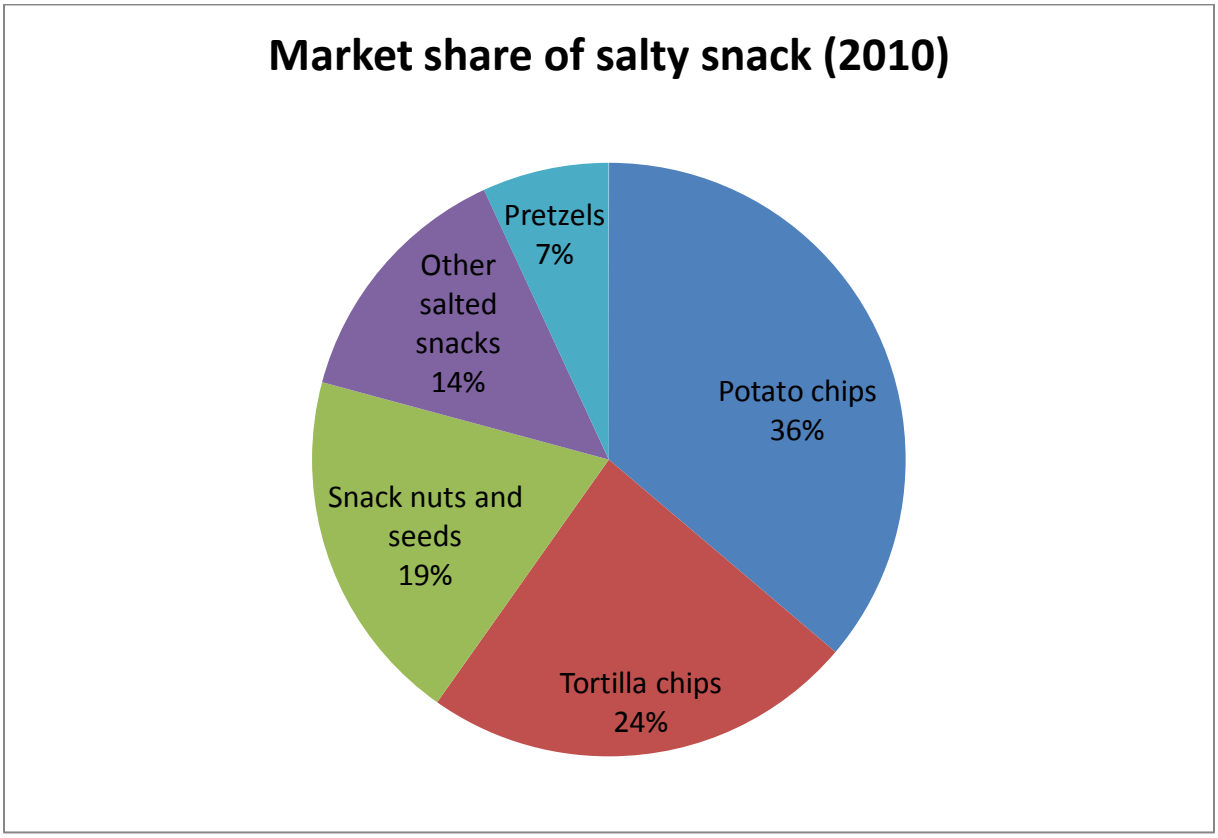


Figure 2.1 Market share of salty snack (Mintel, 2011)

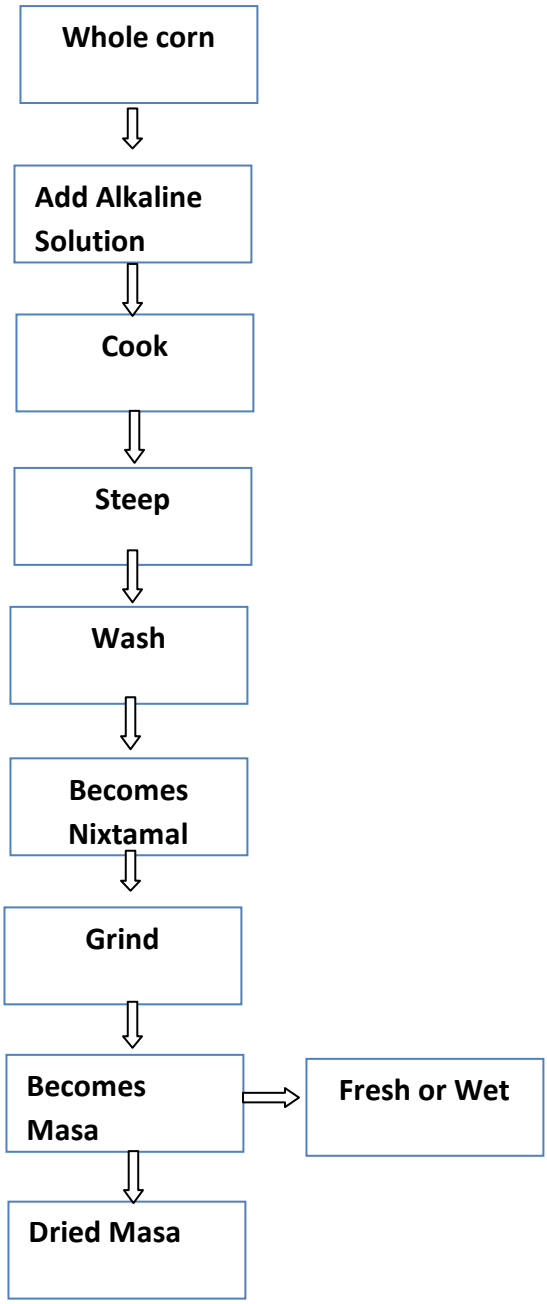


Figure 2.2 Nixtamalization and masa process

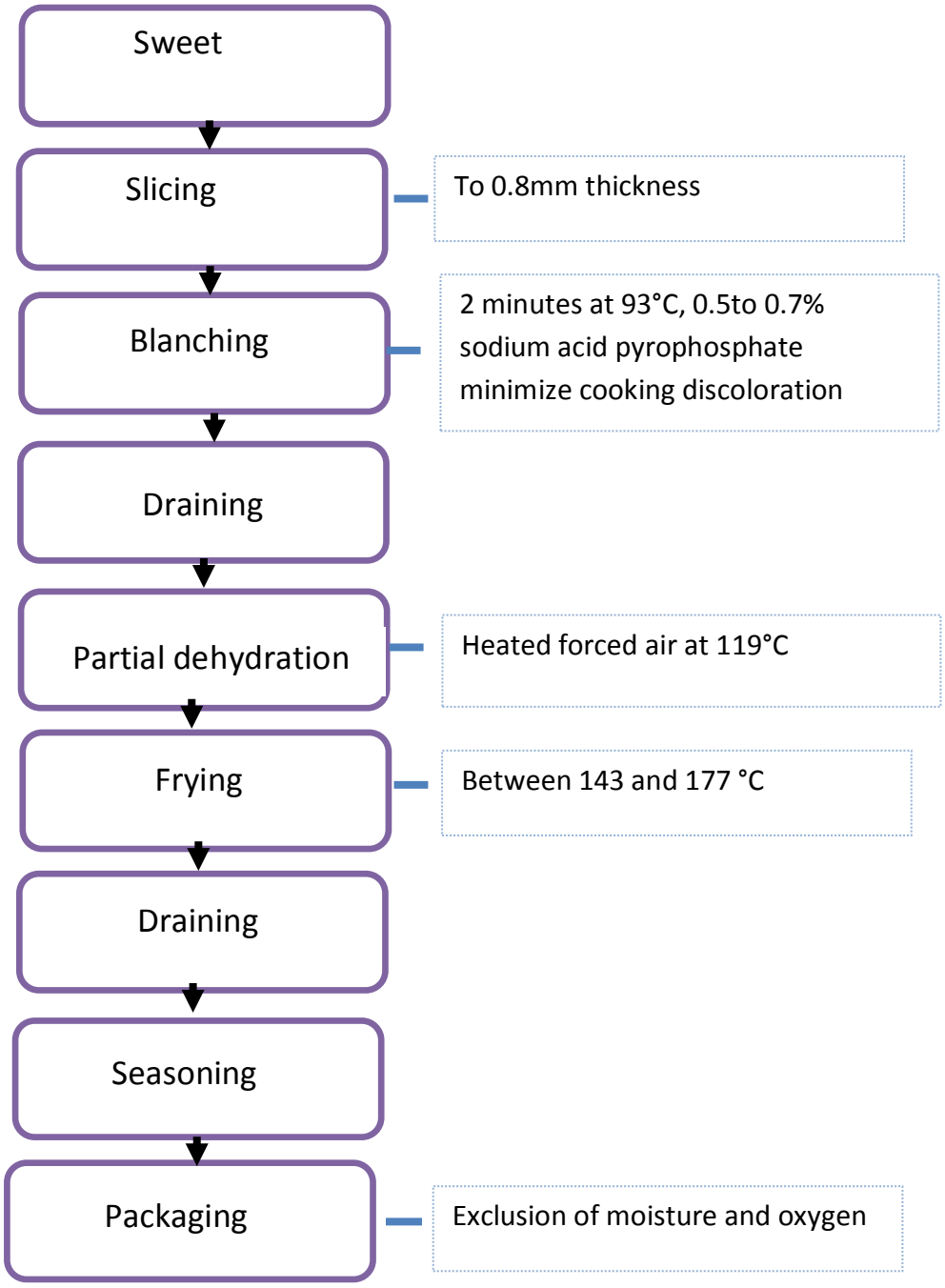
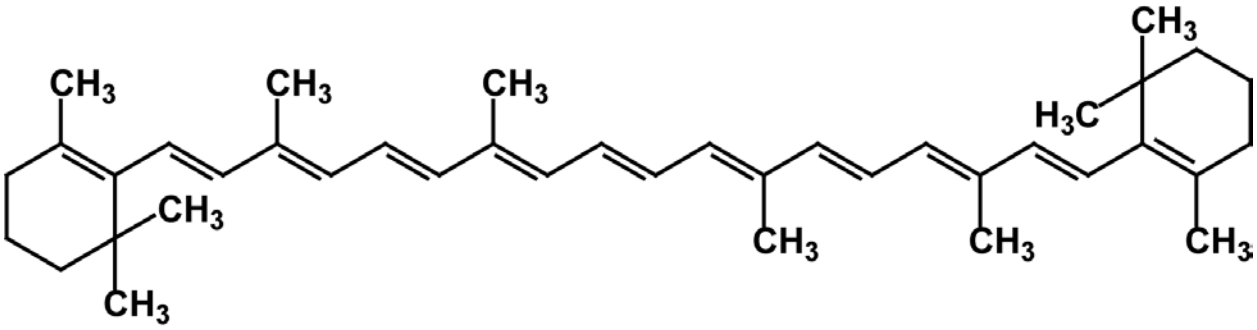
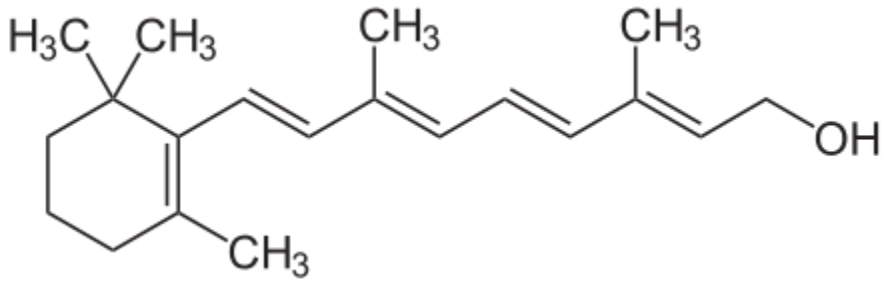


Figure 2.3 Process of preparing sweet potato chips



Beta-carotene



Vitamin A (retinal)

Figure 2.4 Beta-carotene and vitamin A structure

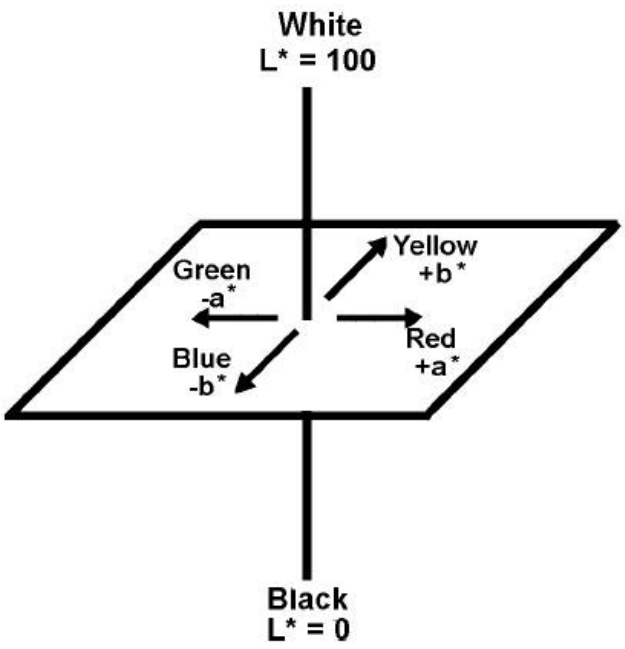


Figure 2.5 CIElab color system

Table 2.1. Nutrition fact of corn flour, whole-grain, yellow (From USDA database)

nutrient	*unit*	*Value per 100g*	*%DV*
protein	g	6.93	14%
Total lipid (fat)	g	3.86	6%
ash	g	1.45	
Carbohydrate, by difference	g	76.85	26%
Fiber, total dietary	g	7.3	29%
water	g	10.91	
Minerals and vitamins			
nutrient	*unit*	*Value per 100g*	*%DV*
Vitamin A	IU	214	5%
Vitamin E	mg	0.42	2%
Thiamin	mg	0.246	16%
Ribo flavin	mg	0.08	5%
Niacin	mg	1.9	10%
Vitamin B6	mg	0.37	18%
Folate	Mcg	25	6%
Calcium	mg	7	1%
Magnesium	mg	93	23%
Iron	mg	2.38	13%
potassium	mg	315	9%
phosphorus	mg	272	27%
zinc	mg	1.73	12%
copper	mg	0.2	11%
Manganese	mg	0.5	23%
Seleium	mcg	15.4	22%
Carotenoids			
nutrient	*unit*	*Value per 100g*	
Carotene, beta	ug	97	
Carotene, alpha	ug	63	
Lutein+zeaxanthin	ug	1355	

Table 2.2 Nutrition fact of sweet potato, raw, non-skin (From USDA database)

Nutrient	Unit	Value (100g) (raw)	Value (100g) (baked)	%daily value
water	g	77.28	75.78	
Energy	kcal	86	90	
protein	g	1.57	2.01	
Total lipid	g	0.05	0.15	
carbohydrate	g	20.12	20.71	7%
Fiber, total dietary	g	3	3.3	13%
Sugars	g	4.18	6.48	
Total ascorbic acid	mg	2.4	19.6	33%
Vitamin A, RAE	Mcg RAE	709	961	
Vitamin A IU	IU	14187	19218	348%
Beta carotene	µg	8509	11509	

Vitamin A, expressed as micrograms of retinol activity equivalents (mcg RAE)

CHAPTER 3

COMPARATIVE STUDY OF PHYSICAL AND SENSORY PROPERTIES OF CORN CHIPS MADE BY CONTINUOUS VACUUM DRYING AND DEEP FAT FRYING

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ABSTRACT

Corn chips were produced by a continuous vacuum drying (CVD) method and compared with those made by conventional deep-fat frying (DFF). The CVD chips developed an expanded structure and contained 1.57-1.82 g oil/100 g, depending on initial thickness, compared to 33.37-34.80 g oil/100g for DFF chips. Consumer panels indicated that 22.7% of panelists would "probably" or "definitely" purchase either CVD or DFF chips. While likability of DFF chips was somewhat higher (hedonic scores of 5.3-6.56) than those for CVD chips (4.25-4.33), panelists indicated that flavor, texture, being low in fat and price were leading factors that would influence purchase. CVD chips had color values closer to fresh corn flour. Texture analysis showed that CVD chips had slightly higher fracture force (778.4 - 2910.4 g) than DFF chips (547.8 - 1955.9 g). Acoustic analysis showed that CVD chips had more sound events and greater sound energy. Frequency analysis showed that both products contained frequencies typical of crisp products, although CVD chips had higher frequency peaks, particularly for thicker chips.

Key words: *continuous vacuum drying, low-fat, corn chips, texture, deep-fat frying, acoustic analysis*

3.1 Introduction

Currently, most crisp snack chips are deep-fat fried in hot oil or fat, resulting in products that have a high fat content. In one study, fried potato chips were found to contain 39.8% fat, corn chips 36.6% fat and tortilla chips 25.2% fat (Moreira, Castell-Perez, & Barrufet, 1999). Excess consumption of fats and oils, especially those containing saturated fats, increases the risk of coronary heart disease, diabetes, hypertension and cancer (Saguy & Dana, 2003). There is also growing concern about rising rates of obesity in the U.S., and fried snacks and other products may be a contributor to the problem. At the very least, there is growing demand for "healthier" or lower-fat products, and this is driving the development of new formulations and processes for producing low-fat snacks with acceptable sensory properties at reasonable price.

There have been several efforts to reduce the fat content of snack chips. Vacuum frying and baking have been two approaches to reduce the fat content of corn and other snack chips. For example, Garayo and Moreira (2002) studied the feasibility of vacuum frying to make low-fat potato chips. They found that the final oil content of vacuum fried products was lower than those fried at ambient conditions. They concluded that vacuum frying could be a feasible alternative for producing low-fat potato chips that have desirable texture and color. However, Troncoso, Pedreschi & Zuniga (2009) found that vacuum frying significantly increased the oil content of potato chips, decreased color and texture parameters, and improved both flavor and overall quality. Kayacier and Singh (2003) measured the fracture force of baked corn chips prepared at different time/temperature combinations. They showed that air cells and cracks formed during baking were important to the textural attributes of samples. Other researches have investigated ways to lower the fat content of fried corn chips by applying pretreatments, such as blanching or impingement drying (LujanAcosta, Moreira, & SeyedYagoobi, 1997) prior to frying.

Texture is one of the prominent quality factors of snack chips, and crispness in particular is correlated with snack chip acceptability (Szczesniak, 1988). Frying helps develop crispness as it lowers the product moisture content so as to produce a glassy state product. In addition, the release of steam as water exits the product creates voids that lead to the structure required for crisp foods. Vacuum drying is a process using reduced air pressure and heat to dehydrate the food. Lowering the pressure lowers the boiling point of water in the food, allowing bubbles to form in the product as water emerges. Lower product temperatures can be realized than would normally be seen in frying or baking operations. Vacuum drying not only maintains the high quality of final products, but can also produce some puffing in the structure. The development of a porous structure that has multiple fractures over time is requisite for crisp snack products.

Continuous belt vacuum systems have been developed in which product advances along a belt, subject to heating by conduction or radiation (Figure 3.1). Currently, continuous vacuum belt driers have been used commercially for dehydrating high quality citrus crystals, instant tea, and pharmaceutical drugs (Potter & Hotchkiss, 1995). There are no reports that we know of using continuous vacuum drying to produce low-fat snack chips.

In this research, we studied the use of a continuous vacuum dryer to develop crisp corn chips with low-fat levels. Chips were compared with conventionally fried chips to determine consumer likability and intent to purchase. Further, we compared the fat content, texture attributes and sensory properties with corn chips made by a more conventional deep-fat frying method.

3.2 Materials and methods

3.2.1 Materials and sample preparation

Nixtamilized corn flour (TC-2) was obtained from Mission Foods (Pendergrass, GA), while non-iodized salt was purchased locally (Kroger, Athens, GA). A combination of 49% (of total weight) corn flour, 1% of salt, and 50% deionized water were mixed together in a Professional 600 mixer (KitchenAid, St. Joseph, MI) for 4 min at speed level 2. The mixture was placed on perforated trays and steamed at 125°C for 3 min (Pyramid Food Processing Eqp., Tewksbury, MA) to gelatinize the starch. The cooked dough was rolled through a Libra Single Dough Sheeter (Moline Machinery Ltd., Duluth, MN) to the desired thickness (1-3 mm), and then cut into circles with a 7 cm diameter. Samples were sprayed with a 10% NaCl solution before frying or drying.

3.2.2 Continuous vacuum drying

Twenty-four pieces of prepared samples were fed into a pilot scale Bucher Dryband continuous vacuum belt dryer (CVD) (Bucher Unipektin AG, Switzerland). The plate temperature was set to 90^{o}C for all drying zones, and vacuum was maintained at ~3,000 Pa absolute. Three thermocouples were put in the middle of three separate samples, respectively, to monitor the temperature during the process. Approximately 24 pieces were dried within a 75 min period. A total of 600 chips were prepared to allow adequate samples for sensory and physical measurements. Samples were removed from the belt when the temperature reached a steady state. Samples were cooled at 20°C and packaged in PET/AL/PE pouches (Stock America Inc., Grafton, WI) flushed with N_2 gas.

3.2.3 Deep-fat frying

Deep fat frying (DFF) was performed in a professional 4-liter stainless fryer (Model 530F, Star Manufacturing Inc., St. Louis, MO). The unit was filled with Frymax Sun ClassicTM (Stratas Foods, Memphis, TN), made from a blend of high oleic sunflower and cottonseed oils. The oil temperature for frying was 180°C and samples were fried between 45 and 120 sec, depending on thickness. Six pieces were fried per batch and the temperature was maintained within 5°C during frying. The fried samples were cooled at 20°C and packaged in PET/AL/PE pouches flushed with N_2 gas.

3.2.4 Oil content

Oil content was determined by a modified AACC method 30-25.01(AACC, 2009). Ground sample (2-5 g) was placed in a thimble and extracted with petroleum ether in a Soxhlet system for 36 h. After extraction, the solvent was removed in a rotary evaporator. Three replicates were conducted.

3.2.5 Sensory evaluation

Untrained panelists (100) were recruited from staff and students at the University of Georgia, and had an age range from 18 to 60 years old. A majority of panelists (67%) were born in the U.S., while others originated from several countries worldwide. In initial evaluations, panelists were asked to evaluate the factors likely to influence their purchase intent. They were asked to evaluate vacuum-baked (CVD) and deep fat fried (DFF) corn chips. For comparison, commercial corn chips were purchased from a local restaurant (Locos Grill, Athens, GA) the evening of the day before the sensory evaluation and sealed in PE/Al bags to prevent moisture and gas transfer. No additional seasonings or flavors were added to the chips. The panelists were asked “How likely would you be to purchase this product?” A 5-point scale was used with 1

being “definitely would not purchase” and 5 “definitely would purchase”. In addition, panelists were asked “Would you be more willing to purchase the product because it has a lower fat content?” and “What factors influence your decision to purchase snack chips similar to these samples?”

In subsequent sensory trials, a separate panel was conducted to determine consumer likability of select chips. A panel of 100 panelists was asked to evaluate 4 samples: vacuum belt dried chips (1 mm and 1.5 mm thick) and deep-fat fried chips (1mm and 1.5 mm thick). Color, texture, flavor, and overall likability were assessed using a 9-point hedonic scale.

3.2.6 Color measurement

A CR-400/410 colorimeter (Minolta®, Minolta, Co. Ltd., Japan) was used to measure the color of chips. Twelve samples from each treatment group were used for evaluation. The color was measured before pretreatment, after pretreatment but before drying/frying, and after full processing. Color was reported as lightness (L*), chroma (C*) and hue (H*). The overall difference in color (ΔE) was also calculated as compared to untreated control. It is most easily calculated in the L*a*b* color system as:

$$\Delta E=\sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \qquad (3.1)$$

3.2.7 Instrumental texture and acoustic analysis

Attributes related to texture were evaluated using a TA-XT2i texture analyzer (Texture Technologies Corp., Scarsdale, NY) equipped with a Crisp Fracture Rig (HDP/CFS) and a 25 kg load cell. The rig consists of an 18 mm hollow cylindrical base sample holder, and a 6.325 mm ball probe that is used to penetrate the sample. The test speed was 1.0 mm/s, with a travel distance of 5 mm. Each sample was randomly selected from the bag just prior to testing, and placed centrally on the sample holder. The fracture force and work were obtained from the force-

distance curve. Fracture force was the maximum force required to break the sample. The work was calculated from the area under the curve up to the fracture point. Test results were obtained from 6 replicate samples.

During the mechanical texture measurements, acoustic data were recorded using Audix TM1measurement microphone (Audix, Wilsonville, OR) using the Audacity 1.3.11 software program. The microphone was fixed at 25 mm from the center of the sample. All tests were performed at room temperature and 25±1 % relative humidity. Sound files were analyzed using a program developed under MatLab (MathWorks, Natick, MA). Sound energy was determined from the total area under the peaks on the sound intensity versus time plots. The number of peaks was determined using the "findpeaks" algorithm in MatLab, in which peak height was chosen to only compute peaks above background threshold, and peak distance chosen to prevent inclusion of local maxima. In addition, the sound in the time domain was converted to the frequency spectrum using a power spectrum function. This was implemented with 1,024 points, a linear frequency scale and the Hanning window, an apodization function used to reduce aliasing.

3.2.8 Statistic analysis

Statistical analysis of the data was performed using SAS statistical software (Version 9.0, 2008). Analysis of variance (ANOVA) was performed, followed by Tukey's test to determine differences amongst the treatment groups. Statistical significance was expressed at the $p < 0.05$ level.

3.3 Results and discussions

3.3.1 Oil content

Table 3.1 shows the oil content of CVD and DFF corn chips, for three sample thicknesses. As expected, the oil content of the CVD chips was much lower than that of DFF chips. The

average oil content was 1.71, 1.82, and 1.57% for 1 mm, 1.5 mm and 2.3 mm CVD chips, respectively. This can be traced to the oil inherent to the corn flour. The oil content of the DFF chips was 34.80, 34.78, and 33.37% for 1 mm, 1.5 mm and 2.3 mm chips. These results are consistent with prior research on fried corn chips. Moreira, Sun & Chen (1997) reported that the oil content of DFF corn chips ranged from 22.33 to 44.92% (or 24.03 to 45.87% on a dry weight basis), and that oil content was significantly affected by the type of pre-treatment, frying oil temperature, and flour particle size. While the difference in oil content resulting from the two processes (CVD versus DFF) was substantial, there were no significant differences due to chip thickness for chips made by the same process.

3.3.2 Sensory evaluation

Results of initial sensory evaluation showed that 14.8% of panelists "might purchase", 16.8% "probably would purchase" and 5.9% "definitely would purchase" the CVD chips (Table 3.2). In comparison, 27.7% of panelists "might purchase", 17.8% "probably would purchase" and 4.9% "definitely would purchase" the DFF chips. Interestingly, 22.7% of panelists indicated they would probably or definitely purchase either CVD or DFF chips. It should be noted that 92% of the panelists indicated that they consider flavor when buying snack chips. As the chips in this study were served without additional flavors, seasoning or sauces, this may have reduced the intent to purchase.

Seventy-one percent of the panelists indicated that fat content is a concern when they purchase snack chips, while 21% do not care about this issue (others do not purchase snack chips). When asked which factors directly influence their decision to purchase snack chips 92% indicated flavor, 78% indicated texture/crispness, 68% indicated price and 53% the calories per

serving. Other factors included appearance (38%), sodium content (23%) and how the product is made (10%).

Results from the subsequent consumer panel are summarized in Table 3.3. In terms of overall likability, DFF chips had somewhat higher scores (6.56 and 5.30 for 1 mm and 1.5 mm chips) than CVD chips (4.33 and 4.25 for 1 mm and 1.5 mm chips). In addition, the thinner chips (1 mm) were somewhat preferred. These results were most closely linked with flavor, with DFF chips having flavor likability (6.47 and 5.39) greater than that of CVD chips (4.33 and 4.25). Textural differences were also significant, with texture likability for DFF chips (6.49 and 5.16) again greater than that of CVD chips (4.65 and 4.35). While the color for the DFF chips was slightly preferred (6.34 and 5.92 for DFF as compared to 5.51 and 5.67 for CVD chips), there were no differences in color likability for chips made by the same process. A few comments suggested that CVD chips had less of the typical flavor associated with fried chips. While CVD chips had more of a natural corn flavor and color, DFF chips had a flavor and color more closely associated with fried snacks. Some studies have suggested that adding flavors can compensate for the loss of fat or oil in normally savory products. For example, Stinson and Tomassetti (1995) showed that the addition of 2% corn flavor improved the overall, flavor and texture acceptability of baked corn chips.

Likability is not the only consideration for consumers, however. As noted, a majority of consumers are trying to “eat healthier”. While both “healthier” and “indulgent” snacks are growing market segments, “healthier” snacks are outpacing “indulgent” snacks (Wyatt, 2011). When deciding on what purchases to make, consumers rely on a variety of inputs. A key aspect of that is how well the concept of “healthier” is communicated on the product package and in the store. This information is actually sought by many consumers. For example, 41% of consumers

surveyed want “comments or symbols on packages to help easily pick out healthier options”. In our studies, we found that even without additional cues, CVD chips had reasonable “intent to purchase”. We also note that CVD chips had color and flavor more like native corn. While in our studies, panelists found that DFF chips had better flavor, as it was more typical of a fried food, with the right communication consumers may better appreciate a more minimally processed flavor and color.

3.3.3 Color measurement

The impact of treatment method on tortilla chip color is shown in Table 3.1. For the same sample thickness, the L* (lightness) values of both CVD and DFF chips were significantly lower than the samples before treatment, indicating that the samples became darker during processing. Overall, the CVD chips (L* of 67.8-70.0) were lighter in color than the DFF chips (L* of 55.9-56.1). Thicker CVD chips were slightly darker than the 1mm CVD chips.

The hue angle of CVD chips ranged from 88.0 to 89.7°, as compared to the untreated control which ranged from 86.9 to 89.3°. As pure yellow has a hue angle of 90°, this reflects that both the control and CVD chips have a color much influenced by the native corn flour. In comparison, DFF chips had values ranging from 83.1 to 85.3. This indicates a change more towards red, which would be consistent with greater browning. This is also seen in the chroma values, which represent the intensity or degree of saturation of the color. Values for the CVD chips ranged from 36.0 to 40.2 (on a scale of 0 to 100), as compared to the untreated control, which had slightly higher chroma values between 37.8 and 46.6. In contrast, the DFF chips had much lower chroma values than CVD chips, ranging between 24.6 and 25.6. Taken together, the L*C*H* values indicate that the CVD chips are only slightly darker than untreated control, and have only slightly lower color intensity. The DFF chips are darker and have a browner, duller

color than the CVD chips. Changes in color during frying have been related to reducing sugar content through the formation of Malliard browning products (Krokida, Oreopoulou, Maroulis & Marinos-Kouris, 2001). Degradation of frying oil may also contribute to color changes. In this study, the presence of carotenoid pigments that are degraded by heat is also likely to lead to color changes. The color difference of DFF chips (ΔE=30.09, 24.98, and 19.42) compared to control was much greater than for CVD samples (ΔE=9.26, 5.83, and 4.34). Again, this indicates that continuous vacuum drying produced less change in the original corn color.

It is worth noting that the yellow color of corn derives from β-carotene, xanthophylls and other carotenoids (Bhaskarachary, Sankar Rao, Deosthale, & Reddy, 1995). β-carotene can be converted to retinal, a form of vitamin A. Several carotenoids act as singlet oxygen quenchers, thus they are phytochemicals that act as anti-oxidants. In addition to the role of β-carotene as a nutrient, carotenoids have potential health benefits including being anti-carcinogenic (Bjelakovic *et al*, 2007). Studies have shown that β-carotene is degraded by heat, and can change through isomerization, oxidation and cleavage. The reactions are temperature dependent. For example, isomerization reactions in Copra oil had reaction rate constants of 0.042 min^{-1} at 120°C and 0.394 min^{-1} at 180°C. Oxidation reactions had rate constants near zero at 120°C and 0.168 min^{-1} at 180°C (Archir, Penicaud, Avallone, & Bohoun, 2011). The vacuum dehydration process occurs at low pressures such that the initial boiling point of water was approximately 40°C. As such, the product temperature remained relatively low throughout the process, and only approached 90°C during latter drying. In contrast, the fried chips used oil at 180°C. Thus, one expects to see greater degrees of browning and degradation of color.

3.3.4 Texture measurements

Fracture force increased with thickness for both the CVD and DFF chips (Table 3.4). For the 1.0 mm and 1.5 mm samples, there were no differences in fracture force due to the processing method. For the 2.3 mm samples, the CVD had greater fracture force than the DFF chips. One possible reason for this is that the oil in DFF chips serves as a lubricant, reducing overall friction within the flexing structure, allowing it to break with slightly less force build-up.

While greater fracture force for the CVD chips might be interpreted to indicate greater crispness, panelists did not indicate greater liking of the CVD texture. In fact, a few written comments indicated that the thicker CVD chips were too hard.

3.3.5 Acoustic measurement

A typical time-amplitude plot for 1.0 mm CVD chips is shown in Figure 3.2. The peaks correspond with the burst of sound as the chip structure was ruptured. In general, the number of sound peaks and total sound energy were greater for CVD chips (Table 3.4). The total number of peaks ranged from 26.8 to 33.5 for CVD chips and from 19.8 to 27.0 for DFF chips. Total sound energy ranged from 10.2 to 11.5 au for CVD chips, and 6.2 to 10.1 au for DFF chips. For both groups, 1.5 mm chips produced the greatest number of sound peaks and total energy. Increased mean height and number of sound peaks has been related to increased crispness of potato chips (Vickers, 1987).

The peaks of the frequency spectrum (Figure 3.3) fell into a similar bandwidth, with the greatest energy in the 1500-6000 Hz frequency range. The highest peaks for 1.0 mm chips appeared at 3100 Hz and 3620 Hz for CVD chips, and at 2890 Hz and 3400 Hz for DFF chips. For CVD chips, chip thickness had little effect on the range of frequency components, although 2.3 mm chips had lower sound intensity. Chip thickness had a more pronounced effect on the

components of DFF chips, with a shift to lower frequencies with increasing thickness. While the largest peaks for 1.0 mm DFF chips occurred at 3100 and 3620 Hz, for 2.3 mm chips peaks they occurred at 2100 and 2800 Hz. Thicker DFF chips also had lower sound intensity.

Overall, the CVD chips had a slightly broader frequency band, had more frequency peaks and more total energy. This was also reflected in the accumulated energy below select frequencies (Table 3.4). For example, CVD chips had between 67.8 and 70.0% of the energy at frequencies below 2500 Hz; for DFF chips between 55.9 and 56.1% of the energy occurred below 2500 Hz. Salvador, Varela, Sanz & Fiszman (2009) showed that the fracture and acoustic events associated with different commercial potato chips are not identical. As noted, the CVD chips tended to have higher frequency components than DFF chips. This likely occurs because the DFF chips contain substantially more oil (34%) which attenuates some of the high frequency harmonics associated with brittle fracture events.

Szczesniak (1988) reported that products (such as turnip) perceived to be crunchy/crackly have relatively low frequency components, while those perceived to be crisp (such as potato chips) had relatively higher frequency components. Dacremont (1995) showed that foods judged to be crunchy have frequency components between 1250 and 2000 Hz, when recorded by air conduction. Crisp foods had components in the range of 2000-6000 Hz. Sounds generated when foods are compressed by instruments may be somewhat different. For example, Seymour and Hamann (1988) found components in the range 1900-3300 Hz for instrumental compression of potato chips. Lee, Deibel, Glembin, & Munday (1988) suggested that for crisp foods, such as potato chips and corn chips, the first chew produces acoustic information with frequencies of 3000-4000 Hz and the second produces frequencies around 6000 Hz. In this study,

the ball probe fractured the sample in one pass, and thus is most similar to the first-bite action during normal chewing.

The acoustic data and fracture force implies that the CVD chips are crisper than the DFF chips, yet they were not deemed to have more likeable texture. One reason for this is that crispness is not always the only attribute that determines acceptability. Meullenet *et al* (2003) showed that while crispness is often correlated with snack chip acceptability, the acceptability of corn chips is associated with several texture descriptors. These include hardness, toothpack, crispness, oily film, moisture absorption, persistence of crispness and loose particles.

3.4 Conclusions

Continuous vacuum drying is a new and feasible method for producing low-fat corn chips with good consumer acceptability. The vacuum process can create a slightly expanded structure that contributes to product crispness. CVD chips had similar force and acoustic signatures to DFF chips, indicating that the important textural attributes could be achieved. While CVD chips had somewhat lower acceptability than DFF chips, consumer panelists indicated a willingness to purchase and a desire for snacks with low-fat content. We would suggest that acceptability could be further improved by the addition of select flavors. CVD chips also had less change in color during processing, suggesting there was less destruction of the carotenoid pigments, which include important nutrient and antioxidant compounds. As there is a growing market for low-fat snacks and minimally processed foods, along with foods that contain greater nutrients and bioactive compounds, continuous vacuum drying may be a means for producing snacks for targeted markets.

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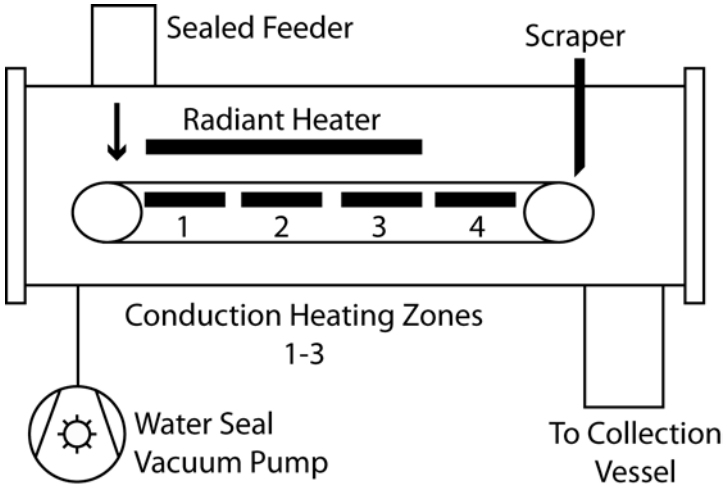

Figure 3.1: Schematic diagram of the continuous vacuum belt drier.

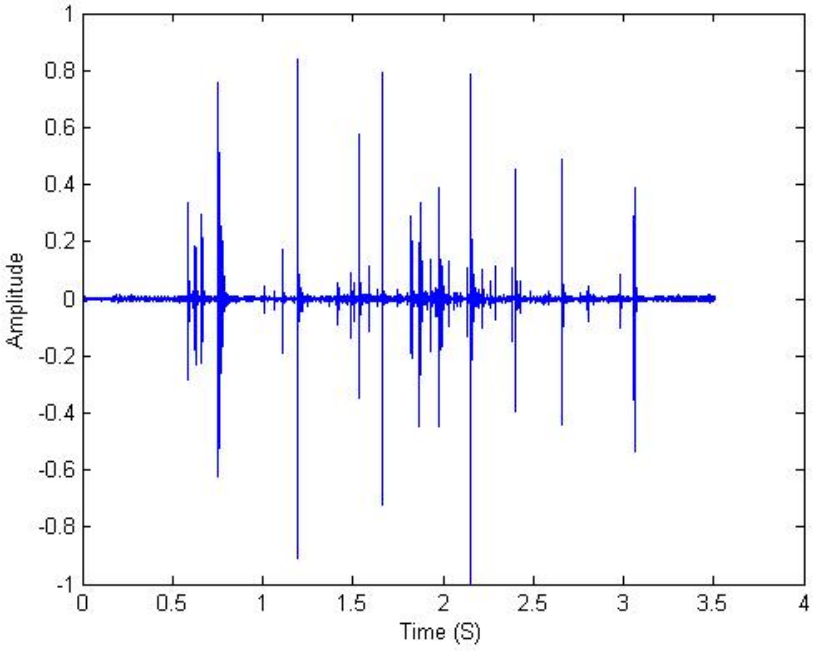

Figure 3.2: Sound profile during fracturing of CVD chips in the Crisp Fracture Rig

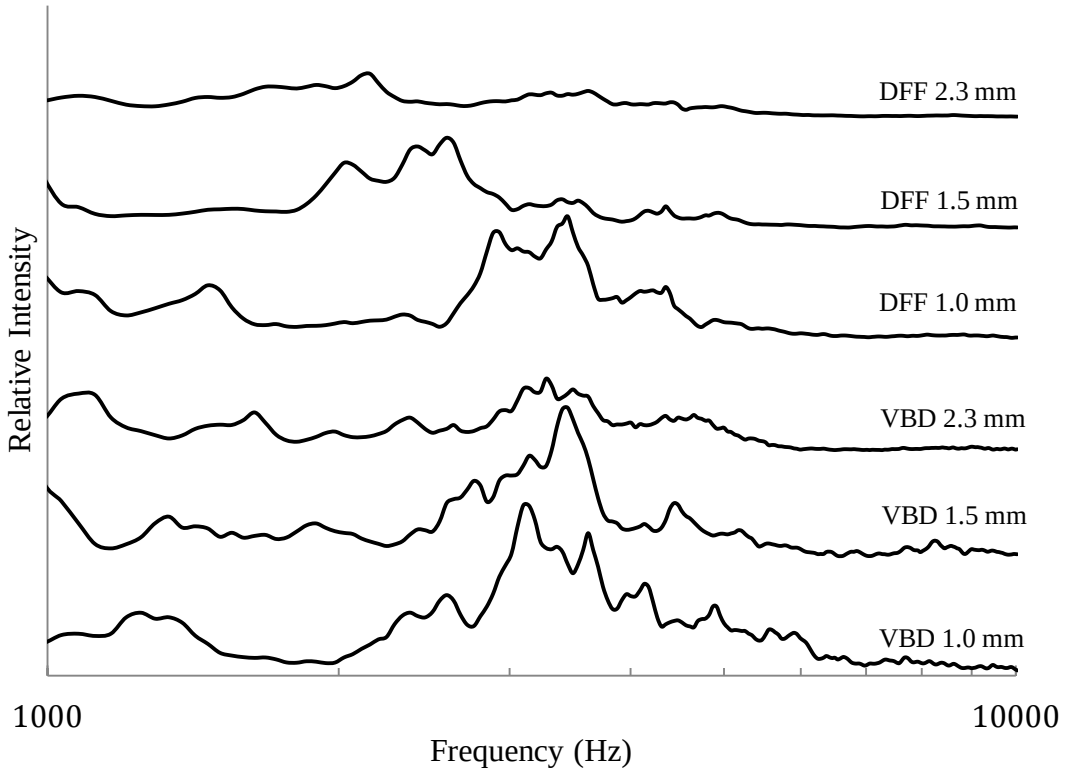

Figure 3.3: Frequency spectrum of CVD and DFF chips of various thicknesses during fracturing in the Crisp Fracture Rig

Table 3.1. Crude fat and color values of corn chips made by continuous vacuum drying (CVD) or deep fat frying (DFF).

		g oil per 100 g	Color L*	C*	H*	ΔE
Pre-drying	1.0 mm		76.2[a]	46.6[a]	89.3[ab]	
	1.5 mm		72.3[b]	44.2[b]	86.9[e]	
	2.3 mm		70.9[c]	37.8[d]	88.6[c]	
CVD	1.0 mm	1.71[a]	70.0[c]	39.8[c]	89.3[b]	9.26[d]
	1.5 mm	1.82[a]	68.4[d]	40.2[c]	88.0[d]	5.83[e]
	2.3 mm	1.57[a]	67.8[d]	36.0[e]	89.7[a]	4.34[e]
DFF	1.0 mm	34.80[b]	55.9[e]	24.6[g]	84.9[f]	30.09[a]
	1.5 mm	34.78[b]	56.0[e]	25.4[g]	85.3[f]	24.98[b]
	2.3 mm	33.37[b]	56.1[e]	25.6[f]	83.1[g]	19.42[c]

Means in the same column followed by different letters are significantly different ($P<0.05$)

Table 3.2. Summary of intent to purchase survey for CVD and DFF chips, along with factors that influence purchase (Total panelists = 100).

	CVD (%)	DFF (%)
Might Purchase	14.8	27.7
Probably Would Purchase	16.8	17.8
Definitely Would Purchase	5.9	4.9
Factors that influence purchase		
Lowfat	71%	
Processing method	10%	
Flavor	92%	
Appearance	38%	
Sodium Content	23%	
Calories per serving	53%	
Texture/crispness	78%	
Price	68%	

Table 3.3 Consumer evaluation of CVD and DFF chip likability (Total panelists = 100).

	Degree of Likability			
Sample	color	texture	flavor	overall
CVD (1mm)	5.51^{bc}	4.65^{bc}	4.28^{c}	4.33^{c}
CVD (1.5 mm)	5.67^{bc}	4.35^{c}	4.27^{c}	4.25^{c}
DFF (1 mm)	6.34^{a}	6.49^{a}	6.47^{a}	6.56^{a}
DFF (1.5 mm)	5.92^{ab}	5.16^{ab}	5.39^{b}	5.30^{b}

Means in the same column followed by same letters are not significantly different ($P<0.05$)

Table 3.4. Number of sound peaks and sound energy, accumulated energy under 2500 and 5000 Hz, and fracture force incurred during fracture of CVD and DFF chips.

		No. Sound Peaks	Total Sound Energy	% < 2500Hz	% < 5000Hz	Fracture Force (g)
CVD	1.0 mm	26.8^{ab}	11.3^{a}	70.0^{a}	89.3^{a}	778.4^{c}
	1.5 mm	33.5^{a}	11.5^{a}	68.4^{ab}	88.0^{a}	1189.3^{c}
	2.3 mm	27.0^{ab}	10.2^{ab}	67.8^{ab}	89.7^{a}	2910.4^{a}
DFF	1.0 mm	20.0^{b}	6.2^{b}	55.9^{c}	84.9^{ab}	547.8^{c}
	1.5 mm	27.0^{ab}	10.1^{ab}	56.0^{c}	85.3^{ab}	1058.5^{c}
	2.3 mm	19.8^{b}	8.3^{b}	56.1^{c}	83.1^{b}	1955.9^{bc}

Means in the same column followed by same letters are not significantly different ($P<0.05$)

CHAPTER 4

MODELING MOISTURE LOSS DURING VACUUM BELT DRYING OF LOWFAT TORTILLA CHIPS

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ABSTRACT

A continuous vacuum drying method was used to develop low-fat tortilla chips with good sensory properties. To better understand the process, drying models were developed to determine the effects of drying thickness and temperature on drying rate. Drying rates were determined at three conduction plate temperatures (80, 90 and 100°C)and three product thicknesses (0.8, 1.5 and 2.3 mm). An effective diffusion model and semi-empirical model were used to fit the data. In addition, a model was developed from the drying rate curves that incorporated a characteristic drying coefficient [k(t)] that varied with time, and could be described by a two-term Lorentzian model. All models had good agreement between experimental data and predicted data, with $r^2>0.98$. With consideration of other goodness-of-fit indicators (SSE and χ^2), results showed that the model that incorporated k(t) gave the best fit. The average effective moisture diffusivity was calculated using nonlinear regression, and ranged from D_{eff} = 1.19 to 1.54×10^{-9} m^2/s. D_{eff} increased with temperature and was described by an Arrhenius equation with E_a = 14.1 kJ/mol.

PRACTICAL APPLICATIONS

Continuous vacuum drying of a pre-steamed corn dough can be used to produce low-fat tortilla chips with high crispness and acceptable sensory properties. The drying rate models presented in this study will help predict appropriate drying times, optimize process conditions, and better understand the mechanisms of drying.

***Key words**: Vacuum drying, tortilla chips, drying models, diffusivity*

4.1 Introduction

The consumption of salty snacks in the U.S. is substantial with market sales in 2009 of $17.7 billion (Mintel, 2009). Potato and tortilla chips are the first and second largest selling snacks. However, most snack chips are processed by deep-fat frying which leaves the products with up to 40% fat content (Moreira, Castell-Perez, & Barrufet, 1999). Consumption of excess fat in the diet contributes to obesity and related chronic diseases. Thus, development of new low-fat snacks or low-fat alternatives of existing products is needed to meet increasing market demands for health-conscious consumers.

A few studies have examined alternative processes for producing low-fat tortilla chips. Vacuum frying has been studied in the production of potato chips, with the hypothesis that vacuum can help more quickly dehydrate the potato and may contribute to a structure that provides crispness. Garayo & Moreira (2002) found that the oil content of vacuum-fried chips was lower than those fried without vacuum. In contrast, Troncosco et al. (2009) reported that vacuum frying increased the oil content of chips, decreased color and texture scores and improved flavor. Kayacier & Singh (Kayacier & Singh, 2003) measured the textural attributes of baked corn tortilla chips. They found that fracture force increased with baking time to a certain point, then decreased, and suggested that important texture attributes were related to air cells and cracks formed during baking. Xu & Kerr (2012) showed that low-fat tortilla chips could be produced in a continuous vacuum dryer using temperatures lower than that used in most baking processes, by pretreating the dough with steam. The dough was made from corn flour, steamed for 3 minutes and rolled to a thickness between 0.7 and 2.5 mm. The vacuum dried chips had significantly lower fat (1.2% versus 34.6%) and developed a multi-celled structure capable of producing crispness. This porous structure was formed by water as it boiled off of the product at

the low chamber pressure. Texture analysis showed that the chips developed much of the mechanical and acoustical properties associated with fried snacks. Except for oil flavor, other characteristics of the dried chips were comparable to deep fat fried chips, and consumer likability was good. In addition, the chips maintained much of the fresh corn flavor along with the color associated with carotenoids.

Monitoring of the continuous vacuum process is difficult, however, particularly as it concerns changes in the product moisture content. Thus, models are needed to predict heat and mass transfer as a function of process conditions in order to optimize the process, produce better product and save energy. A number of papers deal with modeling the vacuum drying of foods. One complication is that there can be several mechanisms involved in the transfer of moisture during vacuum drying of food stuffs (Viollaz, 2005). These include bulk diffusion of liquid, surface diffusion, capillary forces that pull water through narrow tube structures, Knudsen diffusion through long pores, water vapor diffusion due to vapor pressure gradients and vapor flux due to total pressure differences. Mass transfer may occur inside the porous solid food through liquid diffusion, vapor diffusion, or both. The driving force for diffusion can be gradients in water concentration, pressure, and temperature (Hines & Maddox, 1985; Viollaz, 2005; Waananen, 1989).

Some drying models lump these mechanisms into one or more variables that are assumed to stay constant during drying. Baini & Langrish (2007) used the concept of a characteristic drying rate curve to model the drying of banana slices. This approach posits that the drying rate curves for a particular material determined in different conditions are geometrically similar and can be described by a single curve after introducing a normalized characteristic drying rate and moisture content. They found this approach worked well only for continuous drying of the

bananas. Arevalo-Pinedo & Murr (2006) found that vacuum drying of pumpkin could be modeled with a Fickian diffusion model for an infinite slab that incorporated the effects of shrinkage. Lee & Kim (2009) used non-linear regression to fit nine drying models to moisture loss data for vacuum dried white radish slices, and examined the effects of temperature and slice thickness on drying rate. These included a diffusion model that incorporated an effective diffusion coefficient. Of these, a logarithmic model best fit the thin-layer drying of radish slices. Methakhup et al. (2005) studied both vacuum drying and low-pressure superheated steam drying of Indian gooseberry flakes. They found a relatively good fit to the drying data using the empirical Page model. Rajkumar et al. (2007) studied the drying kinetics of tomato slices in a vacuum-assisted solar dryer, using thin-layer drying models that incorporated constants related to the material and drying air temperature.

No research has been reported on modeling vacuum dehydration to prepare corn chips. Kayacier & Singh (2004) used an effective diffusivity model to predict baking of tortilla chips. They concluded that the model did a good job of predicting the evolution of moisture content. They suggested that both vapor diffusion and liquid diffusion were involved in the transport of mass during baking. They also found an Arrhenius type relationship between baking temperature and effective diffusivity.

The objective of this study was to understand the kinetics of moisture removal for tortilla chips prepared in a continuous vacuum drying system. Three models are presented that provided reasonably good fit of the data: one based on internal diffusion, one semi-empirical and one using a characteristic drying coefficient that is a function of time. As part of the modeling, effective diffusivities and related drying coefficients were determined.

4.2 Materials and methods

4.2.1 Sample preparation

Nixtamilized corn flour was obtained from Mission Foods (Pendergrass, GA). A mix of 50% corn flour and 50% deionized water was prepared and mixed in a KitchenAid Professional 600 mixer (St. Joseph, MI) for 4 minutes at speed 3. The mixture was placed on perforated trays and steamed for 3 min in a steam chest (Pyramid Food Processing Eqp., Tewksbury, MA) in order to gelatinize the corn starch. The dough was rolled by a sheeter (Moline Machinery Ltd. Duluth, MN) to a specified thickness (2.3 mm, 1.5mm or 0.8mm) and then cut into circular shapes with a diameter of 61 mm.

4.2.2 Vacuum drying

A schematic diagram of the continuous vacuum belt dryer is shown in Figure 4.1. The prepared samples were dried in a pilot scale vacuum belt dryer (Bucher DryBand LKM101, ZWag, Zschokle Wartwann LTD., CDÖttingen, Switzerland). The dryer had a 20 cm wide Teflon coated fiberglass belt passing directly over three conduction heating plates (25.4 cm long) and one cooling plate. A radiation plate, set at 4.7 mm from the conduction plates spanned the length of all three conduction plates. Nine samples pieces were placed on the belt, and the vacuum pulled with an AquaSeal vacuum pump (Dekker Vacuum Technologies, Michigan City, IN) to 2.67 kPa (20 torr). To test the effects of temperature on drying rate, samples were dried with the conduction plate heaters and radiation heater set to 80, 90 or 100°C. Dried samples were cooled at room temperature and packaged in PET/AL/PE pouches.

4.2.3 Drying curves

The vacuum dryer was modified to obtain drying curves at each temperature. Samples (9 pieces) were placed on a heater plate attached to an electronic digital balance (Reflex HP, Avery

Weigh-Tronix LLC., Fairmont, MN) with a precision of ±0.01 g. The balance was set in a small chamber 30.48 cm above the main vacuum chamber, with a hollow rod connected underneath to the heater plates. Three plate temperatures were used: 80, 90, 100°C. Sample weight was recorded every 10 s on a personal computer. Drying was terminated when the sample weight did not change for 5 min. The temperatures were measured by three thermocouples which were attached to the samples, and temperatures were recorded by a data logger every 10 s. Two replications were conducted for each condition.

4.3 Mathematical drying models

Several models were tested to fit the drying rate data. As noted, there are several moisture transfer mechanisms possible during vacuum drying. As the relative contributions of each may change during the course of drying, it is easier to define an effective diffusivity that encompasses the various resistances to moisture transfer.

Drying rates may also be limited by diffusion of water away from the drying food. This is particularly true during early phases of drying where the product surface is wet, and the ability to get heat to and mass away from the surface becomes limiting. This leads to constant rate drying. Analysis of the drying rate data in this study (Figure 4.4) showed that there was no evidence of a constant rate period. In addition, product temperatures did not stabilize initially as usually seen in constant rate drying. Thus, the drying models developed here are focused on limits to moisture transfer within the product as it moves to the product surface.

4.3.1 Diffusion model

The general differential equation of Fick's Second law for transient diffusion of water during drying is:

$$\frac{\partial M}{\partial t} = \nabla \cdot (D_{eff} \nabla M) \tag{4.1}$$

where D_{eff} is the effective diffusivity (m^2/s), t is the time (s), and M is the moisture content of the drying product (gH_2O/g solid). The dry basis moisture content at any time is calculated from the weight of product at time t (w) and the weight of solids in the product (Fellows):

$$M = \frac{w - w_s}{w_s} \tag{4.2}$$

In this study, the surface area of the flat upper surface was much larger than that of the side (~20-60 times greater), thus water transfer from the side area was ignored. Therefore, the sample was considered as an infinite slab with one-dimensional mass transfer and the changes in thickness were considered negligible. Thus, Equation 4.1 was simplified to the partial differential equation of diffusion in one-dimension (x direction) through the sample thickness (L):

$$\frac{\partial M}{\partial t} = \left(D_{eff} \frac{\partial^2 M}{\partial x^2} \right) \tag{4.3}$$

with the follow boundary conditions:

1) The initial moisture distribution is uniform ($M=M_0$ at $t=0$, $0<x<L$)
2) The surface moisture content approaches the equilibrium value once drying starts ($M=M_e$, at $t>0$, $x=L$)
3) There is no change in moisture gradient where the sample bottom touches the heating plate ($\frac{\partial M}{\partial x} = 0$, at $t>0$, $x=0$)

For convenience, a dimensionless moisture ratio (MR) was used:

$$MR = \frac{(M_t - M_e)}{(M_o - M_e)} \tag{4.4}$$

where M_t is the average moisture content at time t, M_e is the equilibrium moisture content, and M_o is the initial moisture content. Equation 4.3 can be written as:

$$\frac{\partial MR}{\partial t} = \left(D_{eff} \frac{\partial^2 MR}{\partial x^2} \right) \tag{4.5}$$

with the new boundary conditions:

1) MR=1 at t=0; 0<x<L
2) MR=0 at t>0, x=L
3) $\frac{\partial MR}{\partial x} = 0$, at t>0, x=0

The solution of the partial differential equation 4.5 with the above boundary conditions is:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{-(2n+1)^2 n^2 D_{eff} t}{4L^2} \right) \tag{4.6}$$

In addition, the relationship between the average effective moisture diffusivity and the sample temperature was assumed to follow an Arrhenius model:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT} \right) \tag{4.7}$$

where E_a is the activation energy, R is the universal gas constant, T is the absolute temperature and D_0 is a constant. E_a and D_0 can be determined from a linear fit of $\ln(D_{eff})$ versus 1/T, with the slope giving E_a/R, and the intercept giving $\mathrm{Ln}(D_0)$.

4.3.2 Semi-empirical model

Several researchers have used empirical models to predict moisture content during drying (Lee & Kim, 2009; Liu, Qiu, Wang, & Chen, 2011; Rajkumar et al., 2007). Empirical

models generally predict the average moisture content of a product as a function of drying time. While the diffusion model is associated with the physical process of diffusion as described by D_{eff}, empirical models may use fewer variables. Using separation of variables to solve Fick's second law (Equation 4.5), we find that moisture change is a function of both time and distance. For a product of fixed thickness, the moisture ratio can be modeled as:

$$MR = K_1 \exp(-K_2 t) \tag{4.8}$$

where K_1 and K_2 are fitted constants. The model is semi-empirical as neither the diffusion coefficient or thickness is explicitly specified.

4.3.3 Variable drying coefficient model

The above models assume that the effective diffusivity or model constants do not change with time. One improvement is to incorporate a time-dependent constant k that measures effective diffusivity over time. The function that describes k is determined by analysis of an experimental drying rate curve. The drying rate (DR) measures how fast moisture leaves the product:

$$DR = \frac{dM}{dt} = \lim_{\Delta t \to 0} \left(\frac{M_t - M_{t+\Delta t}}{\Delta t} \right) \tag{4.9}$$

where M_t is the moisture content at time t. Thus, when the time between data points is short compared to the drying time, the derivative can be approximated by $\Delta M/\Delta t$. In our case, Δt=10 s as compared to drying times of 50-100 minutes.

The flux φ (in g/m^2s) can be expressed as :

$$\phi = k\frac{(M_t + M_s)}{V} \tag{4.10}$$

where k (m/s) is a characteristic drying coefficient that varies with time, V (m^3) is the sample volume, M (gH_2O/g solid) is the moisture content of the chips, and M_s is the moisture content at the interface between the product surface and surroundings. Once the vacuum is pulled the surface moisture rapidly approaches 0. The drying rate is then:

$$DR = \phi \cdot A = k\frac{M_t}{L} \tag{4.11}$$

where A (m^2) is the surface area of the sample and L (m) is the thickness of the sample. The moisture content can be predicted from:

$$M_{t+\Delta t} = M_t\left(1 - \frac{k}{L}\Delta t\right) \tag{4.12}$$

where at t = 0, $M_t = M_o$. The coefficient *k* is determined by fitting the drying rate data using a model with two Lorentzian distributions:

$$k = f(t) = \frac{\alpha_1}{1+\left(\frac{t-\beta_1}{w_1}\right)^2} + \frac{\alpha_2}{1+\left(\frac{t-\beta_2}{w_2}\right)^2} \tag{4.13}$$

where α, β, w are constants.

4.3.4 Data analysis

While the sample weight and temperature were recorded every 10 s, to improve clarity the drying data, Figures 4.2-4.5 are plotted every 2 min initially, and every 4 min during later drying periods. For the diffusion model, Equation 4.6 was fit to the data using the first 8 terms of

the equation, as higher order terms did not contribute substantially to the calculated moisture. The coefficients for the diffusion and semi-empirical models (Equation 4.8) were calculated by regression analysis using JMP 9.0 software (SAS Corp., Cary, NC). Values for the variable coefficient drying model (Equation 4.13) were determined by regression analysis using Graphpad Prism 5 software (La Jolla, CA). The goodness of fit was evaluated by the coefficient of determination (r^2), sum of squared errors of prediction and reduced chi-square (χ^2). The latter were calculated by:

$$SSE = \sum_{i=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2 \tag{4.14}$$

$$\chi^2 = \frac{\sum_{n=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2}{N - n} \tag{4.15}$$

where $MR_{exp,i}$ is the *i*th experimental moisture ratio, $MR_{pre,i}$ is the *i*th predicted moisture ratio, N is the number of observations, and n is the number of constants in the model. The best-fitting model was considered as one with the highest r^2 and lowest χ^2 and SSE.

4.4 Results and discussion

4.4.1 Moisture changes

The change in moisture ratio of the corn chips over time is shown as a function of temperature (Figure 4.2a) and product thickness (Figure 4.2b). Replications under the same drying conditions varied less than 2%. As expected, as the heater plate temperature was increased from 80 to 100°C, moisture was removed a greater rate (Figure 4.2a). However, differences in drying rate were not large. At 100°C, 2.3 mm chips took 29 min to reach MR = 0.20, while at 90°C they took 33 min and at 80°C 36 min. The effect of chip thickness on drying rate was even greater than that of temperature (Figure 4.2b), with increased thickness leading to

slower drying rates. For example, to reach a MR of 0.20 at 100°C took 11 min for 0.8 mm chips, 20 min for 1.5 mm chips and 29 min for 2.3 mm chips. These observations are consistent with Fick's law (Equation 4.6) which predicts that the change in moisture with time is inversely related to the square of the thickness, while the influence of temperature is manifest through its effect on the diffusion coefficient (Equation 4.7). While drying was relatively rapid for the first 20-30 min, the rate dropped significantly thereafter. For crisp snack foods such as tortilla chips, a final moisture content of 2-3% is typical (Moreira et al., 1999). To reach 3% moisture took 67 minutes at 100° C, 90 minutes at 90° C, and 134 minutes at 80°C.

The inner product temperature was recorded during the vacuum drying and shown in Figure 4.3. The temperature decreased a few degrees in the first few minutes, likely as the boiling point decreased under vacuum and evaporation of water helped remove heat from the product. After 2-3 min, this phenomenon decreased and heat from the conduction plates caused the sample temperature to continuously increase. For drying at 100°C the initial temperature was ~30°C, gradually reached 80°C after 50 mins, and leveled off thereafter. The final internal product temperature was always lower than the heating plate temperature, but very similar to the chamber temperature.

4.4.2 Drying rate

Figure 4.4 shows the drying rate during vacuum drying of tortilla chips at three different plate temperatures. In the drying of high moisture foods, a constant rate period may be evidenced with one or more falling rate periods. During the constant rate period, moisture is always available at the food surface, as water diffuses more rapidly to the product surface than it is carried away from the surface into the surroundings, and drying is determined by the convective mass transfer coefficient (Viollaz, 2005). However, a constant rate period is often

not observed in the drying of food stuffs. During falling rate periods, the movement of internal water to the surface is slower than the rate of water carried away from the surface. Normally the molecular diffusion decides the rate of water transfer during the falling drying, although other factors such as capillary forces and pressure gradients can play a role.

No constant drying rate period was observed during the course of drying in this study. This indicates that the mass transfer of water within the product was the determining factor controlling drying rate, and that the assumptions for the diffusion-based models were reasonable. As noted, drying at higher plate temperatures resulted in higher drying rates. One reason, of course, is that higher temperature promotes faster diffusion as seen in Equation 4.7. The greatest decrease in drying rate occurred as moisture levels decreased below 0.4 gH_2O/g solids.

4.4.3 Drying models

4.4.3.1 Determining model parameters

Diffusion model. The diffusion model (Equation 4.6) predicts that moisture loss during drying is related to the effective diffusivity. The average effective diffusivity was obtained by nonlinear regression of experimental data as a function of temperature and thickness. The average D_{eff} was 1.54×10^{-9} m^2/s, 1.32×10^{-9} m^2/s , and 1.19×10^{-9} m^2/s at plate temperatures of 100°C, 90°C, and 80°C, respectively (Table 4.1). Baini and Langrish (2007) reported the D_{eff} for drying bananas at 60°C of 1.09×10^{-9} m^2/s. Kayacier and Singh (2004) found D_{eff} for tortilla chips baking at 505K-533K was 6.25×10^{-10} to10.97×10^{-10} m^2/s. Many factors influence D_{eff}, including operating pressure, water content, and temperature. Lower moisture levels lead to lower diffusivity, while higher temperatures lead to higher D_{eff}. We calculated somewhat higher values under vacuum drying than reported for baking tortilla chips. This may be due to the enhancement of moisture transfer due to the large pressure gradient. To assess the temperature

dependency, $\ln(D_{eff})$ was plotted versus the inverse temperature (Figure 4.5), and the apparent activation energy E_a determined from the slope using Equation 4.7. For vacuum drying of tortilla chips, E_a was 14.095 kJ/mol. Kayacier and Singh (2004) reported an E_a = 13.4KJ/mol for hot air baking of tortilla chips.

Semi-empirical model. The drying data was also fit to the semi-empirical model (Equation 4.8). Fitted constants for K_1 (the pre-exponential constant) and K_2 (the exponential constant) are shown in Table 4.1. Values for K_1 varied from 1.079 at 100°C to 1.069 at 80°C. Values of K_2 were 0.557 min^{-1} at 100°C to, 0.047 min^{-1} at 90°C and 0.043 min^{-1} at 80°C.

Variable drying coefficient model. For the variable drying coefficient model (4.12), a description of k as a function of time was determined. The drying coefficient k was calculated using Equation 4.11 and plotted in Figure 4.6. The function was determined by fitting to Equation 4.13 (see Table 4.1). There were 4 primary periods for k dependent on time. Initially, k showed a slight decrease over the first few minutes of drying. This may be related to the initial exposure of the product to vacuum in which the temperature drops and rapid evaporation occurs. The value of k increased thereafter until ~40 min. Over this period, the product temperature also increased to a maximum. After reaching a maximum, k decreased steadily thereafter as moisture levels become fairly low. At a critical point (~80 min), k changed very little thereafter.

The temperature and moisture content of the sample both affect the mass transfer of water. After drying commenced, the moisture content of the chips decreased which will tend to decrease k. However, the internal temperature increased, which would tend to increase k. As the product temperature began to rise, the effective diffusivity increased. Thereafter, the temperature stabilized and k decreased as moisture levels continued to decrease.

The two-term Lorentzian model (Equation 4.13)fit the k values well (r^2>0.99) (Table 4.1) at moisture levels above 3%. At higher plate temperatures, higher k values were reached. Thus, the maximum k at 80, 90 and 100°C was 1.22×10^{-4}, 1.47×10^{-4} and 1.80×10^{-4} m/s, respectively. In addition, higher temperature resulted in that peak being reached in a shorter time.

4.4.3.2 Fitted drying models

The weight loss data obtained during vacuum drying were fit to diffusion, semi-empirical, and variable drying coefficient models. The values of the various constants are presented in Table 4.1, along with the goodness of fit as indicated by r^2, SSE and χ^2. All models fit reasonably well with r^2>0.98. Overall, the variable drying coefficient approach gave the best fit and this is seen more clearly by the fits to the data in Figure 4.7. The diffusion model was the least well fit. A likely reason for this is that in the diffusion model, the effective diffusivity (D_{eff}) is considered constant, and ignores the change in temperature and moisture content that occurs during drying. In addition, different drying mechanisms may come into play during the course of drying including capillary forces and different types of diffusion. It becomes difficult to encapsulate all these factors into a single constant. The diffusion model predicted lower moisture content initially than was observed, then higher moisture contents than was observed thereafter.

The semi-empirical model gave a slightly better fit, particularly at higher moisture contents, then predicted slightly higher than observed values at lower moisture contents. This model has a form somewhat similar to the diffusion model, that is, it is essentially exponential. However, the semi-empirical model does not have a constrained pre-exponential factor or explicit thickness. While this allows better fitting, it also means the model does not allow prediction of the effects of product thickness on drying rate.

Allowing for a coefficient that varies with time, thus temperature and moisture, allows for more flexibility in the model. The variable coefficient model gave the best fit overall, with only a slight over prediction of moisture levels in intermediate periods. The fit is likely better as it allows more flexibility in the model, and in fact more closely mimics the changes in diffusivity that occur during the course of drying.

4.5 Conclusions

A diffusion model and semi-empirical model were developed from Fick's law of diffusion. A model incorporating a variable characteristic coefficient was derived from the drying rate data. All models were related to the internal mass transfer of water during the vacuum belt preparation of low-fat tortilla chips. All had reasonably good agreement between experimental and predicted data. Upon consideration of all the goodness-of-fit parameters (r^2, SSE and χ^2), the model incorporating a variable coefficient gave the best prediction of moisture levels over the total course of drying. One beneficial aspect of the diffusion model and variable drying coefficient model is that they explicitly incorporate the product thickness, allowing one to predict how changes in product thickness would affect drying.

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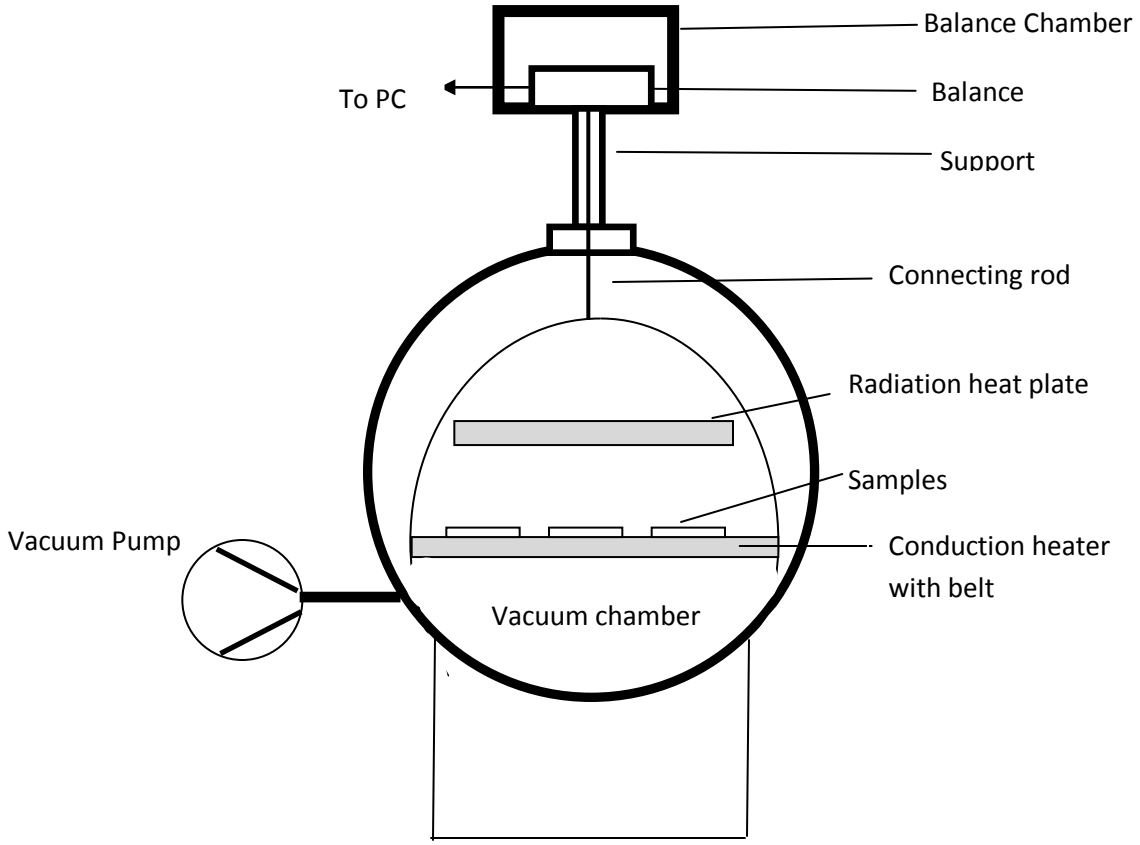

Figure . 4.1. Continuous vacuum belt dryer with attached balance for determining drying rate.

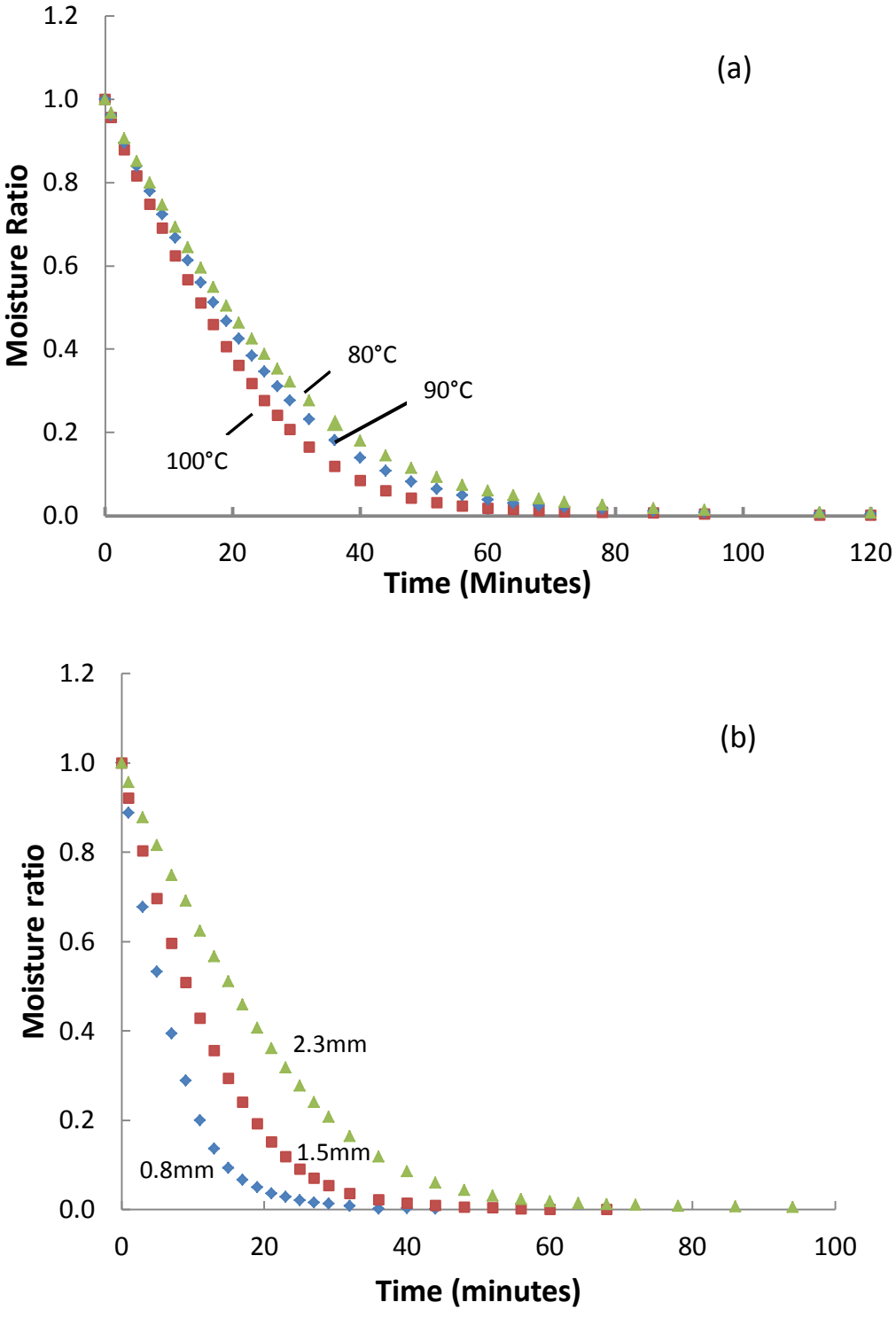

Figure.4. 2. Vacuum drying of tortilla chips as a function of: a. temperature (L=2.3mm) b. thickness(T=90°C).

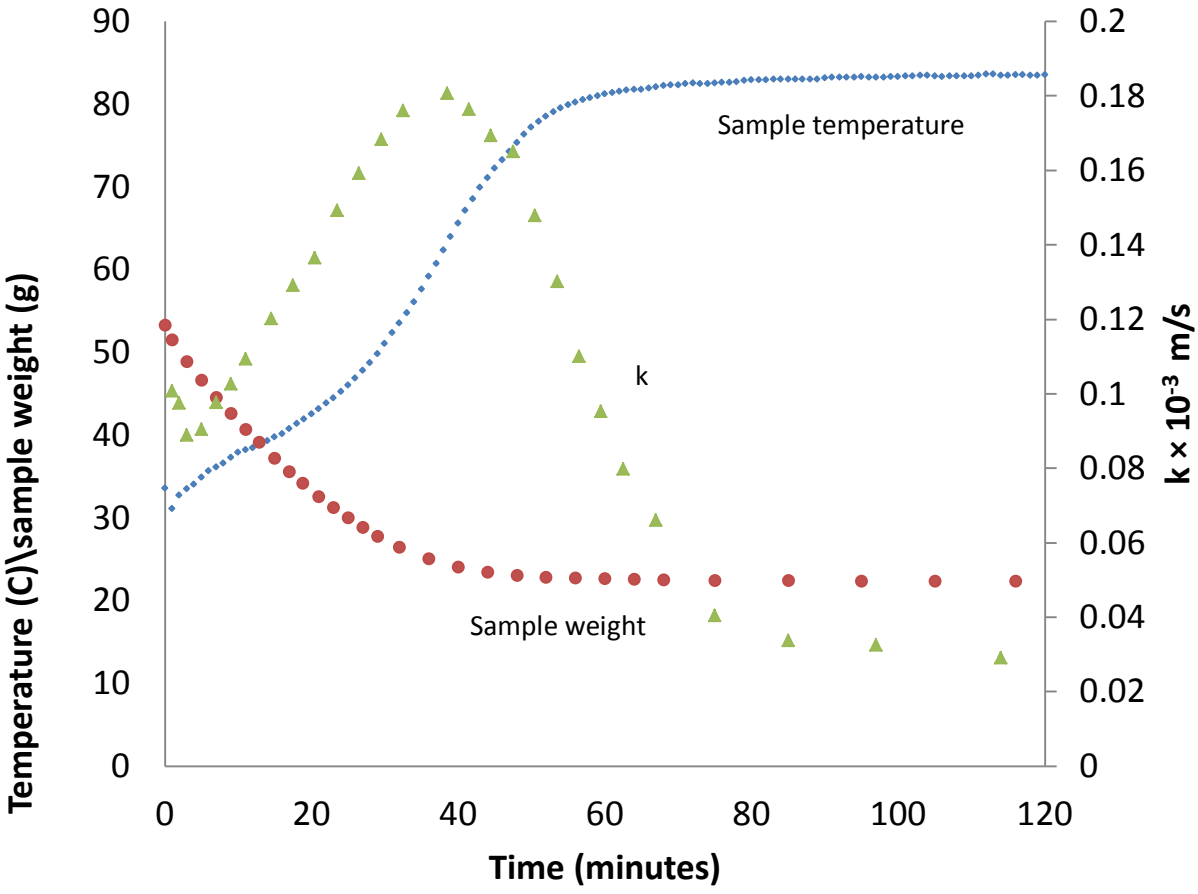

Figure 4.3. Temperature, sample weight and characteristic drying coefficient (k) change as a function of time during vacuum drying: T=100^{o}C, L= 2.3mm, and P=20 torr.

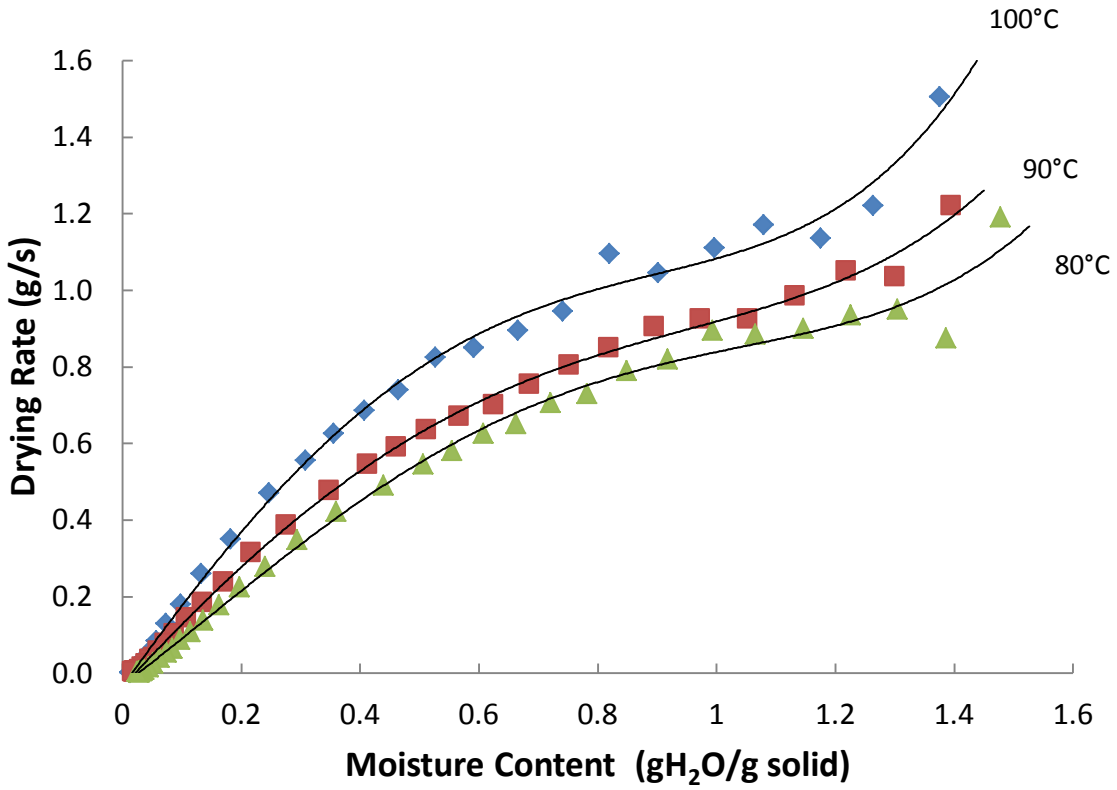

Figure. 4.4. Drying rate during vacuum belt drying of tortilla chips. L = 2.3mm, P = 20 torr. A = 28.26 cm^2.

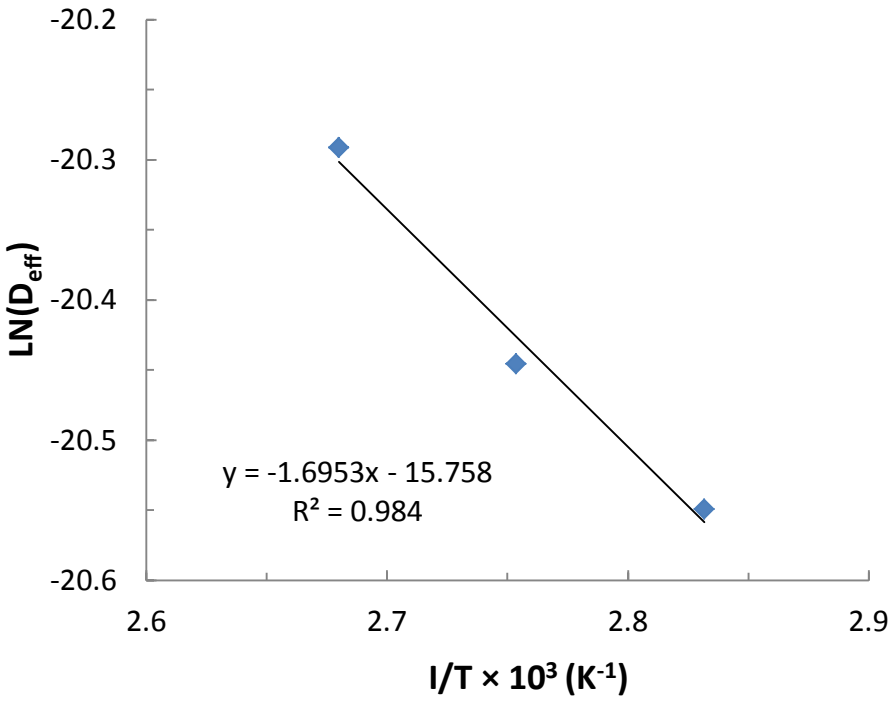

Figure. 4.5. Effect of temperature on the average drying effective diffusivity of the vacuum drying of tortilla chips

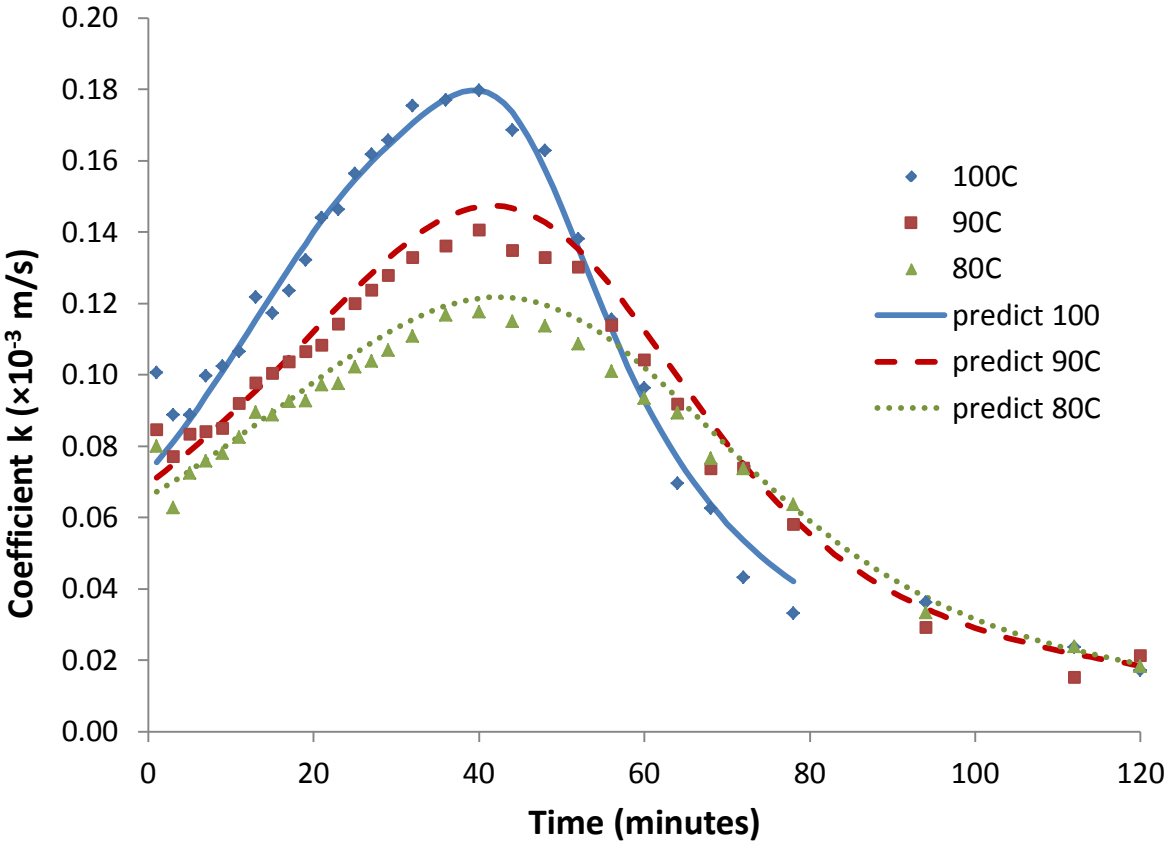

Figure. 4.6. Characteristic drying coefficient (k) as a function of time and fit by a two term Lorentzian model.

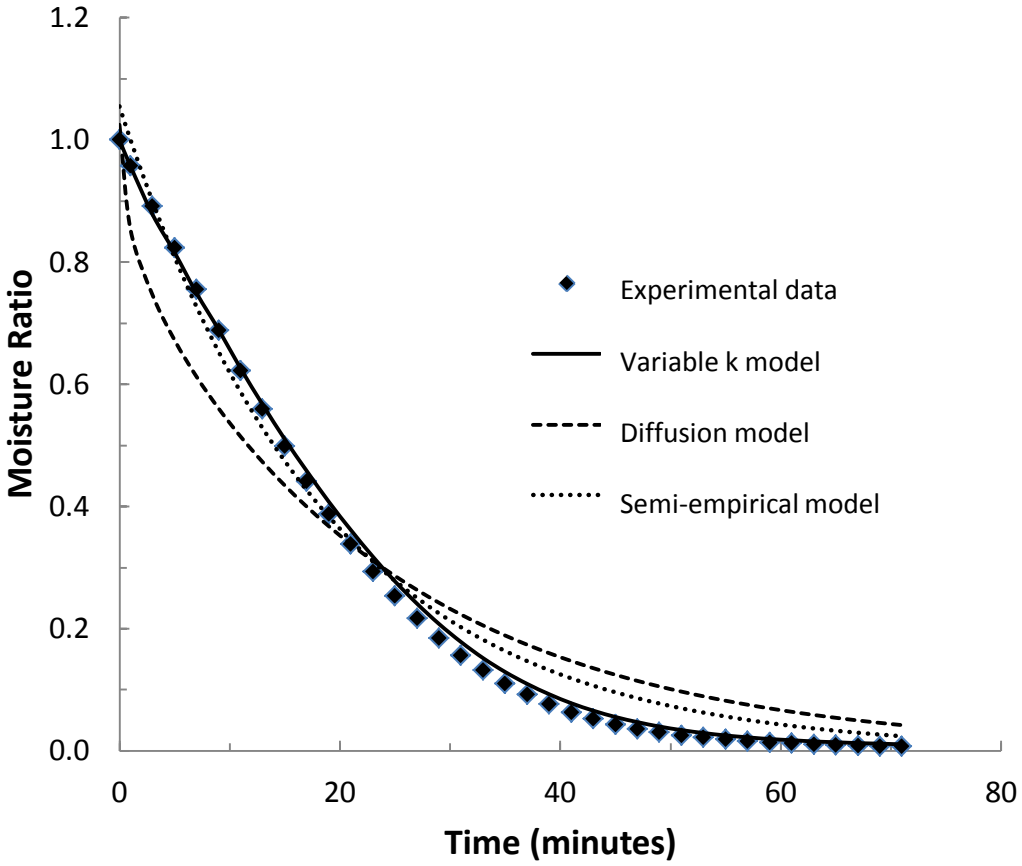

Figure. 4.7. Model fits to drying rate data at T=90°C, L=2.3mm, P=20 torr.

Table 4.1. Drying rate model constants by non-linear fitting and evaluation of goodness of fit

	Temp (°C)	Model constants		R^2	SSE	χ^2
Diffusion Model	100° C	$D_{eff}=1.54\times10^{-9}$ m^2/s		0.9811	0.9163	$1.1*10^{-3}$
	90° C	$D_{eff}=1.32\times10^{-9}$ m^2/s		0.9845	0.81594	$9.74*10^{-4}$
	80° C	$D_{eff}=1.19\times10^{-9}$ m^2/s		0.9893	0.58971	$7.04*10^{-4}$
Semi-Empirical Model	100° C	$K_1=1.07953$		0.9934	0.348382	$4.15*10^{-4}$
		$K_2=0.55667$				
	90° C	$K_1=1.07248$		0.9951	0.282681	$3.37*10^{-4}$
		$K_2=0.04759$				
	80° C	$K_1=1.06928$		0.9959	0.248123	$2.95*10^{-4}$
		$K_2=0.04279$				
Variable Characteristic Drying Coefficient	100° C	$\alpha_1=0.04672$	$\alpha_2=0.04471$	0.9993	0.050612	$6.03*10^{-5}$
		$\beta_1=24.55$	$\beta_2=43.51$			
		$w_1=27.06$	$w_2=17.08$			
	90° C	$\alpha_1=0.8136$	$\alpha_2=-0.7559$	0.9973	0.035137	$4.18*10^{-5}$
		$\beta_1=52.37$	$\beta_2=53.72$			
		$w_1=44.34$	$w_2=-44.73$			
	80° C	$\alpha_1=0.2446$	$\alpha_2=-0.1959$	0.997	0.028477	$3.39*10^{-5}$
		$\beta_1=52.42$	$\beta_2=56.88$			
		$w_1=52.60$	$w_2=54.70$			

CHAPTER 5

THE EFFECT OF DRYING CONDITIONS ON THE QUALITY OF LOW-FAT TORTILLA CHIPS PRODUCED BY VACUUM DRYING

Xu, S. and Kerr, L.W. submitted to *Journal of Food Engineering* .

ABSTRACT

Low-fat tortilla chips were produced by vacuum belt drying. Three levels of chip thickness (2.3, 1.5, and 0.8 mm) and three levels of plate heating temperature (80, 90, and 100°C) were studied. Drying times varied from 34 to 130 min, and chip thickness had the most pronounced effect on drying time. The chips had a deeper yellow color after drying, but there was little difference in color amongst the differently dried chips. Chip hardness increased with thickness, while the number of fracture peaks was greatest for 1.5 mm chips dried at temperatures >90°C. While area shrinkage (22%) was least for 2.2 mm thick chips produced at higher temperature, the greatest expansion (115%) occurred for 1.5 mm chips produced at temperatures > 90°C.

Key words: *tortilla chip, lot fat, drying time, quality drying conditions*

5.1 Introduction

Obesity and overweight have been a growing problem in the United States for the last few decades. Among Americans adult, some 68.0% are overweight or obese (Flegal, Carroll, Kit, & Ogden, 2012). Obesity is correlated with diseases such as diabetes, heart disease, high blood pressure, joint disease and cancer (Mokdad, Marks, Stroup, & Gerberding, 2004). One contributor to this problem is the consumption of high-fat foods, and particularly snacks that provide little other nutrition. Many snack chips, including potato and corn, are produced by deep-fat frying, resulting in a relatively high-fat product. For example, it has been measured 39.8% fat (w.b.) in potato chips, 36.6% in corn chips, and 25.2% in tortilla chips (Moreira, Castell-Perez, & Barrufet, 1999).

Consumer demand for healthy foods is greater than ever. With respect to snack items, surveys show that 88% of customers think “good value” is the key driver for snack selection, while 79% indicate they are trying to “eat healthier” (Wyatt, 2011). The same report indicates that sales of “healthier” snack foods grew 37% between 2005 and 2009. Thus, there is a clear demand for lower fat and more nutrient dense snack foods. The production of such foods must be coupled, however, with the need to maintain acceptable quality and sensory aspects. Several properties determine the quality of snack chips as perceived by consumers, including flavor, texture, color and oil content (Moreira, 1999). For a food processer, energy consumption and product yield are also important.

There have been several efforts to reduce the fat content of snack chips. Vacuum frying and baking have been two approaches to reduce fat in corn and other snack chips (Garayo & Moreira, 2002; Kayacier & Singh, 2003; LujanAcosta, Moreira, & SeyedYagoobi, 1997). Luhan-Acosta et al. (1997) studied the effects of air-impingement drying on drying rate, texture,

shrinkage and microstructure of tortilla chips. Garayo and Moreira (2002) investigated the changes of oil temperature and vacuum pressure on drying rate, oil absorption and quality attributes such as shrinkage, color and texture of vacuum fried potato chips. Kayacier and Singh (Kayacier & Singh, 2003) studied the effects on texture during the baking of tortilla chips. Xu & Kerr(2012a) showed that low-fat tortilla chips could be produced in a continuous vacuum dryer using temperatures lower than that used in most baking processes, by pretreating the dough with steam. The dough was made from corn flour, steamed for 3 minutes and rolled to a thickness between 0.7 and 2.5 mm. The vacuum dried chips had significantly lower fat (1.2% versus 34.6%) and developed a multi-celled structure capable of producing crispness. The system was capable of producing chips continuously by means of a continuous belt that provides heat by conduction, and resides under radiant heaters. While the chips had good consumer acceptability, the many properties that determine sensory and quality aspects have yet to be determined. In addition, the costs of production including energy use need to be considered.

The goal of this research was to better understand how drying conditions determine product characteristics and quality factors of tortilla chips produced by vacuum belt drying. The objectives were to determine how drying temperature and product thickness affect the quality of low-fat tortilla chips as determined by color, texture attributes, shrinkage, and structure. In addition, we hoped to identify how drying conditions affect drying time and energy usage.

5.2 Materials and methods

5.2.1 Design and sample preparation

A 3×3×2 factorial design was used to determine drying conditions, with 3 belt temperatures, 3 dough thicknesses, and 2 replications. The drier heating plates were set at 80, 90, or 100°C, including both the conduction and radiation plates. Details of the dryer have been detailed previously by Xu & Kerr (2010). The dough thickness was rolled to 0.8, 1.5, or 2.3 mm. Corn flour (TC-2, yellow) was obtained from Mission Food (Pendergrass, GA). Corn flour (200 g) and deionized water (200 g) were mixed together in a Kitchenaid Professional 600 for 4 minutes on medium speed. The mixture was placed on perforated trays and steamed for 3 min in a steam chest (Pyramid Food Processing Eqp., Tewksbury, MA) at approximately 125°C. The cooked dough was rolled by a sheeter (Moline Machinery Ltd., Duluth, MN) to the specified thickness. The rolled dough was cut into circular shapes with a diameter of 61 mm.

Prepared samples were introduced into a pilot scale continuous belt vacuum dryer (Bucher, ZWag, Zschokle Wartwann Ltd,. CDÖttingen, Switzerland). For each trial, 9 samples were dried at the specified temperature and at a chamber pressure of 2.67kPa (20 torr). The dried samples were cooled at room temperature (~20°C) and packaged in PET/AL/PE pouches that were flushed with N_2 gas before sealing.

5.2.2 Color values

A CR-400/410 colorimeter (Minolta®, Minolta, Co. Ltd. Japan) was used to measure the color of the chips. Six samples from each treatment group were used for evaluation. The color was measured before pretreatment, after pretreatment but before drying/frying, and after full processing. Color was reported as lightness (L*), chroma (C*) hue (H*), and overall difference in color (ΔE).

5.2.3 Surface area and volume changes

Six samples from each treatment were used to determine the area and volume before and after treatment. The original diameter and thickness were measured by a digital caliper (Mitutoyo Corp, Japan). Because the product somewhat changed shape during drying, the final chip diameter was determined by covering the sample with a paper strip which also covered the center of the sample, then marking the outline of the sample on the paper strip. The average radius was determined by measuring across the marks on the paper with a digital caliper. The thickness of chips was measured at 6 locations for each chip, and the average represented the thickness of that sample. Area was calculated by $A=\pi r^2$, and the volume was calculated by V=A*h where r is the radius and h is the average thickness. The shrinkage in area ($\%S_A$) and expansion in volume ($\%E_V$) were expressed as follows:

$$\%S_A = 100\left(1-\frac{A_i - A_a}{A_i}\right) \tag{5.1}$$

$$\%E_V = 100\left(\frac{V_a - V_i}{V_i}\right) \tag{5.2}$$

where the subscript ‘ i’ means initial value (before drying) and ‘a’ means after drying.

5.2.4 Instrumental texture analysis

Attributes related to texture were evaluated using a TA-XT2i texture analyzer (Texture Technologies Corp., Scarsdale, NY) equipped with a Crisp Fracture Rig (HDP/CFS) and a 5 kg load cell. The rig consists of an 18 mm hollow cylindrical base sample holder, and a 6.325 mm ball probe that is used to penetrate the sample. The test speed was 1.0 mm/s, with a travel distance of 5 mm. One sample was randomly selected from each bag just prior to testing, and placed centrally on the sample holder. The hardness and number of force peaks were obtained

from the force-distance curve. Hardness was the maximum force required to break the sample and the threshold force for peaks was 10 gram. Test results were obtained from 6 replicate samples.

5.2.5 Drying time

Drying time was determined from the drying curve when it reached 3% moisture content. To record the drying curve, 9 pieces were placed on a heater plate attached to an electronic digital balance (Reflex HP, Avery Weigh-Tronix LLC. Fairmont, MN) with precision ±0.01g. The balance was set in a small chamber 12 inches above the main vacuum chamber with a hollow rod connected underneath to the heater plates. Sample weight was recorded every 10 s on a laptop computer. Two replications were conducted for each condition.

5.2.6 Energy use

Electrical energy in the vacuum belt dryer went primarily to run the vacuum pump and the drier heaters. Power consumption was determined from the current (I) and voltage (E), as measured by a Fluke 322 Clamp Meter (Fluke Corp., Taiwan). For 3-phase systems, the power consumption is:

$$P = 1.73 E I \cos\phi \tag{5.3}$$

where the power factor cosφ is specific to each motor. The total energy used was calculated by multiplying by the drying time, and expressed in kWh/kg.

5.2.7 Visual records

Images of the samples before and after drying were recorded with a digital camera (Canon Powershot S21S, Canon U.S.A., Inc., NY).

5.2.8 Statistic analysis

Statistical analysis of the data was performed using SAS statistical software (Version 9.0, 2008). Analysis of variance (ANOVA) was performed, followed by Tukey's test to determine differences amongst the treatment groups. Statistical significance was expressed at the $p < 0.05$ level. The response surface model and figures were fitted and plotted using SigmaPlot 8.0 (SPSS Inc., Chicago, IL).

5.3 Results and Discussions

5.3.1 Visual inspection

Images of the vacuum belt dried tortilla chips are shown in Figure 5.1 for product made at 90°C. The chips retained or had accentuated color after vacuum drying. No brown color or scorched surfaces were found in the final product for all treatments. A variety of air cells formed on the surface as a result of drying. Chips formed at 0.8 mm (Figure 5.1a) had relatively fewer and smaller air cells, and with more uniform distribution. In contrast, chips formed at 2.3 mm had larger air cells that were less uniformly distributed.

Vacuum drying or baking is a process that involves both heat and mass transfer. When the samples are dried in a vacuum chamber with extremely low humidity and relatively high plate temperature, a moisture vapor pressure gradient is formed and rapidly causes the surface moisture to evaporate (Hines & Maddox, 1985). In turn, this increases the movement of interior moisture toward the surface. When the surface has been dried out, a crust layer forms, and the evaporation zone moves to inside the food. The layer of crust acts as a barrier and decreases the moisture vapor movement towards surface. The accumulation of vapor pressure causes the outer layer to bulge and form cavernous air cells. For relatively thin products (such as at 0.8 mm), the moisture evaporation path was short. Moisture evaporation dried out the surface of products but

did not accumulate enough vapor pressure to cause observable large air cells. When the thickness increases (as for chips at 1.5 and 2.3 mm), the accumulated vapor pressure builds at the interior of the food, and the size of the air cells increases.

5.3.2 Drying time

The dependence of drying time on temperature and sample thickness is shown in 5.2. The results showed that increasing the heating temperature decreases the drying time for samples that had the same thickness (Figure 5.2a). For example, 2.3 mm samples took 130 min to dry at 80°C 68 min to dry at 100°C, while 0.8 mm samples took 85 min to dry at 80°C and 34 min to dry at 100°C. The drying time could be correlated exponentially to the heating temperature. In general, each degree increase in temperature shortened the drying time by 2.5-3 min.

A constant rate period was not observed during drying of the tortilla chips. It has been shown that drying rate is determined primarily by the rate of moisture diffusion within the product (Xu & Kerr, 2012b). Increasing temperature increases diffusivity and shortens the drying time. An Arrhenius relationship governs the dependence of average effective diffusivity (D_{eff}) on temperature.

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \tag{5.4}$$

Figure 5.2b shows that increasing thickness significantly increased the drying time. For example, at 90°C 0.8 mm chips took 47.5 min to dry, 1.5 mm chips took 71 min, and 2.3 mm chips took 89 min. The thickness of the product determines the distance over which heat and mass must travel within the product. The drying time could also be modeled as depending exponentially on the product thickness. For each millimeter increase in thickness, the drying time increased 22-35 min.

A more considered approach showed that a thin-layer model based on an effective diffusion coefficient could best describe vacuum drying of chips ((Hines & Maddox, 1985)

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2 n^2 D_{eff} t}{4L^2}\right) \tag{5.5}$$

where MR is the moisture ratio, t the time, and L the product thickness. As previously mentioned, temperature determines the D_{eff} through the Arrhenius equation (Equation 5.4). The removal of water is perhaps more profoundly dependent on the product thickness, as it varies exponentially with the inverse of the thickness squared.

Drying times, which are related to energy consumption, are very important in the food industry. An understanding of the effects of drying conditions on the drying time and quality of the final product can help with scale-up applications and energy savings. During vacuum belt drying, the biggest portion (58%) of energy went to maintaining vacuum within the chamber, and a smaller portion (42%) went to the heaters that provide energy for water evaporation. As seen in Table 5.1, the heaters consumed between 17.84 to 78.22 kWh/kg of dried product, while the vacuum system consumed between 25.08 to 109.99 kWh/kg. Energy consumption was lower when higher heater temperatures were used, primarily because drying times were shorter. Also, energy use was lower for the thicker chips. While thicker chips took longer to dry, and therefore used more energy, when expressed per kg of dried material energy use was lower. That is, there was greater product yield per unit of energy input for the thicker chips.

Wang et al. (2007) showed that the energy consumption of continuous vacuum belt drying systems can be substantially lower than other typical drying systems used for pharmaceuticals. They found the energy used for continuous vacuum belt drying, vacuum shelf

drying and spray drying were 2.5-3.0, 6.93, and 59.95 kWh/kg, respectively. Carlsson-Kanyama and Faist (2000) reported that the energy consumption of freeze dried onion ranged from 11-20 kWh/kg.

5.3.3 Color values

The impact of drying conditions on tortilla chip color is shown in Table 5.2. In general, the color of samples before drying did not depend on chip thickness. The color values for pre-dried samples were L*=55.63-56.45, Hue=83.48-84.49°, and Chroma=24.42-25.74. These values indicate a fairly saturated color that is predominantly yellow. Upon drying, L* values increased to within the range 75.63-79.79, indicating that the dried samples were brighter. In general, thinner samples had somewhat higher L* values than thicker samples. Hue angles also were slightly increased after drying, with values in the range of 88.60-90.95°. Chroma increased with values in the range of 42.30-47.08. This suggests that the dried product was slightly more yellow, with a more saturated color. As a group, 0.8 mm chips had slightly greater Hue angles. Drying temperature had little if any effect on color values in the range studied (80-100°C). Previous studies have shown that consumers like the color of 1.5 mm vacuum-dried corn chips, and that there was no difference in likeability when compared to deep-fat fried chips(Xu & Kerr, 2012a, 2012b) .

Color in the chips originates from the cornmeal. Yellow corn is rich in carotenoids, especially the water soluble carotenoids lutein and zeaxanthin. It also contains relative high beta-cryptoxanthin and oil soluble beta-carotene. These accumulations of carotenoids pigments give the corn product yellow color (Hallauer, 2001). Before drying, all samples had high moisture content which dilutes the color. After drying, the colors are more concentrated, and heating in the vacuum dryer seemed to have little detrimental effect on color. This occurs as the

product temperature remained relatively low during processing, limiting Maillard browning reactions. In addition to amino groups and reducing sugars, Maillard reactions require relatively high temperature and moisture levels (Christen & Smith, 2000). The vacuum drying proceeded at low pressures such that the initial boiling point of water was approximately 40°C. As such, the product temperature remained relatively low throughout the process, and only approached higher temperatures during latter phases of drying.

The overall difference in color (ΔE) was also calculated as compared to untreated control. It is most easily calculated in the L*a*b* color system as:

$$\Delta E = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \qquad (5.6)$$

The color difference in chips compared to control was not different for different temperature treatments, but was slightly affected by sample thickness, with thinner chips showing slightly greater ΔE.

5.3.4 Texture measurement

The number of force peaks and hardness during the fracture of tortilla chips during fracture is shown in Figure 5.3. The surfaces represent a response surface model through the data, using a second order model with interaction terms (r^2 = 0.96 and 0.99 for Figures 5.3a and 3b, respectively).

Figure 5.3a shows that both the temperature and sample thickness affected the product fracturability, as measured by the total number of force peaks during fracture with the ball probe. As the temperature was increased from 80 to 90°C, the number of force peak increased, and reached a plateau at 90°C and above. Typically, greater numbers of force peaks indicate a more fracturable, crisper product. The number of force peaks reached a maximum for 1.5 mm thick chips. Chip thickness also had a pronounced affect on fracturability. Thick chips produced the

fewest number of individual fracture events. That is, while thick chips fractured with greater force, the tended to break apart in only a few places. The thinnest (0.8 mm) chips broke apart in many places during fracture. This observation is consistent with the images in Figure 5.1. Thus, 0.8 mm chips had smaller, more evenly distributed air cells that break in many places. Thicker chips had more uneven distribution of air pockets of different size. Thus, when a minimum force is achieved, they are more likely to break at the weakest point.

The influence of drying temperature and chip thickness on hardness is shown in Figure 5.3 b. As expected, increasing the thickness of the product linearly increased the hardness of the final product. The heating temperature had small non-linear effects on the final product hardness. The products processed at 90°C had slightly lower hardness than those processed at 80°C or 100 °C. These results show that high crispness products, with relatively low hardness were processed at 90°C drying temperature and 1.5 mm thickness. It should be noted that crispness is one of the most important attributes of snack chips. Crispness depends upon the amount of deformation at the first bite of foods such as fried snack chips (Vickers & Bourne, 1976). In this study, we used the number of force peaks and the hardness produced during a compression-snap tests to measure crispness. Previous studies on vacuum-dried corn chips showed that while the texture is acceptable, it is slightly less well-liked than the texture of fried chips (Xu & Kerr, 2012a).

5.3.5 Area and volume changes

Production yield is a significant factor for snack chip processors (Moreira et al., 1999). Shrinkage or expansion is factors that determine product yield as well as final product quality. The rupture, cracking, compression and permanent distortortion of relatively rigid cells during dehydration (either plant cells or other), give the food a shrunken, shriveled appearance (Fellows,

2000). For dehydration processes, including deep fat frying and vacuum drying, in which the surrounding environmental temperatures are much higher than the water boiling point, the turbulence created by escaping water vapor forms air cells and a porous structure under certain conditions. In our studies, vacuum drying tended to reduce the product diameter but expand the product volume .

Figure 5.4 shows the change in the chip surface area (Figure 5.4a) along with the expansion in volume (Figure 5.4b) under different drying conditions. The results showed that both the drying temperature and sample thickness affected the chip area and volume change. In general, all dried products shrunk in area as compared to undried control. The area shrinkage ranged from 22 to 26% of the original surface, equivalent to a 11-16% reduction in diameter. This is similar to vacuum-fried tortilla chips, which was reported to shrink 10-14% from the original diameter (Lujan-Acosta & Moreira, 1997). The volume changes ranged from -40 to + 115% in this study, with negative values indicating that the chip volume was reduced. The area shrinkage was least at 90°C, and slightly higher at 80°C and 100°C. The surface area varied non-linearly with thickness. The area shrinkage was greatest for the thinnest chips. Both temperature and chip thickness had an effect on the final chip volume. The volume expanded as temperature increased from 80 to 90°C, at which point the degree of expansion reached a plateau. The maximum expansion was seen for chips that were 1.5 mm thick. This may influence the crispness attributes as shown previously. That is, 1.5 mm chips produced at higher temperatures had the most expanded structure, along with relatively high snapping force, and a structure that fractures in many places.

5.4 Conclusions

The effects of vacuum-drying conditions on the drying time, color, crispness attributes, and degree of shrinkage on low-fat tortilla chips were investigated. Increasing the heating plate temperature decreased the drying time, while increasing chip thickness increased drying time. Higher heating temperature and thicker samples consumed less energy for per kilogram of dried product yield. Vacuum drying produced low-fat tortilla chips with a relatively bright yellow color within 30 to 130 mins. No signs of browning were detected, and drying conditions did not significantly alter the color. Chips that were 1.5 mm thick and dried at 90°C had high volume expansion, numerous air cells, and multiple fracture points indicative of a crisp product.

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Table 5.1. Estimated energy consumption for vacuum belt dried tortilla chips

Thickness (mm)	Heater Energy Consumption (kWh/kg),[1] Temperature (°C)			Vacuum Pump Energy Consumption (kWh/kg) Temperature (°C)		
	80°C	90°C	100°C	80°C	90°C	100°C
0.8	78.22	43.25	29.45	109.99	60.82	41.41
1.5	50.97	32.02	19.17	71.66	45.03	26.95
2.3	37.40	25.61	17.84	52.59	36.00	25.08

[1] Product yield base on dried product

Table 5.2. Color values of tortilla chips made by vacuum belt drying (CVD) at different conditions

Thickness (mm)	Temperature	L*	Hue	Chroma	ΔE
0.8	pre-drying	55.83^{d}	84.62^{e}	24.42^{c}	
0.8	80	79.36^{ab}	91.87^{a}	44.84^{ab}	31.54^{abc}
0.8	90	79.79^{a}	90.95^{a}	46.65^{a}	32.95^{a}
0.8	100	79.59^{a}	91.08^{ab}	46.39^{a}	32.63^{ab}
1.5	pre-drying	55.63^{d}	84.89^{e}	25.61^{c}	
1.5	80	76.34^{bc}	88.60^{d}	47.08^{a}	29.99^{bcd}
1.5	90	77.80^{abc}	89.06^{bcd}	46.07^{a}	30.29^{abcd}
1.5	100	77.18^{abc}	88.88^{cd}	45.94^{a}	29.74^{cd}
2.3	pre-drying	56.45^{d}	83.48^{e}	25.74^{c}	
2.3	80	75.63^{c}	89.48^{bcd}	45.45^{ab}	27.78^{de}
2.3	90	76.05^{c}	90.51^{abcd}	42.30^{a}	26.18^{e}
2.3	100	75.98^{c}	88.50^{d}	46.92^{a}	29.00^{bcd}

Means in the same column followed by same letters are not significantly different ($P<0.05$)

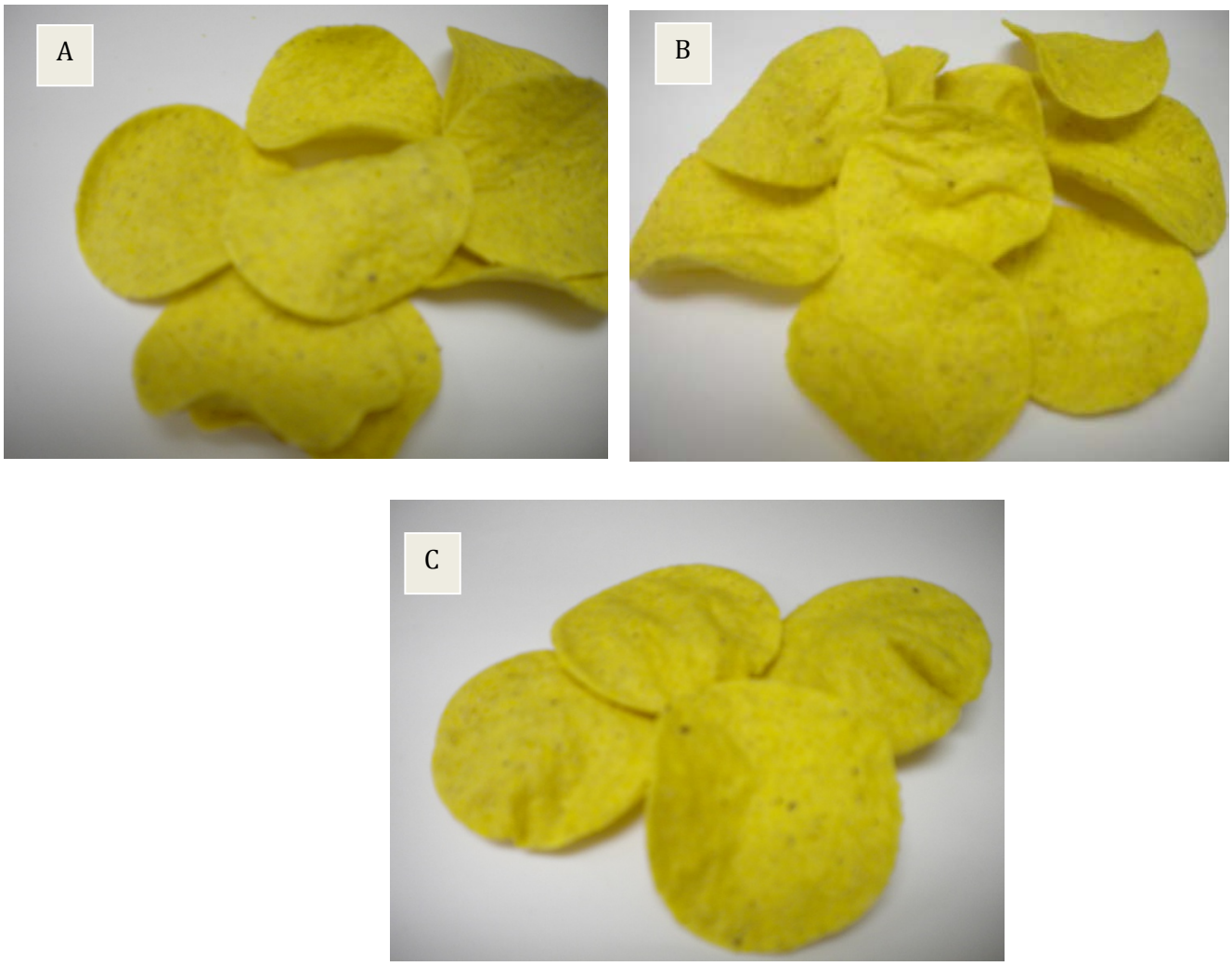
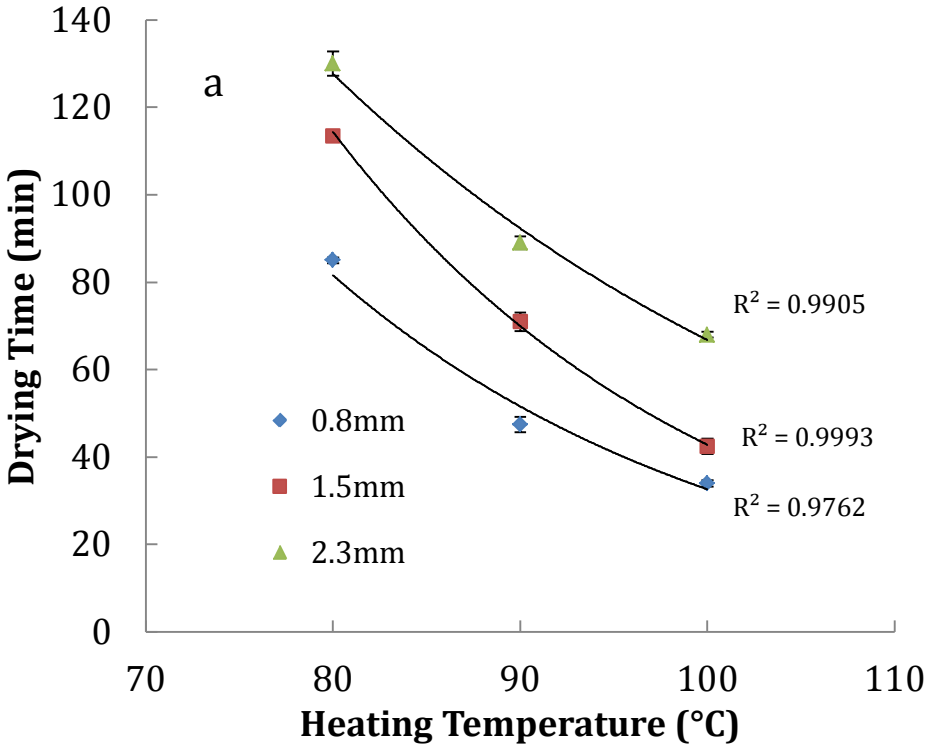


Figure 5.1. Typical vacuum belted dried tortilla chips products.

Drying conditions: temperature, 90°C; pressure, 20 torr; thickness, A. 0.8mm; B.1.5mm; C. 2.3 mm.



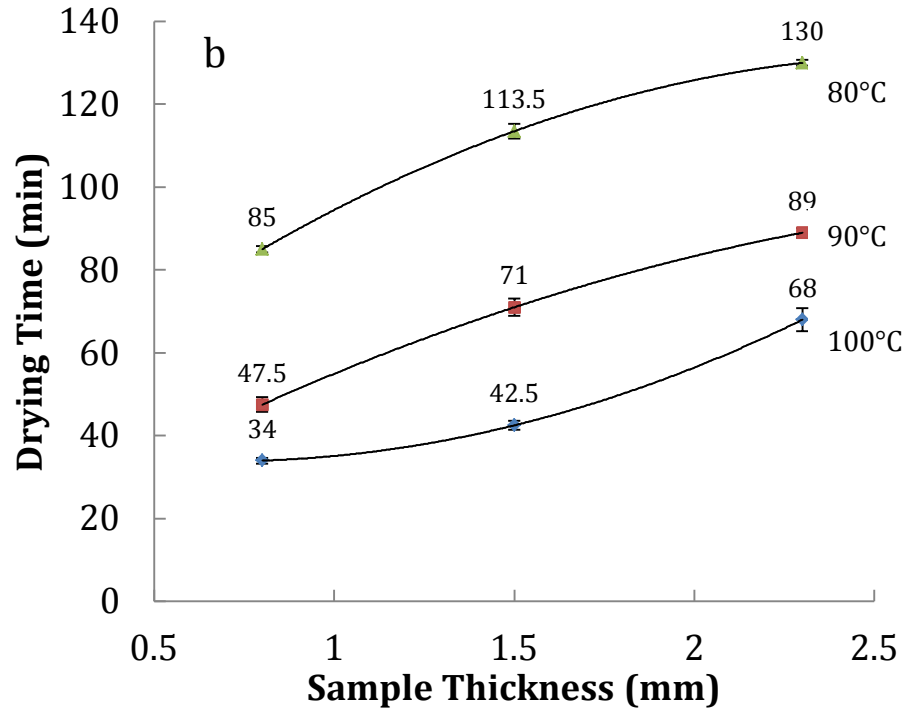


Figure 5.2. Relationship of drying time (time to reach 3% moisture) with (a) heating temperature and (b) chip thickness. Pressure: 20 torr.

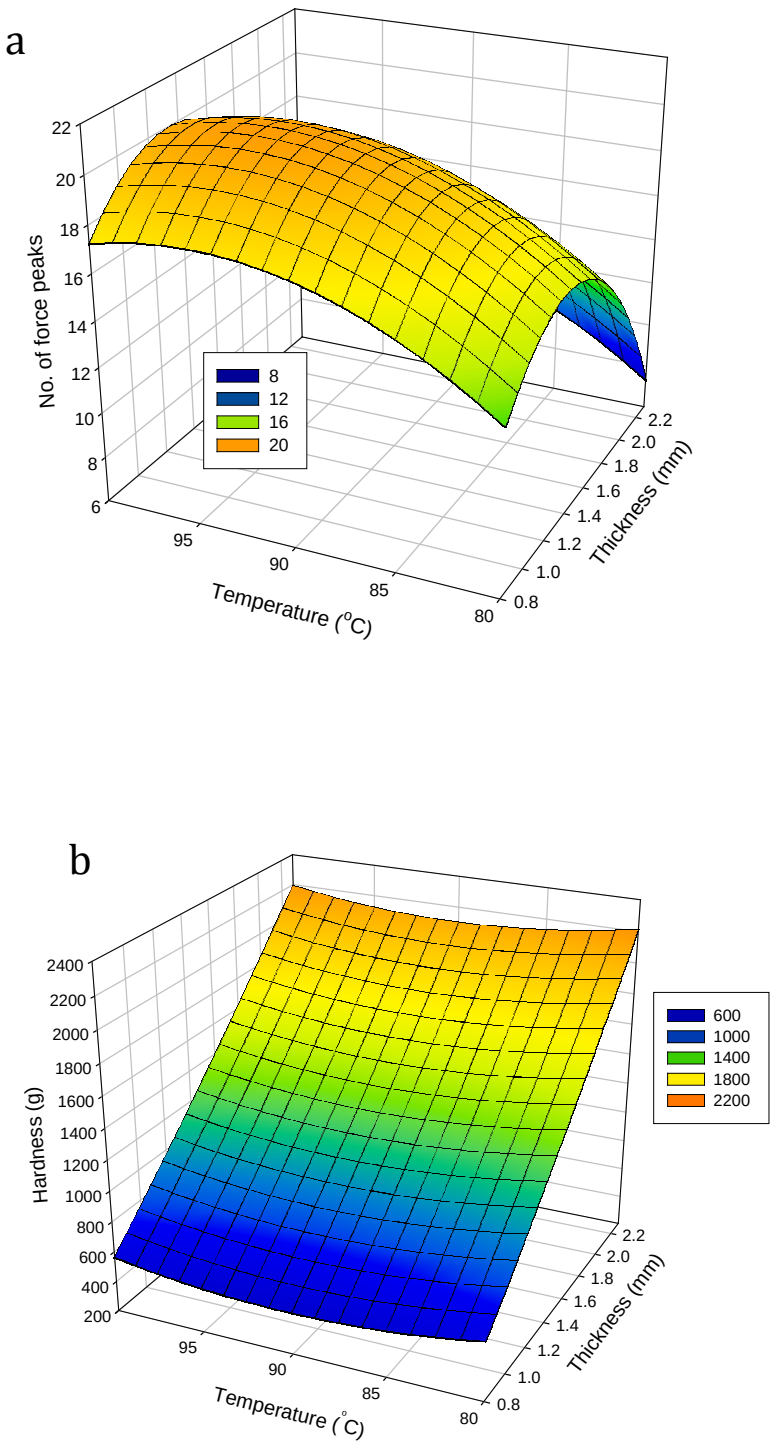


Figure 5.3. Texture attributes of tortilla chips as affected by drying temperature and thickness: (a) Number of force peaks during fracture and (b) maximum hardness

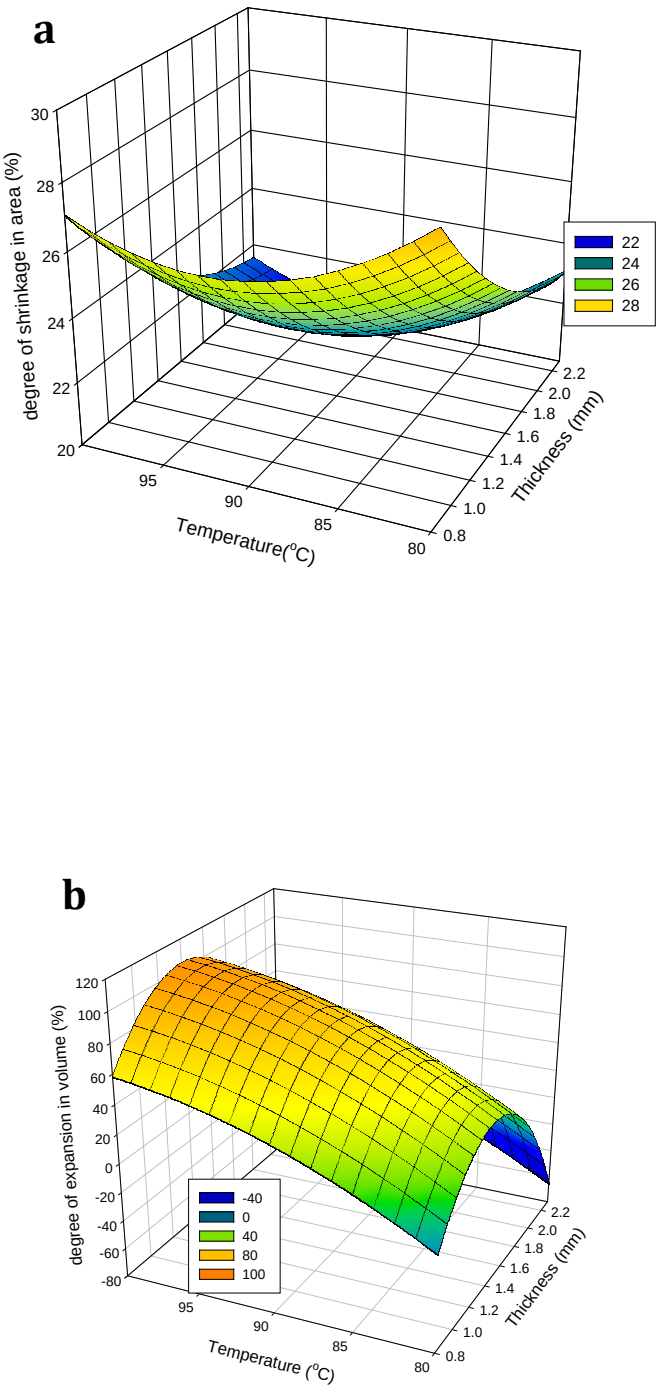


Figure 5.4. Effect of drying temperature and chip thickness on (a) area shrinkage and (b) volume expansion

CHAPTER 6

PROPERTIES OF CONTINUOUS VACUUM BELT DRIED SWEET POTATO CHIPS

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ABSTRACT

Sweet potato chips were produced by a continuous vacuum-belt drying (CVD) process and compared to those made by deep fat frying (DFF). Two chip thicknesses (0.8 and 1.5 mm) and four vacuum drying temperature (100, 120, 140°C, and T-mix=100/120/140°C), were investigated. CVD produced chips with similar texture properties as DFF chips, while maintaining a natural color and β-carotene content. CVD products produced at low temperature had L*, chroma and hue values closest to unprocessed sweet potato. ESEM micrographs showed that chips made at a combination temperature (T-mix) had the most uniform cell structure. CVD chips made at the T-mix conditions, along with DFF chips, had lowest hardness but high fracturability. The former had a hardness of 504.7 g force with 7.75 fracture peaks; the latter had a hardness of 500.6 g force and 925 fracture peaks. DFF chips and CVD chips dried at 140°C had the greatest loss in β-carotene (33.11 and 48.95%, respectively). Retention of β-carotene in CVD chips made at 100°C, 120°C and mixed temperature conditions was 84.22, 79.43 and 94.23%, respectively.

Key words: *sweet potato chips, continuous vacuum belt drying, deep-fat frying, beta-carotene, texture, microstructure*

6.1 Introduction

Sweet potatoes (*Ipomoea batatas*) are one of world's leading food crops. In 2010, the production of sweet potato was 106.5 million tons world-wide and 1.08 million tons in the US (FAO, 2012). Sweet potatoes are relatively inexpensive and have several health benefits. In addition to being a carbohydrate source for humans and animals, sweet potatoes have high nutritive value. They contain substantial amounts of carotenoids (including β-carotene, phytoene, phytofluene and α-carotene, vitamin C, several B vitamins and various minerals including manganese. β-carotene is a precursor of vitamin A which is involved in protein metabolism, synthesis of epithelial tissue, vision and night vision (Christen & Smith, 2000). Burri (2011) suggested that orange-fleshed sweet potatoes are a nutritious and sustainable source for preventing vitamin A deficiency. Sweet potatoes are also rich in complex carbohydrates and dietary fiber, and may have relatively low glycemic index compared to potatoes and yams (Noda et al., 2008). In addition to nutritive value, carotenoids have antioxidant activity and have been studied for potential health benefits such as reducing the risk of lung and other cancers, decreasing hypertension, and decreasing inflammatory processes (Islam, 2006; Paiva & Russell, 1999).

Sweet potatoes are normally consumed fresh after boiling or steaming (J. A. Woolfe, 2008). Sweet potatoes have been sun-dried to form "sweet potato flakes" that are easily stored and consumed in many regions of the world. Pureeing, canning, and freezing are also used to preserve sweet potatoes post-harvest (J. A. Woolfe, 2008). Sweet potato flour and other value-added ingredients have been studied for their use in formulating foods (Akpapunam & Abiante, 1991; Dansby & Bovell-Benjamin, 2003; Walter, Truong, & Espinel, 1999).

Sweet potato snack chips have been marketed in several countries including the United States, China, and Japan, and have received increased attention as a food source for combating vitamin A deficiency (Graham & Rosser, 2000; Jennifer A. Woolfe, 1992). Snack chips are normally prepared by deep fat frying. As such, the fat content can be substantial, typically ranging from 23 to 38% (Moreira, Castell-Perez, & Barrufet, 1999). Other problems that may be encountered during processing and storage of sweet potato chips include oxidation of phenolic compounds that results in darkening of uncooked slices, excessive browning caused by Maillard reactions during frying, oiliness, excessive hardness, and lack of crispness (J. A. Woolfe, 2008). If the chips are subject to moisture pick-up and excessive oxygen post-process, this may cause leatheriness and rancid off-flavors. Several researchers have examined ways to improve the quality of sweet potato chips. Fontes, Oliveira, & Collares-Queiroz (2011) studied the optimization of deep–fat frying of sweet potato chips in palm olein or stearin oil, and found that frying in palm olein at 160°C for 3 min resulted in best sensorial properties. Da Silva and Morlva (2008) researched sweet potato chips produced by a vacuum frying process, finding that the oil content could be reduced by 24%. Taiwo and Baik (2007) studied the effects of pre-treatments such as blanching or osmodehydration on the texture of fried sweet potato chips.

Continuous belt vacuum-drying systems have been developed in which product advances along a belt, subject to heating by conduction or radiation. To date, vacuum belt driers have been used commercially for dehydrating high quality citrus crystals, instant tea, and pharmaceutical drugs (Potter & Hotchkiss, 1995). These drying systems not only produce high quality products, but can also create a puffed and brittle structure necessary for crisp snack foods(Potter & Hotchkiss, 1995). Xu & Kerr (2012) developed low-fat tortilla chips by vacuum belt drying, using drying temperatures that were much lower than those found in frying or baking processes.

The vacuum dried chips had significantly lower fat (1.2% versus 34.6%) and developed a multi-celled structure capable of producing crispness. Except for oil flavor, other characteristics of the dried chips were comparable to deep fat fried chips, and consumer likability was good. Initial chip thickness and drying temperatures were the significant factors that determined the quality of the finished product. There are no reports that we know of using continuous vacuum belt drying to produce sweet potato chips.

In this research, we studied the use of a continuous vacuum dryer to develop crisp sweet potato chips, studying the effects of chip thickness and processing temperature on product quality. The properties of sweet potato chips such as color, texture, microstructure, and β-carotene retention were studied. Further, we compared these properties to conventional deep-fat fried sweet potato chips.

6.2 Materials and methods

6.2.1 Materials and sample preparation

Sweet potatoes (*Ipomoea batatas*) were purchased locally (Kroger, Athens, GA). The sweet potatoes were peeled then cut with a slicer plate in a FP150 food processor (Hobart Corporation, Troy, Ohio) to the desired thickness of 0.80 mm and 1.50 mm, respectively. The cut sweet potatoes were placed on perforated trays and blanched at 125°C for 2 minutes in a steamer chamber (Pyramid Food Processing Eqp., Tewksbury, MA).

6.2.2 Continuous vacuum belt drying

The experimental design for the drying and frying trials is shown in Table 6.1, showing heater plate temperatures, belt speeds and drying times for each treatment. Sliced and blanched samples were fed into a pilot scale Bucher Dryband continuous vacuum belt dryer (CVD)

(Bucher Unipektin AG, Switzerland). A schematic diagram of the drier is shown in Figure 6.1. The plates were set to the desired temperatures (100, 120 or 140°C) and vacuum was maintained at 2.67±0.05 kPa absolute. Samples were dried until a_w~0.2 was reached, with final moisture content of 5.0gH_2O/100g±1.1%. Dried products were cooled at room temperature (~20°C) and packaged in PET/AL/PE pouches (Stock America Inc., Grafton, WI) flushed with N_2 gas.

6.2.3 Deep-fat frying

Deep fat fried (DFF) sweet potato chips were processed in a professional 4-liter stainless fryer (Model 530F, Star Manufacturing Inc., St. Louis, MO). The unit was filled with Frymax Sun ClassicTM (Stratas Foods; Memphis, TN), made from a blend of high oleic sunflower and cottonseed oils. The sweet potatoes were peeled and cut to desired thickness and then directly fried without blanching. The oil temperature for frying was 165°C and samples were fried for 120 seconds. Six pieces were fried per batch and the temperature was maintained within 5°C during frying. The fried samples were packaged in PET/AL/PE pouches flushed with N_2 gas.

6.2.4 Color measurement

A CR-400/410 colorimeter (Minolta®, Minolta, Co. Ltd. Japan) was used to measure the color of chips. Six samples from each treatment group were used for evaluation. The color was measured before pretreatment, after pretreatment but before drying/frying, and after full processing. Color was reported as lightness (L*), chroma (C*) and hue (H*). The L* represents the lightness, with lighter products having higher L* values. Hue indicates the color, with a value of 0° indicating pure red, 45° indicating orange, and 90° indicating pure yellow. The chroma represents the saturation of that color. The higher the chroma value, the purer the color is.

The overall difference in color (ΔE) was also calculated as compared to untreated control. In the L*a*b* color system, ΔE is given by:

$$\Delta E=\sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (6.1)$$

6.2.5 Structural and microstructure features

Images of the sweet potato chips were recorded with a digital camera (Canon Powershot S21S, Canon U.S.A., Inc., NY). Environmental scanning electron microscopy (ESEM) images were obtained with a Zeiss 1450EP variable pressure SEM **(**Carl Zeiss MicroImaging Inc., Thornwood, NY). A broken cross section of sweet potato chip was mounted on aluminum stubs with conductive adhesive and viewed with no further sample preparation. The ESEM used an accelerating voltage of 15-25 kV.

6.2.6 Instrumental texture analysis

Attributes related to texture were evaluated using a TA-XT2i texture analyzer (Texture Technologies Corp., Scarsdale, NY) equipped with a Crisp Fracture Rig (HDP/CFS) and a 5 kg load cell. The rig uses an 18 mm hollow cylindrical base sample holder, and a 6.325 mm ball probe to penetrate the sample. The test speed was 1.0 mm/s, with a travel distance of 5 mm. Each sample was selected from a freshly opened pouch just prior to testing, and placed centrally on the sample holder. The hardness and number of fracture peaks were obtained from the force-distance curve. Hardness was taken as the maximum force required breaking the sample. The number of individual fracture peaks was counted using a threshold value of 10 gram. Test results were obtained from 6 replicate samples.

6.2.7 β-carotene measurement

Extracts from the chips were prepared using a method described by Kurilich Juvik (1999) with slight modification. Ten pieces of sweet potato chips were ground for 90 s in a Model #111338 grinder (General Electric Co., Fairfield, CN). About 0.5 g of ground sweet potato powder were transferred to a 250ml flask by adding 15ml DI water and 50ml ethanol, which contained 0.5% of BHA (w/v). Potassium hydroxide (10ml, 60% w/v) was added to saponify the oil. The flask was filled with nitrogen, wrapped with aluminum foil, and then placed into a water bath at 50°C for 30 minutes, with vortexing and swirling at 5 min intervals. After saponification, 50 ml of hexane was added and the sample was vigorously shaken. The flask was filled with nitrogen gas, covered with aluminum foil, and stored overnight in the dark. Next, the sample solution was filtered through glass wool. The flask and glass wool were rinsed 3 times with 25 ml DI water and then with 25 ml hexane. After vigorous shaking, the solution was allowed to sit for 30 min until the layers had separated. The bottom layer was removed, and the top layer containing extracted beta-carotene left for further analysis.

Total carotenoids, expressed as β-carotene, were analyzed using an UV/visible spectrophotometer (Spectroinc® Genesys™, Spectronic instruments Inc. Rochester, NY . Three milliliters of extracted solution was transferred to a clean 1 cm standard cuvette and the absorption at 450 nm was recorded. The spectrophotometer was calibrated and zeroed against a hexane blank. The β-carotene content was determined using Beer's law ($A=\varepsilon lc$), using a molar absorptivity of $\varepsilon=138730$ $Lmol^{-1}cm^{-1}$ (Anonym, 2012; Zechmeister & Polgar, 1943). Each sample was extracted and analyzed in duplicate.

6.2.8 Statistic analysis

Statistical analysis of the data was performed using SAS statistical software (Version 9.0, 2008). Analysis of variance (ANOVA) was performed, followed by Tukey's test to determine differences amongst the treatment groups. Statistical significance was expressed at the $p < 0.05$ level.

6.3 Results and discussions

6.3.1 Drying times

Table 6.1 shows the drying times needed to reach a_w~0.2. As expected, thinner (0.8 mm) chips took less time, with drying times of 35, 45 and 60 min at temperatures of 140, 120 or 100°C. For 1.5 mm chips, those times were 60, 70 and 80 min, respectively. When using a combination of temperatures (140/120/100°C), drying times were 45 and 70 min for 0.8 mm and 1.5 mm chips.

6.3.2 Color retention

Retention of natural color is an important indicator of quality in sweet potato chips. Color values are shown in Table 6.2. In addition, the color difference (ΔE) with respect to the unheated slices is shown. Values for the 1.5 mm fresh slices were L*=69.78, H*=65.87°, and C*=48.56. The values are indicative of a strong orange color with relatively high lightness. As a group, vacuum dried samples were somewhat darker with L* values in the range 44.32-61.07. Hue angles for dried chips were not different than for the fresh slices, with values in the range of 64.95-69.85. Chroma values of the vacuum dried chips (27.49-51.38) were lower than fresh slices. Fried chips were much darker (L*=37.61) and with lower color saturation (C*=27.30).

Differences in color between the fresh slices and processed chips show that frying produced more color changes (ΔE=38.70) than drying (ΔE=12.31-31.65). Thickness of the sweet

potato slices did not significantly affect ΔE, with the exception of samples (T-140) dried at 140°C. Higher drying temperatures led to lower values of L*, hue and chroma. ΔE also indicated that higher temperatures were associated with greater color differences. Although increased plate temperature decreased the L* value for chips of the same thickness, there were no significant effects on hue or chroma for temperatures below 140°C. At 140°C, chips were darker and had lower color saturation. Thinner chips (0.8 mm) produced at 140°C had much greater change in color than 1.5 mm chips, as well as all other dried chips.

Compared to fresh slices (L*=69.78), blanched sweet potato slices were slightly darker (L*=62.44). After blanching, slices were more yellow (h=74.98°) and with higher chroma than fresh slices. After vacuum drying, however, the color was more similar to the fresh slices. The color in sweet potatoes derives from the carotenoids it contains (J. A. Woolfe, 2008). Upon blanching, some of the β-carotene can be degraded by the heat treatment. These changes can be traced to isomerization reactions, particularly the formation of 13-cis-β-carotene(Chandler & Schwartz, 1988). During vacuum drying, water is removed, and this can concentrate the remaining β-carotene giving the product a more intense orange color.

As noted, when all plates were held at the same temperature, increased temperature led to darker chips. In one trial (T-mix), a combination of temperatures were used in which the first zone was set to 140°C, the second zone set to 120°C, and the third zone set to 100°C. In this case, the values for L*, C* or H* were no different than those in which all zones were set to 100°C. The color change (ΔE) was also least for the T-mix samples. Previous studies showed that the temperature of tortilla chips produced by vacuum drying were relatively low during the initial drying period. Thus, while the first plate was at 140°C, the actual sample temperature was

much lower. Subsequent zones were set at 120 and 100°C. Thus, in later periods when the sample temperature began to rise, it did not get higher than the 100°C zone.

Samples dried only at 140°C, or prepared by frying, had the greatest color change. These samples were noticeably browner than the others, as witnessed by lower L* values, and a shift to hues with more redness. Browning proceeds primarily through Malliard reactions. In addition to amino groups and reducing sugars, Maillard reactions require relatively high temperature and optimal moisture levels (Christen & Smith, 2000). Time, temperature, pressure, water activity and the interaction between these factors also determine the rate of Malliard browning (BeMiller, 2007). The vacuum drying proceeded at low pressures such that the initial boiling point of water was approximately 40°C. As such, the product temperature remained relatively low throughout the process, and only approached higher temperatures during latter phases of drying.

Changes in color were also reflected in the appearance of the product (Figure 6.3). Products dried at 100 or 120°C were not noticeably brown, nor were those prepared at mixed temperatures (140/120/100°C). Samples dried at 140°C were visibly browner, and those prepared by frying at 165°C were quite brown, and had little of the pure orange color associated with the carotenoids in sweet potato. Da Silva and Moreira (2008) reported that vacuum fried (130° C, <1.33 kPa) sweet potato chips had much less color degradation than those prepared by conventional deep fat frying (165°C, 101.3 kPa), and attributed this to the lack of oxygen in the vacuum process. Diminished browning was also noted for simulated bread crust baked in a vacuum oven (Ziderman and Friedman, 1985). Likewise, packaging of dried apples with oxygen-scavengers markedly decreased non-enzymatic browning during storage (Bolin & Steele, 1987). However, our results show that some browning still occurs when sweet potato chips were dried

at 140°C at pressures less than 2.65 kPa torr. While oxygen can influence Maillard reactions, it is not strictly needed for browning to occur.

6.3.3 Microstructure

Figure 6.2 shows typical ESEM cross sectional views of the sweet potato chips. Fried chips (Figure 6.2d) had small air cells filled with oil, and were relatively free of larger voids (~0.1-1mm). The matrix is composed of gelatinized starch, denatured proteins, lipids and cell walls (Aguilera & Stanley, 1999). Figure 6.2 a-c shows microstructural features of chips that were vacuum dried at 100°C, mixed temperatures (140/120/100°C) and 140°C, respectively. Thin (0.8 mm) chips dried at 100°C showed the numerous porous spaces created as water evaporated from the product. Some fracture of the cell walls was also noted, and the product was denser than other treatments. Samples dried at 140°C (Figure 6.2c) showed more evidence of large tunnels on the order of 1-10mm, surrounded by more dense material. This likely occurred as the drying temperature was much higher than the initial product boiling point ($\Delta T \sim 100°C$), creating a relatively rapid exit of steam from the product. However, as the temperature became elevated later in the drying process, a collapse of the structure can occur, particularly if the temperature is much greater than the associated glass transition temperature. Samples created at mixed temperatures (140/120/100°C) had the most expanded structure, with a relatively narrow range of air cells. As with drying sole at 140°C, initial escape of water can create many expanded cells. As later drying proceeds at lower temperatures, however, there is less opportunity for structural collapse.

6.3.4 Texture

Textural attributes are very important to snack chip quality. For example, Xu and Kerr (2012) showed that 78% of consumers felt that good texture/crispness directly influenced their

decision to purchase tortilla chips, ranking it just below flavor in importance. The textural properties of hardness and degree of fracturing, as measured by maximum force and the number of fracture peaks, are shown in Table 6.3. As expected, thickness had a significant effect on product hardness. For 0.8 mm thick chips, hardness varied from 326.3 to 497.4 g, while for 1.5 mm chips hardness varied from 504.7 to 687.8 g. In comparison, fried chips had a hardness of 500.6 g. Samples prepared with mixed temperatures were less hard than other samples of the same thickness. Chips prepared at 140°C also had relatively low hardness. The more expanded nature and numerous air cells may contribute to decreased hardness of these products.

Chip thickness also influenced the number of fractures measured in the chips. With the exception of chips made at 140°C, thinner chips had more force peaks during fracture with the ball probe. Snack chips are expected to have a high level of crispness, and increasing crispness is highly correlated with textural preference (Vickers & Bourne, 1976). Crisp products, while relatively firm, should not be overly hard and should snap within a short distance. Greater number of fracture events is also associated with crisp products, as this leads to the complex forces in the mouth along with the relatively loud noisy sounds associated with crisp products. In this study, chips from treatment groups T-mix, T-140, and DFF had modest hardness and displayed more fracture events than chips from other treatment groups, suggesting that these would have greater crispness. Again, this likely relates to the lower steam pressures developed at low drying temperatures, resulting in a less porous and denser product. Thus, while these denser chips fractured with greater force, they tended to break apart in only a few places.

Table 6.3 shows that products from the T-mix treatment had textural properties closest to the fried chips. For example, 1.5 mm T-mix chips had a hardness of 504.8 g and an average of 7.75 peaks; fried chips had a hardness of 500.6 g and 9.25 force peaks.

6.3.5 β–carotene

As β-carotene is a key vitamin A precursor and important phytochemical in sweet potatoes, it was chosen as an index for nutritional quality of the chips. β-carotene content of the fresh, blanched, and differently processed chips is shown in Table 6.4. Fresh sweet potato slices had 37.3 µg/g of β-carotene, or 197.4 µg/g when expressed on a dry basis. In general, sweet potato subject to any heating steps (blanching, drying or frying) had some loss of β-carotene. This is consistent with previous research (Jennifer A. Woolfe, 1992), which showed that sweet potato carotenes increase during post-harvest storage, but were decreased by further processing. Fried chips showed the greatest loss of β-carotene, retaining only 33.1% of the levels found in fresh sweet potatoes. Samples prepared at 140°C had the second greatest loss (34.2%), supporting the notion that exposure to high temperatures is most detrimental β-carotene retention.

β-carotene content of chips processed at 100 or 120°C, or with the mixed temperatures (T-mix) retained 55.5 to 65.8% of the β-carotene found in fresh sweet potato. Much of the β-carotene was lost during blanching, which was needed to inactivate polyphenol oxidase enzymes and gelatinize starch. After exposure to steam at 125°C for 2 min, blanched slices retained 69.9% of the β-carotene of fresh slices. Mosha (1997) observed a loss in carotenes after blanching and thermal processing in several vegetables. Chips from the T-mix, T-100, and T-120 had 79.43 81.2, and 94.2 % retention of β-carotene as compared to the blanched slices. Again, during initial phases of vacuum drying the product temperature stays relatively low (~22°C). Temperatures only approach the plate temperature later in drying, when the product has the lowest moisture content and is least vulnerable to chemical changes.

Changes in β-carotene were consistent with visual (Figure 6.3) and color (Table 6. 2) changes in the products. Fried chips, or those dried at 140°C, appeared the most visibly brown,

were darker (having lower L* values), and had the greatest change in hue. These samples also had the greatest losses in β-carotene. Samples dried at 100°C, 120°C, or with mixed temperatures were brighter, more orange-yellow, and had higher levels of β-carotene.

When expressed per gram of solids, dried chips (except for T-140) had between 109.6 and 130.0 µg/g solids β-carotene, as compared to 197.4 µg/g solids for fresh slices, and 65.4 µg/g solids for fried chips. When viewed on a total-weight basis, that is as the material would be consumed, dried chips had between 105.6 and 125.6 µg/g β-carotene, fresh slices 37.3 µg/g solids, and fried chips 64.2 µg/g solids. Thus, drying concentrates the carotenoids. In terms of serving sizes, 1 medium size fresh sweet potato (132 g) would provide 4924 µg β-carotene, a 1.2 oz (34 g) serving of dried chips 4270 µg, and a 1.2 oz serving of fried chips 2195 µg.

6.4 Conclusions

Continuous vacuum belt drying is a feasible process for producing high quality sweet potato snack chips. Dried chips also had less fat than fried chips. The removal of water under vacuum allowed for relatively low temperature dehydration. In addition, it led to a porous structure with crisp texture attributes. Thin chips (0.8 mm) fracture into more pieces than thicker (1.5 mm) ones, indicating texture attributes most like the fried chips. Products dried at 100 or 120°C had the best retention of yellow-orange color and β-carotene. Drying time could be substantially reduced by using a mixture of heating plate temperatures in the three conduction zones. By setting the first plate to 140°C, rapid drying could be attained while the product was relatively wet, but without elevating the product temperature. Subsequent water was removed at lower temperatures. Thus, chips produced with this temperature combination also had good color and β-carotene retention, and texture attributes most similar to fried chips.

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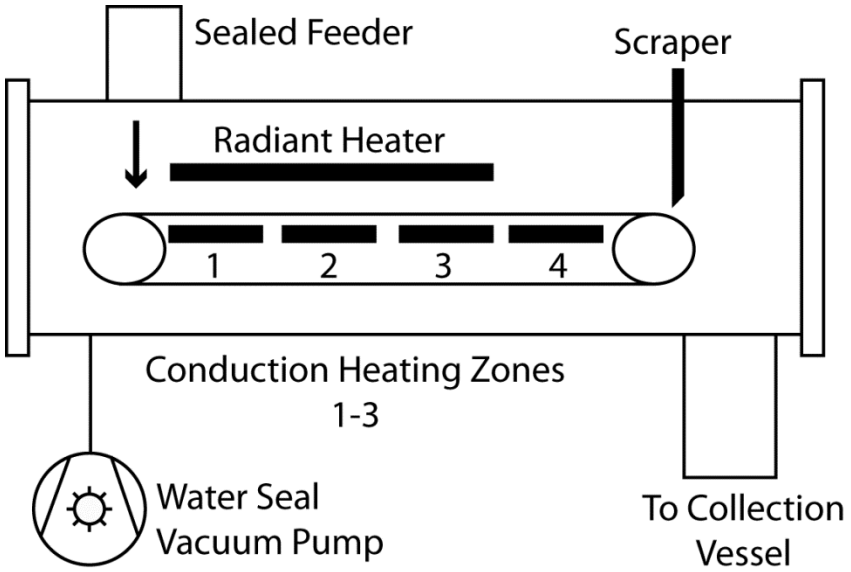
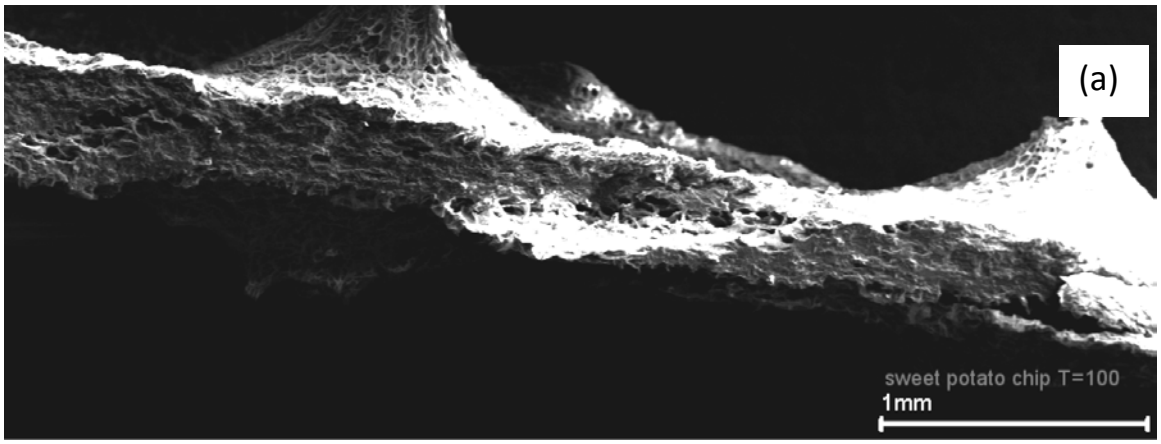
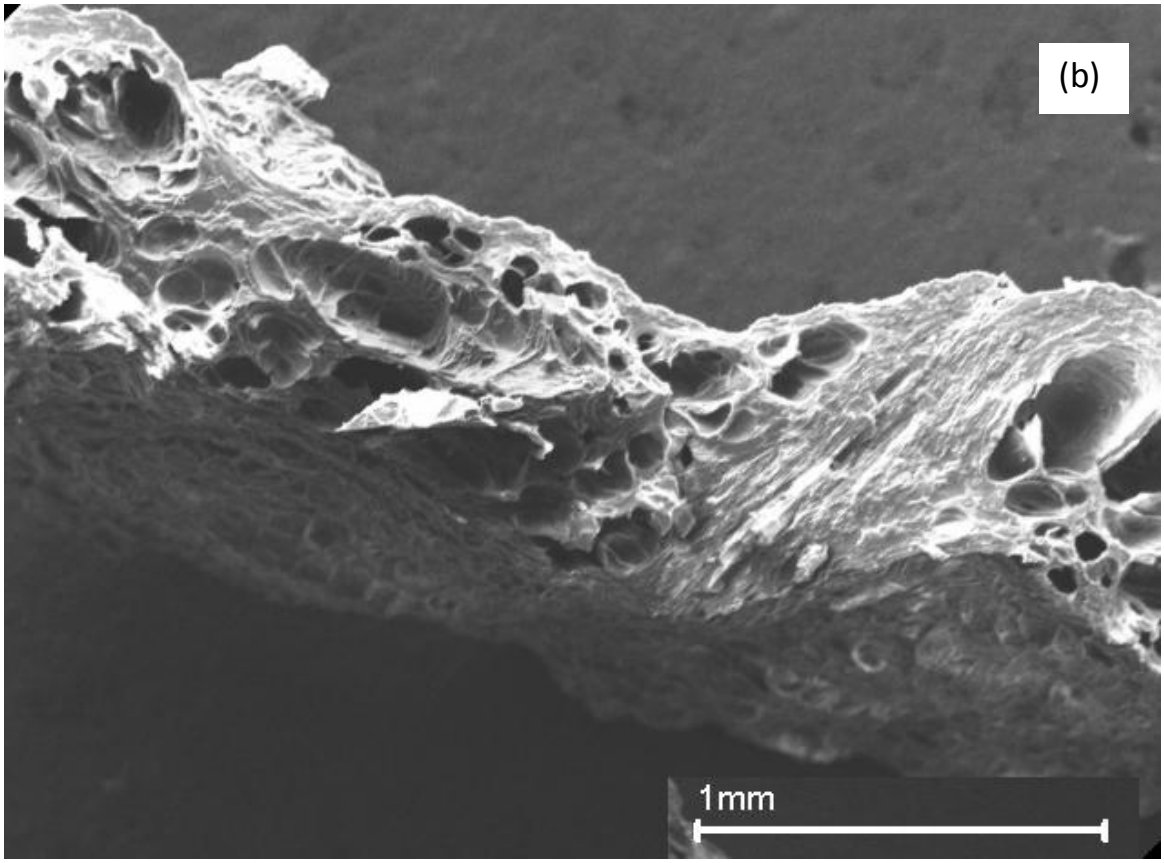


Figure 6.1: Schematic diagram of the continuous vacuum belt drier.


(a)
sweet potato chip T=100
1mm


(b)
1mm

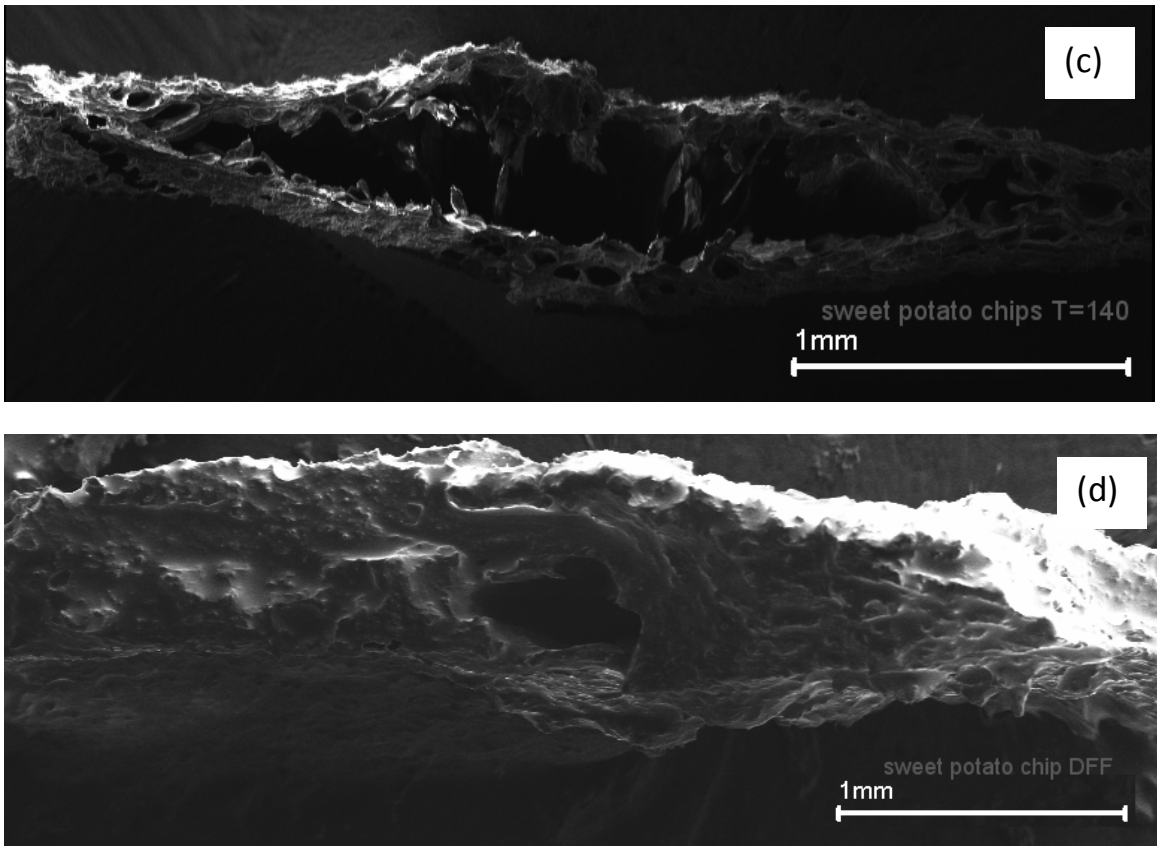


Figure 6.2. Environmental scanning electron microscopy, cross-sectional view of sweet potato chips. Thickness: 0.8 mm. Heating temperature (a) 100° C, (b) Mix:140/120/100°C, (c) 140° C, (d) deep-fat fried, 165 ° C.

(a)

(b)

(c)

(d)

(e)

Figure 6.3. Vacuum belt dried and deep-fat fried sweet potato chips (0.8 mm thick). Processing conditions: Vacuum dried at: (a) 100° C, (b) 120° C, (c) 140° C, (d) Mix temperature; (e) deep-fat fried, 165 ° C.

Table 6.1. Experimental treatments for dried and fried sweet potato chips showing heating zone temperatures and fryer conditions. Zones 1-3: conduction heaters; Zone 4: radiation heater

Sample thickness (mm)	Heater Temperatures	Trial	Zone 1 (°C)	Zone 2 (°C)	Zone 3 (°C)	Zone 4 (°C)	Belt speed (mm/s)	Drying time (min)
0.8	Mix 140/120/100°C	T-Mix	140	120	100	100	0.316	45
	140°C	T-140	140	140	140	140	0.410	35
	120°C	T-120	120	120	120	120	0.316	45
	100°C	T-100	100	100	100	100	0.241	60
1.5	Mix 140/120/100°C	T-Mix	140	120	100	100	0.204	70
	140°C	T-140	140	140	140	140	0.241	60
	120°C	T-120	120	120	120	120	0.204	70
	100°C	T-100	100	100	100	100	0.178	80
Deep-fat fried	165°C	DFF	n/a	n/a	n/a	n/a	n/a	2

Drying time was decided by the time the samples moved from beginning of heater 1 to the end of heater 3.

Table 6.2. Color values of sweet potato chips before and after processing.

Treatment	Thickness (mm)	L*	Hue (°)	Chroma	Δ E
Fresh	1.5	69.78^{a}	65.87^{de}	48.56^{bc}	n/a
Fresh	0.8	70.47^{a}	67.12^{cde}	45.01^{cd}	n/a
Blanch	1.5	62.44^{b}	74.98^{a}	52.92^{a}	12.31^{ef}
T-mix	1.5	60.3^{bc}	68.82^{bc}	51.38^{ab}	10.96^{ef}
T-mix	0.8	61.07^{bc}	69.85^{b}	41.47^{de}	10.81^{f}
T-100	1.5	57.57^{cde}	67.69^{bcd}	47.64^{bc}	12.86^{def}
T-100	0.8	58.54^{cd}	67.01^{cde}	40.03^{e}	14.44^{def}
T-120	1.5	54.81^{de}	66.99^{cde}	45.25^{cd}	15.68^{de}
T-120	0.8	54.01^{e}	66.57^{cde}	46.89^{c}	16.94^{d}
T-140	1.5	49.195^{f}	66.36^{cde}	38.96^{e}	23.19^{c}
T-140	0.8	44.32^{g}	64.95^{e}	27.49^{f}	31.65^{b}
DFF	1.5	37.61^{h}	62.180^{f}	27.30^{f}	38.70^{a}

Within a column, results followed by the same letter are not significantly different at $p<0.05$

Table 6.3. Texture properties of processed sweet potato chips

Treatment	Thickness (mm)	Hardness (g F)	Force peak count
T-mix	0.8	326.3^{c}	9.75^{a}
T-100	0.8	497.4^{bc}	6.5^{bc}
T-120	0.8	346.2^{c}	8.25^{abc}
T-140	0.8	332.3^{c}	7.00^{abc}
T-mix	1.5	504.7^{abc}	7.75^{abc}
T-100	1.5	685.5^{ab}	6.00^{c}
T-120	1.5	687.9^{a}	5.25^{c}
T-140	1.5	588.8^{ab}	8.25^{abc}
DFF	1.5	500.6^{abc}	9.25^{ab}

Within a column, results followed by the same letter are not significantly different at $p<0.05$

Table 6.4. β-carotene value of sweet potato chips

Treatment	β-carotene (µg/g)	β-carotene (µg/g solids)	%Retained from fresh	%Retained from previous step
Fresh sweet potato slices	37.29 ±2.23[d]	197.42 ±11.79[a]	n/a	n/a
Blanched slices	18.04 ±0.17[e]	138.01±1.29[b]	69.91	69.91
T-mix	107.87±0.67[b]	109.63±0.69[c]	55.52	79.43
T-100	105.55±2.23[b]	112.09±2.37[c]	56.77	81.22
T-120	125.65±3.28[a]	130.05±3.39[b]	65.87	94.23
T-140	64.65±2.52[c]	67.555±4.42[d]	34.21	48.95
DFF	64.17±2.52[c]	65.375±2.57[d]	33.11	33.11

Within a column, results followed by the same letter are not significantly different at $p<0.05$

CHAPTER 7

CONCLUSIONS

This dissertation focused on developing low-fat tortilla and sweet potato chips by continuous vacuum belt drying. Important properties of the chips including sensory, texture, color, oil content and microstructure were investigated and compared to deep fat fried chips. To better understand the mechanism of the process, drying models were developed. The effects of drying conditions on drying time and final product attributes were also studied. The drying rate models and effects of drying conditions will help predict appropriate drying times and optimize process conditions for the dryer.

This research found that continuous vacuum belt drying is a feasible process to produce low-fat snack chips that have good consumer acceptability. The vacuum process can create a slightly expanded structure that contributes to product crispness. Key features of CVD products are that they have significantly lower fat than fried chips (1.2% versus 34.6%), have good color and nutrient retention, and have similar texture attributes as fried chips.

The effects of vacuum-drying conditions on the drying time, color, crispness attributes, and degree of shrinkage on low-fat tortilla chips were investigated. Increasing the heating plate temperature decreased the drying time, while increasing chip thickness increased drying time. Higher heating temperature and thicker samples consumed less energy per kilogram of dried product yield. Vacuum drying produced low-fat tortilla chips with a relatively bright yellow color and produced sweet potato chips with strong yellow-orange color. In most cases, drying conditions did not significantly affect the color change and no browning was found in CVD

tortilla chips. Sweet potato chips produced at 140°C showed some color change compared to other treatments and browning was observed. Tortilla chips that were 1.5 mm thick and dried at 90°C had high volume expansion, numerous air cells, and multiple fracture points indicative of a crisp product. Sweet potato chips dried at 100 or 120°C had the best retention of yellow-orange color and β-carotene. Using a mixture of heating plate temperatures in the three conduction zones (by setting the first plate to 140°C, following by 120°C and 100°C) produced sweet potato chips that had good color and β-carotene retention, and texture attributes most similar to fried chips.

A diffusion model and semi-empirical model were developed from Fick's law of diffusion. A model incorporating a variable characteristic coefficient was derived from the drying rate data. All models were related to the internal mass transfer of water during the vacuum belt preparation of low-fat tortilla chips. All had reasonably good agreement between experimental and predicted data. Upon consideration of all the goodness-of-fit parameters (r^2, SSE and χ^2), the model incorporating a variable coefficient gave the best prediction of moisture levels over the total course of drying.

The objectives of this dissertation were achieved. However, further study is needed to better understand the process of continuous vacuum belt drying applied on high quality solid foods, to improve the product quality and to save energy, and to plan for scale-up.

The drying conditions affected both product quality and energy consumption. However, only sample thickness and heating temperatures were investigated in this study. Operating pressure levels, initial solids content, and the addition of flavor and other ingredients are additional factors that could be investigated. In this research, measurements were conducted shortly after the products had been processed. However, the packaging and storage conditions

will also affect the shelf life of tortilla and sweet potato chips. Thus, the time over which the products maintain good flavor and texture, and retain nutrients such as β-carotene is important. It is recommended to conduct more research on quality factors of vacuum dried snack chips during storage. This study showed that lack of oil flavor is the main reason that CVD product is less favored than DFF snack chips. Thus, future work could investigate ways of improving flavor of the chips. Finally, this work was conducted using a pilot plant-scale continuous vacuum belt drier, and future work could consider factors that would be necessary for scaling up to an industrial line.