

PROCESSING SWEET POTATOES INTO FRENCH FRIES

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Abstract

Sweet potatoes are a significant crop and are popular among consumers, particularly as french fries. Because the processing steps of making white potato french fries may be detrimental to the quality of a sweet potato fry, it is important to understand the impact of processing on quality and consumer acceptability. The variety of sweet potatoes can affect the texture, appearance, and consumer preference. Peeling processes have evolved from harsh lye treatments to more quick and efficient methods such as steam peeling. Blanching is one of the most important steps because it deactivates enzymes, including polyphenol oxidase and amylases, that affect texture and appearance. While hot water blanching is used by majority of french fry manufacturers, novel techniques like microwave blanching may be similarly effective and less detrimental to the texture and nutritional composition. Time and temperature of the blanching method can affect the texture and flavor by weakening cell walls and leaching sugars. Drying of sweet potato fries prepares the product prior to frying. Drying drives moisture off and allows the starch on the surface of the fries to gelatinize. Many types of dryers, including vacuum, hot air, and fluidized bed, have been evaluated for the rate of moisture loss and final product texture. Drying should not be done too quickly because case hardening will occur and make the product have a tough and chewy bite. Frying uses oil at elevated temperatures to develop color, flavor, and a crispy external texture. The type of oil, oil temperature, and time of frying will affect the finished product attributes. Low oil temperature may lead to higher oil uptake into the sweet potato fries. Vacuum frying compared to deep fat frying can create sweet potato fries with less darkening and less oil uptake, but this method would be difficult in large scale manufacturing. Opportunities in creating high quality sweet potato french fries are directly related to consumer acceptability and manufacturing capability.

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Chapter 1 - Importance of Sweet Potatoes

Sweet potato (*Ipomoea batatas* L. Lam) is the seventh-most significant crop based on global annual production. The sweet potato is extremely important for worldwide food security. China produces the most sweet potatoes, which accounts for 80% of production worldwide; whereas, the United States accounts for 0.8% of sweet potato production (Leksrisompong *et al* 2012). In 2009, the foremost producing countries included China, Russian Federation, India, Ukraine and the United States (Oke and Workneh 2013). In the United States, sweet potatoes are mostly grown in North Carolina, Louisiana, and California. Other states produce at lower production volumes, such as Mississippi, Alabama, New Jersey, Texas, and South Carolina (Pszczola 2011).

Sweet potatoes are roots and part of the morning glory family. They are not related to the regular white potato (*Solanum tuberosum*), which is a tuber (Pszczola 2011). Sweet potatoes have a great potential for use in developing countries due to the high yields of dry matter. When grown in the tropics, sweet potatoes have a short growing cycle of about 4 months. They are harvested after the leaves turn yellow, and the harvesting is labor intensive because the crop must be picked by hand to avoid damaging the sweet potatoes. Mechanical harvesters have been developed to lift the sweet potatoes, remove the vines, and sort, but these do damage the sweet potatoes. Sweet potatoes can be used as livestock feed and are eaten as a major carbohydrate in the human diet. Specifically in developing countries, sweet potatoes can be dried in the form of chips and used as a constant source of food when other food staples have been depleted (Diop 1998).

Sweet potatoes can be served to kindergarten through 12 grade school children as a part of their lunches. Students, who participate in the National School Lunch Program, are provided

with meals each day; therefore, schools are in a significant position to positively influence children nutrition and food choices. This program is designed to provide school children with proper nutrients including protein, calcium, iron, and vitamins A and C from various foods. Of these required food components, the program recommends three-fourths cup of fruit or vegetables and requires students to take one or the other. Oftentimes, students take the required serving but then toss it. Food choices made by students need to be addressed and understood to prevent large amounts of food waste. Smith and Cunningham-Sabo found that elementary and middle school students chose fruit over vegetables with lunch. Because of the low consumption of vegetables, children may be deprived of important nutrients such as vitamins A and C (Smith and Cunningham-Sabo 2013). Common fruit and vegetable options include apples, carrots, grapes, oranges, bananas, melons, strawberries, tomatoes, celery, broccoli, and cucumber (Olsho et al 2015). The National School Lunch Program recommends a new red/orange vegetable category for K-12 students (DiMartino 2013). Ultimately, the sweet potato can fulfill the demand for the newly required healthy options because sweet potatoes are rich in dietary fiber, beta carotene, vitamin C, and vitamin B6, especially in the orange fleshed varieties (Pszczola 2011).

The sweet potato trend is increasing in the retail and food service markets. Sweet potatoes are being used in a variety of ways, such as twice baked sweet potatoes, chips, and sweet potato bread with raisins. Sweet potato fries are making appearances in fast food restaurants, such as White Castle, Carl's Jr, Wendy's, and Burger King. Cape Cod launched a sweet potato chip served with a cinnamon and sugar coating. Conagra Foods and Lamb Weston have multiple types of sweet potato products as part of the *Sweet Things* brand. The sweet potatoes are made into fries, wedges, puffs, and mash. Simplot, also, has their *Simplot Sweets* brand that offers an entrée-cut and thin-cut fries, as well as, roasted-medley options. Another

company, J.R. Short, creates extruded sweet potato pellets that are used in many different snack blends. McCain Foods offers their brand, “Harvest Splendor,” which includes sweet potato products such as deep groove crinkle cut sweet potato fries (Nguyen 2007). Sweet potatoes were named on the top 10 sweet flavor trends for 2011 by Bell Flavors and Fragrances. Mintel indicated sweet potatoes as a hot trend in 2010 because of the functional and nutritional benefits. They are being blended with a multitude of unique and creative spices pairings. Wixon Inc created a prototype sweet potato chip called *Argentinean Asado*, which offered a blend of smoky, paprika, red wine, cumin, garlic, and sea salt. McCormick Flavors developed some recipes around the holiday season and in particular, one recipe involved sweet potatoes and cinnamon pecans (Pszczola 2011).

The North Carolina Sweet Potato Commission promotes sweet potatoes for the nutritional aspects. Their website offers recipes using sweet potatoes depending on the month of year. Recipes range from seasoned sweet potatoes wedges to mixing sweet potato puree in ground turkey for a flavor twist in a turkey burger. Step-by-step instructions are given for how to cut, grill, microwave, and bake sweet potatoes. Consumers can also find information on varieties of sweet potatoes and how to grow them (North Carolina Sweet Potato Commission 2015). Also, in North Carolina, Trinity Frozen Foods LLC creates sweet potato fries for food service and retail markets and built a processing facility specifically for sweet potatoes in 2013 (IFT 2013).

Sweet potatoes have proven to be versatile and are gaining popularity among consumers. They can be used especially in schools to fulfill the new National School Lunch Program guidelines and provide an excellent source of vitamin A, which is lacking in lunches today (Smith and Cunningham-Sabo 2013). The potential of sweet potatoes as a fry option is high and may be very profitable for french fry manufacturers. The processing steps of making regular

white potato french fries may be detrimental to the quality of a sweet potato fry. This paper will review the processing steps involved in making french fries and how these techniques are applied to sweet potatoes. It is important to understand the impact of processing on sweet potatoes because this will affect the final product quality and consumer acceptability.

Chapter 2 - Sweet Potato Varieties

There are hundreds of varieties of sweet potatoes with colors ranging from white, orange, and purple. Carotenoids and phenolic compounds give sweet potatoes the distinct flesh color. White Delight is a variety with white flesh, and NC414, NC415, Purple 04-069 and Okinawa are purple fleshed (Leksrisompong et al 2012; North Carolina Sweet Potato Commission 2015). The more consumer-recognized orange flesh sweet potato varieties include Beauregard, Hernandez, Jewel, Carolina Ruby, Porto Rico, Cordner and Covington (North Carolina Sweet Potato Commission 2015). Because of the varying flesh colors, the nutritional content can vary as well as the consumer acceptance.

The nutritional content of sweet potatoes according to the United States Department of Agriculture (USDA) is shown below in table 2-1. Raw, unprepared sweet potatoes are a good source of carbohydrates, vitamin A, dietary fiber, potassium, calcium, magnesium, sodium, phosphorus, and iron (USDA 2009). The phytochemicals, such as carotenoids and flavonoids, among the different varieties can differ from each other. Teow and others (2007) assessed the antioxidant activity, phenolic, and beta carotene contents of sweet potatoes with different flesh colors, which ranged from white, cream, yellow, orange, and purple. White flesh sweet potatoes were found to have the lowest antioxidant activity. The orange flesh varieties had a medium range antioxidant activity, and the darker orange flesh had slightly higher antioxidant activity.

The purple flesh sweet potatoes had the highest antioxidant activity values, which was similar to that of fruits and vegetables, such as apples, avocado, cherries, broccoli and eggplants. The purple flesh varieties also had the highest phenolic content; contrastingly, the white flesh sweet potatoes had the lowest phenolic content. The anthocyanin content varied among the sweet potato flesh colors, which the purple and orange flesh varieties had anthocyanins that were detectable. For beta carotene, the orange flesh sweet potatoes had the highest amount versus the other varieties (Teow et al 2007).

Table 2-1 Nutritional value of raw sweet potato per 100 g (USDA 2009)

Nutrient	Unit	Value per 100 g
Water	g	77.28
Energy	kcal	86
Protein	g	1.57
Total lipid (fat)	g	0.05
Carbohydrate	g	20.12
Fiber, total dietary	g	3
Sugars	g	4.18
Calcium	mg	30
Iron	mg	0.61
Magnesium	mg	25
Phosphorus	mg	47
Potassium	mg	337
Sodium	mg	55
Zinc	mg	0.3
Vitamin C	mg	2.4
Thiamin	mg	0.078
Riboflavin	mg	0.061
Niacin	mg	0.557
Vitamin B-6	mg	0.209
Folate	µg	11
Vitamin A	µg	709
Vitamin A	IU	14187
Vitamin E	mg	0.26
Vitamin K	µg	1.8
Fatty acids, total saturated	g	0.018
Fatty acids, total monounsaturated	g	0.001
Fatty acids, total polyunsaturated	g	0.014

The protein in sweet potato is also good in quality. Mu and others (2009) analyzed the sweet potato protein of a specific Chinese variety called 55-2. Aspartic acid and glutamic acid were the predominant amino acids, 18.5% and 9.3% respectively. The other amino acids that made up 40.7% of the protein included isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine (Mu et al 2009). Another study analyzed the Jewel and Centennial varieties and found similar results as Mu and others. The major amino acids were aspartic acid and glutamic acid in the white protein and chromoplast fractions (Walter and Catignani 1981).

The amylose and amylopectin of sweet potato starches can vary from variety to variety. Among the cultivars in the Caribbean, the sweet potatoes, Lovers Name, Big Red, and Black Vine, had amylose and amylopectin values ranging from 19.5% to 24.6% for amylose and 75.4% to 80.5% for amylopectin (Ali et al 2012). In another study, eight Korean sweet potato varieties were analyzed for amylose. The values for amylose ranged from 14.66% to 30.51%, and these were the same flesh color. The amylose and amylopectin ratio can affect the gelatinization temperature and the stickiness or tackiness of the sweet potatoes during french fry processing. With the Korean sweet potatoes, pasting temperatures ranged from 69.4°C to 76.4°C (156.9°F to 169.5°F), which the lower pasting temperature, 69.4°C, related to the lowest amylose content and the highest pasting temperature, 76.4°C, related to the highest amylose content. Kim and others also found differing shape and size of the starch granules among sweet potato varieties, which can influence the pasting temperature (Kim et al 2013). With the Caribbean sweet potatoes, Lover's Name, Big Red, and Black Vine had pasting temperatures ranging from 73.05°C to 75.9°C (163.49°F to 168.62°F). The researchers found the sugar content affects the

pasting temperatures because sugar binds water and does not allow the water to hydrate the starch. The higher the sugar content, the higher the temperature needs to be to reach the gelatinization temperature (Ali et al 2012).

The cooking methods can vary due to the flesh color of the sweet potato including textural and gelatinization properties. The toughness of the sweet potatoes was measured lowest with an orange fleshed variety and highest with a white fleshed variety. The cutting force is an indication of how much energy is required to cut sweet potatoes into slices or chips. The most cutting energy was needed for a cream fleshed variety and the least was needed for a white fleshed variety. The most fiber and moisture content was in the cream colored varieties. The highest mealiness based on textural and pasting properties was found in the white fleshed varieties. The differential scanning calorimetry (DSC) gelatinization value was the highest for a cream colored variety; whereas, the lowest DSC gelatinization was recorded with a white flesh type. Based on the gelatinization temperatures, starches may differ in the varying flesh colored types, which affects the cooking properties. Also, the structure of amylopectin may vary amongst botanical sources for sweet potato resulting in differences in gelatinization properties. The researchers concluded no significant differences between the colored varieties due to texture of the raw sweet potatoes. Based on the pasting parameters and DSC gelatinization results, the sweet potatoes with the same flesh color can be predicted to display similar characteristics (Sajeev et al 2012).

Consumer acceptance is affected by sweet potato variety. Afuape and others (2014) conducted sensory evaluations of fourteen sweet potato varieties with different flesh colors that ranged from white, cream, orange, and yellow. The researchers found all the test varieties were acceptable amongst consumers. For the boiled versions of the sweet potatoes, the flesh color,

mouthfeel and aroma were all significant for consumer acceptability. Only the flesh color and taste were significant in the fried versions of the sweet potatoes. A major conclusion of this work was root flesh color does impact consumer acceptance (Afuape et al 2014). Leksrisonpong and others (2012) also evaluated the effect of sweet potato color on consumer preference using varying colors (white, yellow, orange, purple). The orange fleshed sweet potatoes were shown to have higher surface moisture and a softer texture versus the other flesh colors. The purple colored sweet potatoes were thought to be more fibrousness and were more firm in texture. The orange and purple sweet potatoes had higher aroma values. For acceptance based on color, the orange flesh was liked the best. The researchers did find that the color may not be a major driver of liking, and the flavor and texture were the major drivers of liking. Consumers were accepting of unique flesh colors only if the flavor and textural attributes were also well liked (Leksrisonpong et al 2012). In Ali and others study, the Caribbean sweet potatoes, Lovers Name, Big Red, and Black Vine, were not significantly different from each other in terms of appearance, taste, texture, and overall acceptance (2012). In another research study, Laurie and others (2013) tested orange and cream colored sweet potatoes with consumers. A total of twelve sweet potato varieties were used, which nine were orange colored and three were cream colored. The cream fleshed samples had high scores for sweet potato flavor, and the orange colored samples had high scores for pumpkin flavor. The color of each of the varieties did not impact the consumer acceptability significantly. The sweet flavor, dry mass, and maltose content of the sweet potatoes contributed to a significant positive correlation to consumer preference. Sweet potatoes with excessive moisture did not perform well in terms of consumer acceptance (Laurie et al 2013).

Chapter 3 - Processing Techniques

Harvesting and Storage

Harvesting for good quality sweet potatoes must be completed very gently. Sweet potatoes have a delicate skin that can be damaged by equipment and rough handling, which can lead to poor appearance or diseases. Sweet potatoes are plowed using a mechanical digger followed by hand harvesting, which includes workers gathering the sweet potatoes by hand into bushels. Pallets of the sweet potatoes should not be overfilled because this can cause damage when stacking. Once the sweet potatoes are dug, they may be susceptible to sunscald or chilling if they are left too long. Sunscald is a darkening of the skin as a result of exposure to sunlight. Injury caused by chilling can occur in late-season harvest when the temperature reaches below 50F (10C). To avoid injury, sweet potatoes should be immediately hand-picked and brought to the curing facility for 3 to 5 days after harvest. The sweet potatoes are cured at 85°F (29°C) and at a relative humidity of 85 to 90% with good air circulation. The curing process provides many benefits including improving eating quality (color, texture, taste, aroma, and fiber content), healing of wounds, and setting the delicate skin or peel into a more robust skin. Sweet potatoes should then be stored at 55°F (13°C) with 85-90% relative humidity and good air ventilation (Edmunds et al 2008).

Sweet potatoes are washed and disinfected prior to peeling. During disinfection, pathogenic bacteria, fungi, viruses, and other microorganisms are destroyed, and chemicals, such as chlorine, are used. Potable water and higher temperatures are employed to increase the efficiency of the chlorine. The concentration and length of exposure can affect the rate of disinfection. Sweet potatoes can be disinfected in a dump tank with chlorine at a concentration of 100-150 ppm (Suslow 1997).

Peeling

Peeling is the first step in sweet potato processing and must be done to minimize product loss, maximize peel loss, minimize heat ring, and minimize chemical usage and pollution. Many methods can be used for the peeling process, such as steam, lye, abrasion, knives, and flame. Oladejo and others (2014) evaluated steam and lye peeling processes on sweet potatoes. The high temperature in steam peeling increases the pressure inside of the sweet potato. Pectins and polysaccharides begin to breakdown resulting in loss of cell structure. With lye peeling, the lye dissolves the epicuticular and cuticular waxes followed by breaking down the epidermal and hypodermal cell walls; therefore, separating the skin. For steam peeling, a steam bath was used at temperatures of 80 - 100°C (176 – 212°F) and times of 5-15 minutes. After the steam peeling was done, the peel loss and the unpeeled areas were assessed. For the lye peeling process, sodium hydroxide solutions were prepared at 8%, 10%, and 12% concentrations. The sodium hydroxide solutions were heated in a water bath with temperatures of 80 - 100°C (176 – 212°F) and the peeling times were set at 3-5 minutes. For steam peeling, the average peel loss was 6.87%. It was determined the peeling time was the major factor affecting the peel loss more than the temperature. The higher peel loss was found with the higher temperature and longer time due to the decrease in sweet potato tissue integrity. The average unpeeled area for steam peeling was 28.16% resulting in a peeling efficiency of 71.84%. The optimum steam peeling that gives the minimum peel loss and unpeeled surface area is at 100°C for 5 minutes. For the lye peeling method, the average peel loss was 13.7%. The increase of peel loss was due to the higher peeling time and temperature, and the lye concentration had a minimal effect on the peel loss. The average unpeeled area was 13.35% resulting in a peeling efficiency of 86.65%. The optimum process that gives the minimum peel loss and unpeeled surface area is with 8.89% lye

concentration at 100°C for 4.76 minutes. The researchers concluded that lye peeling overall was a better peeling process for sweet potatoes (Oladejo et al 2014).

In another study, many peeling methods were compared including boiling water, salt solution, lye solutions at varying concentrations, oven, mineral oil, gas flame, mechanical, and knife by hand (Bouwkamp 1985). The mechanical method produced very high peel loss, which can be detrimental to a large-scale production. The gas flame did not peel evenly, and the oven and boiling water methods were insufficient in removing the peel. The lye method, which used 7-10% lye concentration for 6 minutes, produced good peeled sweet potatoes. Steam peeling is the most commonly used method in the industry for potato peeling, and compared to lye peeling, it is easier to dispose of the waste with steam peeling. Different pressures have been researched with steam peeling, and a good steam peeling method was completed using 15-20 psi for 5-6 minutes immediately followed by the release of the pressure. The color evenness can be affected by the length in time of the peeling process because of the release of specific enzymes. The cambial areas of the sweet potatoes contain polyphenol oxidase, which can darken the sweet potato during processing. The evenness of color may be improved if the peeling does not penetrate to the cambial level (Bouwkamp 1985).

Lye peeling was further evaluated in Walter and Schadel's study on Jewel sweet potatoes. Several lye peeling methods were used to examine the effect on the cell level, discoloration, and starch gelatinization. The figure 3-1 below displays the relative locations of sweet potato root tissues and cell types including the periderm (outermost layer), lenticifer, cambium, and xylem element (innermost tissue). The lye peeling treatments used 104°C (219.2°F) with 10% lye concentration for 6 minutes and 15 minutes. The most tissue removal was with the 15 minute peel and the least with the 6 minute peel. The 15 minute peel treatment removed tissue at or

below the cambium level. Starch gelatinization, as an effect from the heat penetration of the treatments, was detected most in the 15 minute treatment and least in the 6 minutes, and this was similarly found with the cell wall detachment. Discoloration of sweet potatoes after peeling heat treatments occurs in the laticifer-cambium levels. The researchers explained that the heat can reach to the varying depths, but the heat may not be enough to inactivate polyphenoloxidase (PPO); therefore, PPO is allowed to react with dihydroxy phenols (DP) to create brown colored products. The most discoloration was found in the 6 minute treatment because the heat penetration was not sufficient to destroy PPO. In the other treatments, the heat did destroy the laticifer cell structure and the PPO located in the laticifer level (Walter and Schadel 1982).

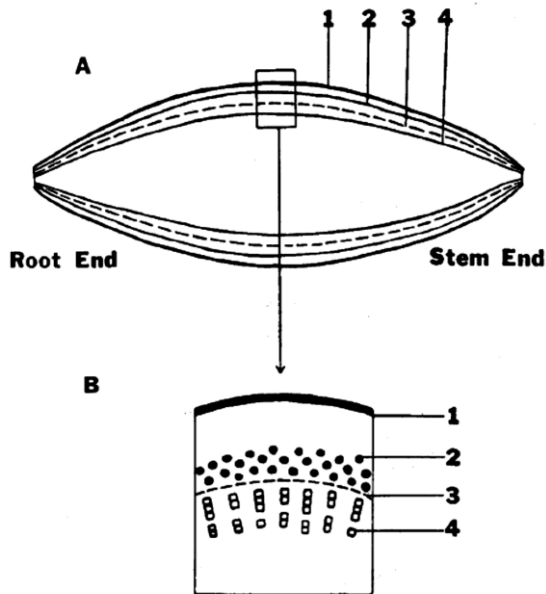


Figure 3-1 Sweet potato root sections with relative locations of tissues and cell types: 1 - Periderm; 2 – Laticifer; 3 – Cambium; 4 – Xylem element (Walter and Schadel 1982)

In similar research, yams were evaluated on the peeling method including hand peeling, lye peeling, and flame peeling. Hand peeling is too laborious for industrial scale-ups and is not a sustainable option for sweet potato manufacturers. Lye peeling is a popular method, and the

effectiveness is determined by the chemical concentration, temperature, and immersion time. The researchers emphasized the negative attributes of the lye method. The lye method involves handling large quantities of a corroding chemical at high peeling temperatures. The peel and lye must be rinsed thoroughly; therefore, this method wastes water and causes more issues on how to handle the wastewater. The researchers used lye concentrations at 10, 15, 20, and 25% for 8, 5, and 3 minute immersion times. The optimal conditions for lye peeling were 15% lye concentration at 98°C (208.4°F) for 5 minutes. Flame peeling was evaluated as a possible method to replace the lye method. In flame peeling, the high temperatures, around 857°C (1574.5°F), are able to loosen the bond between the peel and the flesh, and the peel can be removed with brushes and steam. The pressure from the steam allows the peel to lift off slightly, which also allows the bond between the peel and flesh to weaken. An experimental flame peeling operation was created for this research in order for the equipment to manage the irregularly shaped yams allowing the yams to rotate horizontally through the flame burners. The flame time and distance from the burner greatly affected the peel loss and browning of the yams, and the optimal conditions were 857°C (1574.5°F) for 9 minutes. The flame peeling method was determined to be a sufficient method, instead of lye peeling, when lye is expensive and difficult to obtain or use (Onayemi et al 1985).

Edmond and Ammerman (1971) reviewed the methods for peeling sweet potato including mechanical abrasion, sodium hydroxide, extended time in flowing steam, shorter time in high pressure steam, and combinations of these. The mechanical method is not suitable for large-scale production because of the high peel losses. Lye peeling had been used extensively, but it was not ideal due to the large waste and disposal of the chemicals. The recommended lye method was 10% lye concentration at 93.3°C (200°F) for 8-10 minutes. Following the lye treatment, sweet

potatoes were rinsed thoroughly with water, and the water pressure along with brushes helped remove the excess peel. Steam peeling was found to be a satisfactory method. The sweet potatoes were placed into a steam chamber, which temperatures can reach up to 148.9°C (300°F), and time can vary from seconds to a few minutes. After the steam peeling is completed, a series of water sprays and brushes aid in removing the excess peel. (Edmond and Ammerman 1971).

Smith and others compared three methods of peeling including: high pressure steam peeling with flash cooling with water injection in the chamber, high pressure steam peeling with post-cooling using spray washing, and lye peeling. Too much peeling can contribute to high amounts of waste and possible discoloration of the product. The peel losses can vary with the length in time of the peeling method and concentration of the chemical used. The researchers analyzed Red Jewel sweet potatoes under the three peeling treatments to determine the effect of the flash cooling within the chamber on the peel loss and product quality. The peel losses and recovery of the steam peeling with flash cooling was similar to the steam peeling with post-cold wash and lye peeling. In the steam peeling with flash cooling method, the sweet potatoes were exposed to a release of pressure and a sudden stop of heat. The steam peeling with post-cold water wash still had the sudden release of pressure, but the heat was reduced slowly outside of the peeler chamber. The steam peeling with flash cooling method reduced the heat ring and discoloration compared to the other methods. This particular method may reduce peel losses and lead to higher quality sweet potato products (Smith et al 1980).

Blanching

Blanching is a critical step in making sweet potato french fries. Blanching alters textural properties and imparts a soft or firm bite on sweet potato fries. The combination of temperature

and time in the blanching process can create a creamy or firm internal in the sweet potato fry through the level of pectin and cell wall breakdown. Enzymes such as pectinmethylesterase can reinforce structure and increase firmness by making new linkages between pectin molecules (Walter et al 2003). Also, sweet potatoes are prone to browning reactions after peeling, and blanching can help prevent the sweet potato fries from becoming discolored by denaturing enzymes, such as polyphenol oxidase (PPO) and amylase. Polyphenol oxidase (PPO) is an enzyme that discolors sweet potato products through reactions that form pigments called melanins (Lourenco et al 1992). Other reactions can also discolor sweet potato french fries during processing, such as non-enzymatic browning. Non-enzymatic browning is the formation of dark pigments, also known as the Maillard reaction. It is a browning in foods caused by a chemical reaction between reducing sugars and a primary amino group of a protein molecule (Damodaran et al 2008). Proper blanching techniques need to be used to create high quality sweet potato fries that do not have extensive dark discoloration or an unacceptable bite.

Enzymatic Browning

Enzymatic browning can occur through polyphenol oxidase (PPO) reactions. PPO catalyzes the process of oxidation of mono, di, and poly phenols to *o*-quinones (Lourenco et al 1992). The browning pigments are not formed by PPO enzymatic activity, but the pigments are formed by chemical condensation reactions that follow. The resulting amines or proteins condense and form pigments called melanins. The temperatures used to deactivate PPO range from 30-50°C (86°F-122°F), but the stability of the enzyme is high and can take up to several minutes to deactivate at those temperatures. Especially during the heat processing of sweet potatoes, PPO can exist for many minutes and discolor the product extensively (Damodaran et al 2008). To understand how enzymatic browning happens, some researchers investigated

polyphenol oxidase (PPO) and what treatments would inhibit its function. Lourenco and others (1992) extracted PPO from sweet potato tissue to determine the physicochemical properties. Ascorbic acid was a poor inhibitor of PPO activity, while dithioerythritol, sodium metabisulfite, *p*-coumaric acid, and cinnamic acid were effective sweet potato PPO inhibitors (Lourenco et al 1992). Another study also found ascorbic acid to be a poor inhibitor of PPO activity (Walter and Purcell 1980). Lourenco and others (1992) found the compounds, *p*-coumaric acid and cinnamic acid, used competitive enzyme inhibition. The inhibitors were able to prevent color development by reducing the quinones to the colorless *o*-dihydroxyphenols. Other amino acids were also able to inhibit the sweet potato PPO such as *L*-methionine, glycine, *L*-isoleucine, and *L*-glutamine. The amino acids were able to react with copper at the active site of PPO and prevent enzymatic activity. Also, Lourenco and others found that sucrose and salt stabilized PPO activity. The researchers attributed the stabilization by sucrose to its cohesive force of sucrose. This force increases surface tension in the water, which aided in the protection of PPO against heat denaturation. For salts, the most protective to the least protective salt were $(\text{NH}_4)_2\text{SO}_4$, Na_2SO_4 , NaCl , and KCl . The stabilization effect from salt can be related to the concentration in the solution and the salt ionic strength (Lourenco et al 1992).

Ma and others (1992) used water blanching to decrease the polyphenol oxidase (PPO) activity in sweet potatoes varieties, including Jewel and Centennial. Overall, the researchers found that blanching leads to a significant reduction of the PPO activity. The water blanching treatments included 2 blanching temperatures, 94°C (201.2°F) (a commercially used temperature) and 100°C (212°F), and 3 blanching times of 1, 3, or 5 minutes. Minimum darkening was found in sweet potatoes with the blanching treatment of 100°C (212°F) for 3 minutes. No other significant differences were found post 3 minutes at 100°C (212°F). The 94°C

(201.2°F) temperature treatment was time dependent according to the darkening potential, and a total of 5 minutes resulted in acceptable product. Both Jewel and Centennial required 3 minutes at 100°C (212°F) or 5 minutes at 94°C (201.2°F) to reduce the dark color formation and produce acceptable product (Ma et al 1992). Lourenco and others also found that higher temperatures deactivated the enzyme quicker and more effectively. At 80°C (176°F), PPO was completely inactivated at 15 minutes, whereas PPO was fully inactivated in 1 minute at 90°C (194°F) (Lourenco et al 1992). Ma and others concluded the PPO activity was the main factor in dark pigment formation for blanched sweet potatoes because the PPO activity decreased as a result of the blanching treatments (Ma et al 1992).

Instead of PPO, Liu and others used the enzyme peroxidase as the representative enzyme to evaluate different blanching treatments. The treatments used were microwave blanching, hot water blanching, and steam blanching on purple-fleshed sweet potatoes. Microwave blanching was completed in a domestic oven with input power at 1200 W, output 700 W, at maximum power. The steam and water blanching were completed at temperatures of $98 \pm 2^\circ\text{C}$ ($208.4 \pm 2^\circ\text{F}$). The degradation of 90% of peroxidase activity took 130 seconds for hot water blanching, 110 seconds for steam blanching, and 60 seconds for microwave blanching. The hot water blanching took the longest and the microwave blanching took much less time to degrade the enzyme activity. Microwave blanching is able to effectively heat the product from the core to the outside at the same time, which leads to a more efficient enzyme degradation rate. In terms of color, the microwave blanched samples had the brightest color, whereas the steam blanched sample had the darkest appearance; though, the steam blanched samples were closer to purple than the other treatments. The hot water blanching imparted poor color uniformity because the heat from blanching degraded cell membranes allowing anthocyanins to release into the water. Though the

microwave blanched samples did not display the dark purple color similar to that of the steam blanched samples, microwave blanching had a decreased time required to degrade peroxidase activity and retained the highest level of anthocyanin content (Liu et al 2015).

Non-Enzymatic Browning

The process of starch hydrolysis creates reducing sugars that further react with proteins and form dark pigments. The enzymes α -amylase and β -amylase hydrolyze starch during heat processing into reducing sugars, such as maltose, which take part in the Maillard reaction. It is important to learn the location of the amylase enzymes in sweet potatoes to understand the darkening potential of the finished product. Hagenimana and others (1992) found the highest level of the α -amylase was in the outermost level of the sweet potato or the periderm in all the varieties tested, which were Jewel, Porto Rico, Regal, and White Delight. They concluded that α -amylase was predominant in the periderm and cambium areas. For β -amylase, it was found mainly in the inner tissues of all of the varieties, except White Delight. The β -amylase was reasonably well-distributed in the tissues of White Delight. Because the β -amylase is unable to attack ungelatinized starch, it was concluded that β -amylase has little effect on the starch hydrolysis. Both α -amylase and β -amylase denature at 73°F-75°C (163.4-167°F), which is also the temperature range that sweet potato starch begins to gelatinize. α -amylase can attack native starch granules and is attributed to the elevated starch hydrolysis into maltose and dextrans during peeling processes. The researchers concluded that the concentration of maltose in the outer layers of the sweet potatoes interact with amino acids and lead to the formation of brown pigments in a Maillard browning reaction (Hagenimana et al 1992). When developing a blanching technique, a french fry manufacturer needs to understand the nature of amylase enzymes and consider their impact. These enzymes will render themselves inactive only if proper

blanching treatments with appropriate times and temperatures are utilized; therefore, the final sweet potato french fry product will not be discolored if these enzymes are effectively destroyed during the blanch process.

Texture

Blanching is performed for appearance and color as described in enzymatic and non-enzymatic browning; however, blanching is also completed for textural purposes. In a study by Walter and others (2003), low temperature blanching (LTB) was used to promote the firmness of sweet potato cylinder strips. This study with LTB treatments contrasts the previous studies using high temperature blanching, which were conducted by Liu and others, Lourenco and others, and Ma and others. Jewel cultivar sweet potatoes were cut into cylinder strips and subjected to LTB at 62°C (143.6°F) for 45 and 90 minutes. Another set of samples were blanched at 100°C (212°F) for 2 minutes. The longer blanch time at 90 minutes decreased the dry matter content because starch and other low molecular weight components, such as carbohydrates and amino acids, were leached out of the cells. However, the 90 minute treatment increased the firmness of the cylinder strips when compared to 45 minutes at 62°C (143.6°F) and untreated samples. The 90 minute treatment was also firmer than the samples blanched at 100°C (212°F) for 2 minutes. Walter and others first hypothesized that pectinmethylesterase activity was contributing solely to the firm texture of the sweet potato strips. The researchers analyzed the pectinmethylesterase activity, and it had decreased about 80% after 20 minutes of blanching and about 90% after 40 minutes of blanching (see figure 3-2); therefore, the firm texture was not completely attributed to pectinmethylesterase activity. Pectinmethylesterase can assist in making new linkages between pectin molecules, which reinforces structure and increases firmness, but other factors may assist in the firm texture, such as degrading of starch and leaching of cell wall materials (Walter et al

2003).

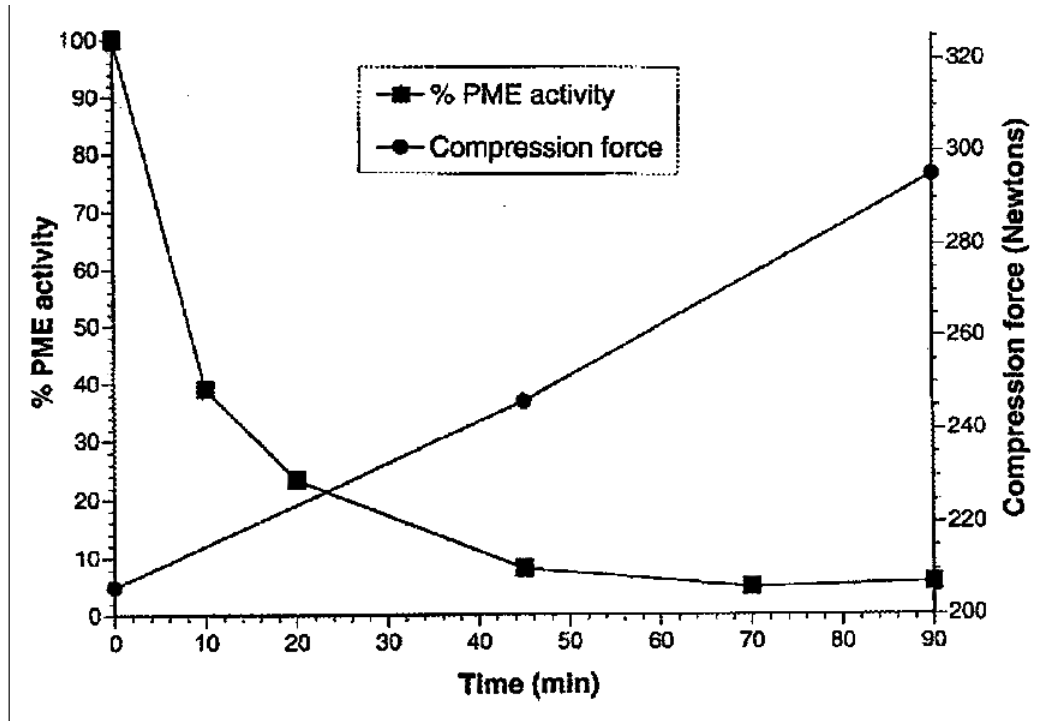


Figure 3-2 Comparison of percent pectin methylesterase activity and compression force plotted on blanch time. Blanch temperature set at 62°C (Walter et al 2003)

In similar research, Oner and Wall evaluated the blanching of purple-fleshed sweet potato strips with hot water blanching rather than LTB because hot water blanching is the preferred method of french fry manufacturers. The strips were blanched for 0, 5, and 10 minutes in boiling water, which was about 98°C (208.4°F). Oner and Wall used high temperature blanching that readily decreased the force in which to penetrate the strips, and ultimately, the softest texture was observed in the 10 minute blanched strips. Although, the strips blanched for 10 minutes had more oil absorption after frying because the surface cell integrity was damaged allowing more water to release and oil to be absorbed (Oner and Wall 2012).

Blanching treatments can affect young or fresh sweet potatoes differently than older or storage sweet potatoes. As sweet potatoes age in storage, cell wall integrity breaks down, which leads to a sweet potato product with a softer bite. Older sweet potatoes may require less intense blanching treatments to maintain a firmer texture. If the sweet potatoes are fresh from the ground, these cell wall components are more intact requiring a more intense blanching treatment to achieve the desired texture. The length of storage of sweet potatoes can affect the finished texture of sweet potato fries. Sylvia and Walter (1997) evaluated the firmness of sweet potatoes after 3 months from harvest and after 1 year in storage. The cell wall components, like pectin, contribute to the texture, and these components can degrade during time in storage. Treatments involving vacuum infusion and infiltration of multiple compounds, such as calcium chloride, acetic acid, and sodium phosphate, were used to determine texture firming capabilities. The sweet potatoes were sliced into strips and treated to Infiltration-Blanching-Infiltration or Infiltration-Infiltration-Blanching. For the 3 month aged sweet potatoes, the blanching order and the infusion treatments did not have a significant effect in overall acceptability or taste attributes tested with untrained panelists, although the sodium phosphate solution did increase the texture acceptability. For the sweet potatoes stored for 1 year, the samples treated with Infiltration-Infiltration-Blanching had higher overall and taste acceptability with the panelists. When the sweet potato strips were fried, the control sample treated only with water infiltration had the highest moisture content followed by the sodium phosphate treated samples and the sodium phosphate with calcium chloride samples. The control absorbed the least fat followed by the sodium phosphate treated samples and finally, the sodium phosphate with calcium chloride samples. It is important to note the most accepted sample was not the sample with the most firm texture, but it was the sample with a moderate level of firmness. The researchers concluded that

the 3 month samples all had higher sensory acceptance scores when compared to the 1 year samples, and the most desired texture was the sample with moderate firmness, which may be related to the resistance to chewing (Sylvia and Walter 1997).

Overall, many blanching techniques have been evaluated for enzymatic activity, color, and textural properties. Hot water blanching is the most commonly used method amongst french fry manufacturers. Low temperature blanching technology may not deactivate enzymes nor give the consumer-desired texture. Sucrose and salts added during the blanching process may stabilize enzymes, and these ingredients should not be added until after the enzymes are deactivated. High blanching temperatures deactivated the enzymes that lead to discoloration and poor quality product. High temperatures were used to alter textural attributes, but treatments using high temperatures with long blanching times can result in very soft sweet potato french fries. Consumer acceptability requires a medium bite that is not too firm or too soft. Ultimately, consumer preference will help define the optimized sweet potato french fries.

Drying

Drying of sweet potato fries prepares the product prior to frying. Drying involves heat application to remove a majority of water normally present in a food. Factors that can affect how air removes moisture from a food include water vapor content already in the air, air temperature, and the amount of air passed over the food (Fellows 2008). Drying drives moisture off and allows the starch on the surface of the fries to gelatinize. By driving the moisture off prior to frying, this prevents too much water entering the frying oil, which can lead to quick oxidation and short life span of the frying oil (Dinrifo 2012). Too rapid of drying and high temperatures can lead to case hardening of the sweet potato fries, which is undesirable in a finished fry

product. Case hardening is when molecules at the surface of the fries form an impermeable and tough skin, which causes the surface to be very dry and the internal very moist (Fellows 2008).

The moisture ratio is calculated after a drying experiment using the following formula, which M_e is equilibrium moisture content (kg water/kg dry matter), M_o is initial moisture content (kg water/kg dry matter), and M_t is moisture content at any time (Dinrifo 2012).

$$MR = \frac{M_t - M_e}{M_o - M_e}$$

The rate of drying can be calculated by using the following equation, where D_R is drying rate, M_t is moisture content at any time, M_{t+dt} is M_t after a specific amount of time, D_t is the total amount of drying time.

$$D_R = \frac{M_{t+dt} - M_t}{D_t}$$

(Dinrifo 2012)

Vacuum belt drying was utilized by Xu and others (2013) to create sweet potato chips that were dried instead of fried and still retain the nutritional components of sweet potatoes, such as beta carotene, and exhibit similar crispness as fried chips. The vacuum dryer had 4 zones, which were set to a temperature ranging from 100 - 140°C (212 – 284°F). The vacuum was set to 2.67 ± 0.05 kPa absolute, and the samples were dried until A_w of 0.2 was achieved and a final moisture content of 5.0 g H₂O per 100 g \pm 1.1%. Samples were also deep fat fried instead of dried for comparison. The oil used was a blend of high-oleic sunflower and cottonseed and set to a temperature of 165°C (329°F). The sweet potato slices were fried for 120 seconds. The samples were tested by untrained panelists. The chips that underwent the various temperatures in the vacuum drying had the highest overall liking. When the vacuum dryer was set just at 140°C (284°F), the chips appeared and tasted burnt. The chips from the 100°C (212°F) temperature

treatment had a great appearance, but the texture was not liked by the panelists. The deep fat fried chips were much darker brown compared to the vacuum belt dried samples due to Maillard browning reactions. The color of the vacuum belt dried samples was more similar to the fresh cut slices. The color can be attributed to the beta carotene in the samples, and the drying further concentrates beta carotene creating a more orange color. Increased drying temperatures created darker colored samples overall. The researchers also identified the microstructure of the sweet potato chips with Environmental Scanning Electron Microscope (ESEM) micrographs. The samples vacuum dried at 100°C (212°F) had small porous holes that the water used to escape, and this product was denser than the others. The 140°C (284°F) treatment created larger pores because of the higher temperature set across the entire drying time. The structure also began to collapse because of the high temperature toward the end of the drying treatment. The treatment that utilized a mixture of temperatures had the most expanded structure with narrow tunnels of air. Overall, the researchers found the treatment with the blend of temperatures performed the best because the moisture was able to be driven off initially with the high temperature, but the reduction in temperature toward the end prevented the samples from being abused detrimentally (Xu et al 2013).

A pilot scale tray dryer and a fluidized bed dryer were investigated on 6 varieties of sweet potatoes by Hatamipour and others (2007). Samples were evaluated for weight loss and dimensions. The drying treatments included temperatures of 60, 70, and 80°C (140, 158, and 176°F) on the tray dryers and 40, 50, and 60°C (104, 122, and 140°F) with the fluidized bed dryer. The air velocity had a significant effect on the drying time to reach the desired moisture content, as shown in figure 3-3 below. The fluidized bed dryer was the quickest method to reach the final moisture content. The forced convection tray dryer took a longer time than the fluidized

bed dryer, but the free convection dryer was the slowest method for moisture migration. The researchers concluded that the drying time could be reduced the most by using the fluidized bed dryer or a tray dryer with high air circulation (Hatamipour et al 2007).

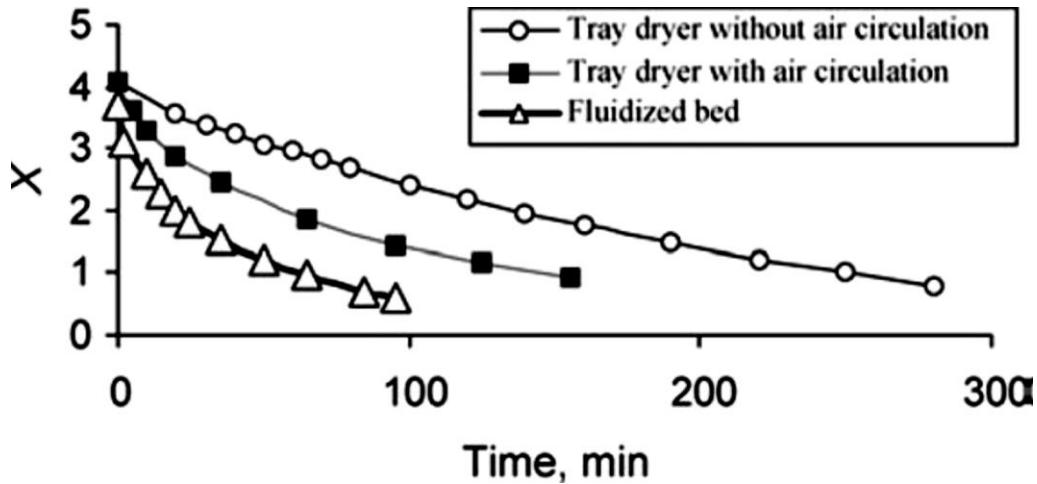


Figure 3-3 Drying curves of fluidized bed dryer and tray dryers with and without air circulation (Hatamipour et al 2007)

Dinrifo (2012) used hot air convective drying with sweet potato slices. The dryer temperatures evaluated were 50, 60, 70, and 80°C (122, 140, 158, and 176°F) with an air velocity of 1.25 m/s. Also, the sweet potato slices had slightly different pre-treatments to determine if this had an effect on the drying process. Sweet potato slices were blanched in hot water at 100°C (212°F) for 2 minutes, dipped in 0.01% sodium meta-bisulphite at 100°C (212°F) for 2 minutes, and untreated. The drying rate was very high at the start of the drying process, but the moisture ratio decreased as the drying time increased for all the samples. The higher temperatures at 80°C (176°F) increase the drying rate when compared to the drying rate at 50°C (122°F). The lower drying temperature at 50°C (122°F) had only slight effect on the different pre-treated sweet potato slices, which the pre-treated samples had a slower drying rate compared

to the untreated samples. The samples reacted more differently at the higher drying temperature of 80°C (176°F). For instance, the samples treated with sodium meta-bisulphite and hot water blanching both had higher drying rates indicating a less resistance for moisture release when compared to the untreated sweet potato slices (Dinrifo 2012).

Similar to Dinrifo's research, Falade and Solademi investigated the characteristics of drying fresh and blanched sweet potato slices. A portion of the sweet potato slices were blanched at 100°C (392°F) for 2 minutes. The fresh and blanched sweet potato slices were dried using a hot air dryer at 50, 60, 70, and 80°C (122, 140, 158, and 176°F). Like in Dinrifo's conclusions, the researchers found the moisture was released very rapidly at the beginning of the drying process and the rate of moisture migration decreased as the amount of moisture in the samples decreased. Also, another similar finding included the blanched sweet potato slices retaining more moisture over time. In other words, the blanched samples took more time to dry from a starting moisture content to a desired moisture content when compared to the untreated or fresh samples. These researchers relate the long drying time of the blanched samples to gelatinization. Blanching can cause gelatinization of starches in the sweet potatoes, slowing the rate of moisture migration. The drying rate increased with an increase in the drying temperature, which also led to shorter drying times (Falade and Solademi 2010).

Another study by Abdulla and others (2014) identified the effect of blanching and drying treatments on the quality of the fried sweet potato chips. In this research, sweet potato slices were dried at 70°C (158°F) for 0, 30, 50, and 70 minutes using a hot air dryer. One group was fresh then dried, and another group was submitted to 0.1% citric acid solution and then dried. As expected, the moisture content of the samples decreased as the drying time increased. The pre-drying treatment also reduced the moisture content and the oil absorption after frying. Sensory

evaluation was also conducted on the sweet potato samples. The pre-drying overall had a beneficial effect on the brittle bite and acceptability of the sweet potato chips (Abdulla et al 2014).

Frying

Deep fat frying is a transfer of heat via convection within the hot oil and conduction to the interior of the food. Oil absorption occurs as the moisture is released from the food. Low frying temperatures can increase the uptake of oil in a food, and high oil temperatures can produce a crust that creates a crispy external bite in french fries. Main factors that affect the color, flavor, and texture of a fried food include type of oil used, age and history of the oil, boundary between the oil and the food, temperature and time of frying, size and surface characteristics of the food, and moisture content of the food. Pretreatments, such as blanching and drying, can affect oil uptake by the product and final product texture. Food products, like sweet potato french fries, are deep fat fried to develop color, flavor, and crispy external texture (Fellows 2008).

In Abdulla and others research (2014), sweet potato slices were pretreated with a drying, blanching, or citric acid treatment prior to frying. Sunflower oil was used as the frying medium in a home deep fat fryer machine. The frying temperature was kept at $170\pm 1^{\circ}\text{C}$ ($338\pm 1^{\circ}\text{F}$), and the time was adjusted for each sample to ensure a bright color and crisp texture. The pre-drying treatment reduced the amount of oil absorption during frying. The blanched sweet potatoes had the highest fat absorption, which may be attributed to the porosity reduction after blanching.

The process of frying is affected by the type of oil used. Different oils can be unique in the chemical composition, such as unsaturated, polyunsaturated, and saturated fatty acids. Other

properties that can affect how the frying oil behaves includes melting point, physical-chemical properties such as free fatty acids, peroxide value, moisture content, and color, and the presence of contaminants and additives. Frying oil needs to resist oxidation and foam formation, have a low melting point, and a lack of undesirable odors (Fontes et al 2011). In Fontes and others (2011) research, palm olein and stearin were evaluated for deep fat frying of sweet potato chips. Palm oil is obtained from fruit pulp and is 54-70% saturated fat. Palm oil contains unsaturated fats (39% oleic acid and 10% linoleic acid) and saturated fats (44% palmitic acid and 5% stearic acid). Palm olein is obtained from the fractionation of refined palm oil that the operations did not use chemical additives. Palm olein is trans-fat free, resistant to oxidation, and is liquid at room temperatures because it has a low α -linolenic acid content. Palm stearin is also obtained from the fractionation of refined palm oil that the operations do not use chemical additives. Palm stearin is also trans-fat free, but it contains more saturated triacylglycerols that have a higher melting point; therefore, unlike palm olein, palm stearin is solid at room temperature. Fontes and others (2011) evaluated palm olein and stearin in deep fat frying of sweet potato chips to create a healthy product with low calories and fat. The sweet potatoes were cut into slices and fried in either of the oils at temperatures varying from 140 to 180°C (284 to 356°F) for 3 to 4 minutes. The lowest frying temperatures for both palm olein and stearin created sweet potato chips with a higher level of moisture content and sweet potato color more similar to that of the natural color of sweet potatoes, but the sweet potato chips were described as raw when tasted by the researchers. The sweet potato chips also had more oil uptake with the longer frying time. The temperature had the greatest effect on moisture content for both palm olein and palm stearin. The amount of frying time did not affect the moisture content of the sweet potato chips fried in either oil. Temperature also was significant for a desired color of the sweet potato chips. The optimal

temperature for the best color was between 160 to 175°C (320 to 345.2°F). To create a healthier sweet potato chip, less oil needed to be absorbed. The frying time of 3 minutes and 30 seconds in either palm olein or stearin resulted in a product with the lowest oil uptake. Oil uptake was not affected by temperature for palm olein; however, for quality purposes, the temperature should not be below 140°C (284°F) or above 180°C (356°F) for chips fried in palm stearin. The chips fried in palm stearin had a fat content of 13.1% when fried at 180°C (356°F) for 3 minutes and 30 seconds, and the chips fried in palm olein had a fat content of 14.46% when fried at 160°C (320°F) for 3 minutes and 30 seconds. Overall, the researchers developed a time and temperature profile for each oil type that created the best color, texture, and fat content (Fontes et al 2011).

Vacuum frying methods have been used to create fried snacks that are lower in fat content. Da Silva and Moreira (2008) compared attributes of the fried sweet potato chips cooked in the vacuum fryer and traditional fryer. The oil used was canola oil. The vacuum fryer was set at 1.33 kPa, $130\pm 1^{\circ}\text{C}$ ($266\pm 1^{\circ}\text{F}$), and 120 seconds. The product was submerged into the oil once the pressure was reached in the vessel. For traditional frying, the oil temperature was set at $165\pm 1^{\circ}\text{C}$ ($329\pm 1^{\circ}\text{F}$) and the product was fried for 240 seconds. The sweet potato chips had 24% less oil under vacuum frying compared to the traditional frying. Under traditional frying, lower frying temperatures impart higher oil content and undesirable texture; however, lower frying temperatures can be used with vacuum frying because the boiling point of water is reduced allowing the water vapor to release quickly. The color of the sweet potato chips was lighter and more yellow than the traditionally fried sweet potato chips. The vacuum method was able to create a product without excessive darkening because the process eliminates oxidation. Overall, vacuum frying can create sweet potato chips that have a more desirable color and less oil uptake (Da Silva and Moreira 2008).

Finished quality characteristics from frying can be affected by the type of sweet potato cultivar. Odenigbo and others (2012) studied changes in moisture loss, oil uptake, texture, and color during deep-fat frying on cultivars Ginseng Red, Beauregard, White Travis, Georgia Jet clone #2010, and Georgia Jet. The frying oil used was canola oil maintained at $180\pm 2^{\circ}\text{C}$ (356°F). The frying times included 1, 2, 3, 4, and 5 minutes. The initial moisture content ranged from 64.76 ± 1.64 to $78.42\pm 1.19\%$ on a wet basis. White Travis and Ginseng Red had significantly lower moisture contents when compared to the other cultivars. The average oil uptake ranged from 4.80 ± 0.17 to $9.61\pm 0.91\%$ on a dry matter basis. The cultivars with the higher initial moisture content (Beauregard, Georgia Jet clone #2010, and Georgia Jet) and low moisture loss rate had high oil absorption during frying. Typically, the oil absorption rate correlates to the rate of moisture loss, but this was not observed for the White Travis cultivar. The researchers indicated that the oil uptake can be affected by cellular structures in the different sweet potato varieties. Textural properties were evaluated by a compression test. The maximum force to compress decreased as frying time increased. The force to compress did increase slightly when the 4 to 5 minute frying time was used, which may be attributed to the crust development in the longer frying times. Crust development and sealing of the surface of the sweet potato fries can result in a low oil uptake. Other factors that can affect texture of sweet potato french fries are gelatinization of starch, sugar content, α -amylase activity, breakdown of cell wall, and protein denaturation while frying. All of the sweet potato varieties browned more with increased frying time due to the Maillard reaction that uses the reducing sugars in the sweet potatoes. Overall, Ginseng Red had the lowest oil content and the best crispy texture (Odenigbo et al 2012).

Chapter 4 - Nutritional Changes

Sweet potatoes are a good source of antioxidants, vitamin A, C, and E, which can help eliminate free radicals in the body that otherwise could lead to poor health conditions such as heart disease and colon cancer. Sweet potatoes can be cooked in a variety of ways including baking and deep-fat frying. Chukwu and others (2012) evaluated the effects of baking and frying on the antioxidants in sweet potatoes. The orange fleshed sweet potatoes were obtained from a Nigerian market. Sweet potatoes were sliced and fried at a lower temperature for 10 and 15 minutes or baked at 100°C (212°F) for 10, 15, and 20 minutes. For vitamin A content, the baked samples at 10 and 15 minutes had significantly highest overall antioxidant composition (8.13 ± 0.57 mg/100) versus raw (4.99 ± 0.09 mg/100) and fried samples at 10 and 15 minutes, respectively (6.52 ± 0.26 mg/100 and 6.18 ± 0.10 mg/100). Frying at 10 minutes had higher vitamin A than frying at 15 minutes, but this was not a statistically significant difference. For vitamin C content, baking had the overall highest antioxidant composition (0.89 ± 0.07 mg/100), but the baked treatments were not statistically significantly different than frying at 10 minutes (0.67 ± 0.09 mg/100). For both vitamins A and C, the raw samples were significantly lower than both the baked and fried treatments (Chukwu et al 2012). Because carotenoids like vitamin A are fat soluble, they many still be entrapped within vegetable matrices which can impair the absorption by the human body (Damodaran et al 2008). The cooking methods allowed these nutrients to release from the entrapped matrices and become more bioavailable. The raw form had the highest vitamin E antioxidant composition (0.35 ± 0.01 mg/100), followed by the fried samples at 10 and 15 minutes, respectively (0.33 ± 0.01 mg/100 and 0.32 ± 0.01 mg/100), and lastly, the baked samples at 15 and 20 minutes, respectively (0.29 ± 0.01 mg/100 and 0.26 ± 0.02 mg/100). Chukwu and others overall chose baking as the best method to retain vitamin A and C

(Chukwu et al 2012). In Abdulla and others research (2014), sweet potatoes were obtained fresh from an Egyptian market and pretreated with citric acid prior to frying and drying. The vitamin C content was measured in all samples. The vitamin C content in raw sweet potatoes was 63.38 mg 100g⁻¹. The vitamin C content decreased with increased drying time, but the citric acid pre-treatment enabled the retention of more vitamin C during the drying and frying process than only blanching and drying treatments (Abdulla et al 2014). Although the skin is not usually consumed from sweet potatoes, Padda and Picha (2008) found that the skin had the highest phenolic and antioxidant capacity compared to the inner tissue types, cortex and pith, after baking in a conventional oven, microwave oven, and boiled. The phenolics of the inner tissue could be forming other macromolecules when the heat treatments are applied. The antioxidant capacity of the sweet potato skin was similar to blueberries, which are regarded as fruit with high antioxidant capacity (Padda and Picha 2008).

Carotenoid content is high in sweet potatoes, but processing methods such as boiling, steaming, drying, and frying can reduce the carotenoid content. Bengtsson and others (2008) evaluated the retention of provitamin A carotenoids in boiled, steamed, deep-fried, dried orange fleshed sweet potatoes. Sweet potatoes were cooked in the following treatments: Boiled for 20 minutes, steamed at 93°C (199.4°F) for 30 minutes, deep-fried in sunflower oil at 160 - 170°C (320 – 338°F) for 10 minutes, oven dried in a forced-air cabinet at 57°C (134.6°F) for 10 hours, solar dried in a tunnel solar dryer at 45-63°C (113-145.4°F), and open-air sun dried at 30-50°C (86-122°F). The retention of all-trans-β-carotene did not significantly differ between boiling, steaming, and frying. The all-trans-β-carotene content ranged from 70-81% in boiled samples, 69-81% for steamed samples, and 76-80% for deep-fried samples (Bengtsson et al 2008). Da Silva and Moreira (2008) explored various frying methods and found that the vacuum frying

method did not decrease the carotenoid content as much as traditional frying. Vacuum frying had 20-50% higher total carotenoids compared to deep frying (Da Silva and Moreira 2008).

Bengtsson and others (2008) emphasized that deep-frying did not reduce the β -carotene content much when compared to other methods, such as steaming and boiling. The all-trans- β -carotene content was reduced by 12% in oven dried samples, 9%, in solar-dried samples, and 16% with open-air sun dried samples. None of the dried samples were significantly different from each other in all-trans- β -carotene content. The researchers did conclude that the nutritional content of the sweet potatoes was still acceptable in steamed, boiled, fried, and dried samples (Bengtsson et al 2008).

The proteins in sweet potatoes vary with cultivars and can be affected by heat processing. Sun and others (2012) evaluated the sweet potato protein in the variety, Mi xuan No. 1. The researchers isolated the sweet potato protein and compared it to soy protein isolate and whey protein isolate after boiling, microwave boiling, drying, and autoclaving. The protein content of sweet potato protein was 69.0 ± 0.6 g/100g. The essential amino acid content was 402 mg/g protein, which was 40% of the total amino acid content, and this was higher than soy protein isolate but lower than whey protein isolate. The ratio of essential amino acids to non-essential amino acids was 67%. Sweet potato protein had higher contents of threonine, valine, phenylalanine, and tyrosine than soy protein isolate and whey protein isolate. Lysine was the first limiting amino acid in sweet potato protein. The first limiting amino acid can vary according to cultivar and storage conditions. Sweet potato protein in vitro digestibility significantly improved after boiling, microwaving, and autoclaving. Autoclaving was the most effective method since the in vitro digestibility of sweet potato protein increased from 52.8% to 99.2% compared to boiling at 100°C (212°F) for 20 minutes ($77.2 \pm 0.1\%$), boiling for 1 hour ($85.7 \pm 1.4\%$),

microwave boiling at 700W for 3 minutes ($94.1 \pm 1.8\%$) and drying at 130°C (266°F) for 1 hour ($54.7 \pm 0.4\%$). The most effective methods from best to least of heat processing on sweet potato protein in vitro digestibility were autoclaving, microwave boiling, boiling, and drying. The researchers theorized that the heat treatment allows the proteins to be more available for enzymatic attack. Sun and others concluded that autoclaved sweet potato protein could be utilized as a good protein source (Sun et al 2012).

Some research has investigated acrylamide formation in sweet potato products. Asparagine and reducing sugars are the main components that form acrylamide during the heat processing of foods. Truong and others (2014) assessed the mitigation strategies of acrylamide formation in sweet potato french fries as a result of common french fry practices. Sweet potatoes were washed, peeled, and cut into strips. For the first treatment, the fries were only cut and fried and not soaked or blanched. In the second treatment, the fries were blanched at $95 \pm 2^{\circ}\text{C}$ (203°F) for 3 minutes, soaked in 0.5% sodium acid pyrophosphate solution, air dried, and fried at 165°C (330°F) for 1 minute in canola oil. The third treatment was similar to the second treatment with an additional soaking step in 0.4% calcium chloride solution prior to drying. All the samples were frozen and re-fried at 165°C (330°F) for 2, 3, and 5 minutes. Blanching and soaking treatments, in water or calcium chloride, decreased the glucose, fructose, and sucrose contents, which was about 17% reduction in total sugar levels in the raw sweet potato strips. The maltose content increased in all three treatments because the starch converted over to maltose as a result of amylase activity. The sugar levels were not much affected by the par-frying step. The reducing sugars (glucose, fructose, and maltose) were 50.21-59.93 mg/g and sucrose was 52.34-70.55 mg/g in the final fried samples. The amount of asparagine was found to be lower in sweet potatoes than in white potatoes. The level of asparagine was 0.66 to 0.88 mg/g fresh weight

compared to white potatoes with 1.5-17.7 mg/g fresh weight. The acrylamide concentration in the par-fried samples linearly increased from 125-452 ng/g fresh weight during final frying for 2, 3, and 5 minutes, which was within the 50-1823 ng/g acrylamide range found in white potato french fries. Blanching and soaking in sodium acid pyrophosphate significantly reduced the acrylamide content to 16, 37, and 58 ng/g in the final fried product for 2, 3, and 5 minutes, respectively. The researchers attributed this reduction to the leaching out of reducing sugars and asparagines in the blanch process. Soaking in acidic solutions, such a sodium acid pyrophosphate, reduced the acrylamide and pH from 6.2 to 5.2. The asparagine amino groups at this low pH are protonated, which prevents Schiff base intermediates in the acrylamide formation. Also, calcium chloride helped reduce the acrylamide content to 6, 18, and 35 ng/g in the final fried product at 2, 3, and 5 minutes, respectively. The calcium cation was hypothesized to interact with asparagine and prevent the Schiff base formation (Truong et al 2014).

Purple fleshed sweet potato chips were assessed for acrylamide formation treated with different frying oils (Lim et al 2104). The researchers found a 1.976 ± 0.006 mg/g dry basis of asparagine which is equivalent to 0.68 mg/g fresh weight. This was within the range of asparagine content that Truong and others found. The various vegetable oils used were palm olein, coconut oil, canola oil, and soya bean oil. The mean acrylamide content was highest when soya bean oil was used (2019 $\mu\text{g}/\text{kg}$) and lowest for palm olein (1443 $\mu\text{g}/\text{kg}$). The average acrylamide content for coconut oil and canola oil were 1722 and 1711 $\mu\text{g}/\text{kg}$, respectively. The researchers attributed the low acrylamide content in the palm olein samples to the saturation of the fats, which are less prone to oxidation. The samples were re-fried for 10 consecutive sessions, which led to an increase of acrylamide content in the sweet potato chips and free fatty acids in all of the vegetable oils (Lim et al 2014).

Conclusion

Sweet potatoes are an important crop and are an increasing trend with consumers in the form of french fries. The processing techniques used to make sweet potato french fries can affect the color, texture, and nutritional composition. Peeling is the first step to make french fries, and steam peeling is the most common method used by french fry manufacturers. Lye peeling can be too expensive due to disposal of chemicals, and flame peeling can impart burnt flavors. Evenness of color can be affected by the peeling time. For blanching methods, hot water blanching is the most commonly used method amongst french fry manufacturers. Low temperature blanching technology may not deactivate enzymes nor give the consumer-desired texture. Sucrose and salts added during the blanching process may stabilize enzymes, and these ingredients should not be added until after the enzymes are deactivated. High blanching temperatures deactivate the enzymes that lead to discoloration and poor quality product. Blanching may help retain some moisture after drying. Drying should not be done too hot or too quickly because this may cause case hardening and deform the structure of the french fry. Methods such as vacuum drying may lead to more appealing color, but this may be difficult to conduct in large scale manufacturing. Drying, overall, can help reduce oil uptake during frying. Shorter frying times may lead to less oil uptake as well as higher frying temperatures. The oil type can also affect the amount of oil absorbed into the finished product. Moisture loss during frying may correlate to oil uptake in sweet potato french fries, but the sweet potato cultivar and the cellular structure can affect the oil uptake. All french fry methods may reduce the antioxidant content, but protein content may become more bioavailable with heat processing. Consumer acceptability should be taken into consideration as each method can affect the appearance, texture, nutritional composition, and flavor of sweet potato french fries.

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