# ABSTRACT

NSHIMIYIMANA, EMMANUEL. Application of Windhexe Dehydration Technology for Producing ß-carotene Rich Flours From Sweetpotatoes. (Under the direction of Dr. Van-Den Truong.)

Sweetpotato ranks seven among the most important food crops in the world. With high carotene content, the orange-fleshed cultivars have a great potential in combating vitamin A deficiency (VAD). Processing sweetpotato into flour would increase its shelf-life while providing good quality food during off-season. Various dehydration technologies such as hot air drying, drum drying, and spray drying have been used to produce sweetpotato flour. However, these technologies are labor intensive and time consuming. Due to the demand of sweetpotato flour as an ingredient in food processing industry, there is a need to develop more efficient dehydration technologies to produce sweetpotato flour. Sweetpotato flour processing requires washing, peeling, slicing or shredding, soaking, blanching, and drying. All these steps are associated with nutrient losses and increases in cost of production. Vortex dehydration technology® (VDT), also known as the Windhexe, was introduced by GreenShift CleanTech Corporation. This technology simultaneously pulverizes and dries any material using heated, compressed air and with this technology, food materials do not require pre-drying treatments that are usually performed for all commercially available drying technologies. This study aimed to investigate the efficacy of VDT in processing orange-fleshed sweetpotato (OFSP) into beta-carotene rich flours and evaluate the nutrient retention and physical properties of Windhexe OFSP flour as compared to the flours produced by hot air drying (HD) and freeze-drying (FD). Windhexe technology required less drying time and labor yet it produced OFSP flour at 110$^{o}$C with higher nutrient retention as compared to the most commercially feasible drying technology, hot air drying.

The Windhexe achieved a significant retention of carotenoids as well as total phenolic and ascorbic acid as compared to hot air drying ($p<0.05$) though lower than that achieved by freeze drying. Smaller mean particle size and more homogenous distribution was observed for the Windhexe flour, whereas both freeze drying and hot air drying produced flours with larger particle size and a less homogenous size distribution. Smaller particle size of the Windhexe dried flour makes it suitable for application in food products where uniform dispersion is desirable for acceptable consistency of end product. Blanching and long drying time negatively affected the pasting properties and color of the hot air dried flour. Windhexe drying produced a pre-gelatinized flour with a high cold paste viscosity appropriate for use as thickening ingredient. Overall results demonstrated that Windhexe dehydration technology can produce OFSP flour that can be used as a functional ingredient in food processing. Further research can focus on energy consumption of Windhexe dehydration technology as well as its process optimization for industrial applications.

# Application of Windhexe Dehydration Technology for Producing ß – Carotene Rich Flours from Sweetpotatoes

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# DEDICATION

For Constance Uwambaye who taught me how to read and write as a kid.

For the families, Papias Kazawadi, Theophile Ruzindana, Charles Niyomugabo, Etienne Munyanziza and Mbaga Nzabakurana, for all the support you provided for me throughout my academic pathway.

# BIOGRAPHY

Emmanuel Nshimiyimana was born and raised in Kigali, capital city of Rwanda on a brighter morning late October, 1979. His childhood was full of outdoor and church activities. He attended Lycee de Kigali high school and became intensely fascinated with biology and chemistry. At the age of 14, he survived genocide in his country that took away the lives of his parents, and many of his aunts, uncles, cousins and childhood friends. Seven years later, he earned a government scholarship and went to National University of Rwanda and graduated with a Bachelor degree in Agricultural Sciences. Emmanuel worked as a teaching assistant at the Higher Institute of Agriculture and Animal Husbandry in Rwanda before earning a highly worldwide competitive Fulbright scholarship to pursue his graduate studies at North Carolina State University. He began a Master’s program in food science under the supervision of Dr. Van-Den Truong. Next, he is starting a six month apprenticeship in quality assurance and operations management at *Butterball, LLC*. Mt. Olive, NC. He is excited to see what the future holds for him.

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# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

Sweetpotato *(Ipomea Batatas)* is an important vegetable. It is a nutritious food crop with high potential use in human food system, though it is under-utilized (Van Hall, 2000; Walter et al., 2002). Sweetpotato is different from regular potato *(Solanum Tuberosum)* commonly called Irish potato and from tropical yam *(Dioscorea Alata)*. The Nutrition Action Health Letter rated sweetpotato as number one, with 582 points, followed by raw carrot with 434 points, among 58 vegetables, after summing up the fractions of recommended daily allowance (RDA) for Vitamin A and C, folate, iron, copper, calcium, and fiber (Farinu and Baik, 2007; Cummings, B. (2005). The Center for Science in the Public Interest (CSPI) classified common vegetables based on their nutritional value and sweetpotato, once again, received the highest score of 184 points whereas regular Irish potato scored 83 after a similar preparation (Farinu and Baik, 2007; Cummings, B. (2005). In the United States, sweetpotatoes are grown mainly in the southern states of North Carolina, Louisiana, Mississippi and Texas and its popularity increases. However, beyond raw roots for fresh markets, there are still very few products derived from sweetpotato and due to its high moisture content, sweetpotato storage and handling is a challenge.

Therefore, sweetpotatoes as any other tropical root crops can be preserved by converting them into flour using dehydration techniques (Iwuoha et al., 1998; Avula et al., 2007, Truong and Avula, 2010). By reducing water activity, dehydration transforms the perishable sweetpotatoes into a stable product and extends shelf-life much longer than that of raw fruits and vegetables (Zhang et al., 2006).

Sweetpotato flour (SPF) can be used as ingredients in processed sweetpotato products including soups, sauces, snacks, noodles and bread (Chun et al., 2006). The functional properties of the flour could depend on, among other factors, the varieties, handling history, as well as drying technology.

Drying technologies are quite diverse in research and commercial application (Barbosa-Canovas, 2004). Several drying methods have been used for the production of SPF including sun drying (Agwunobi, 1999), hot air drying (Prabhavat et al., 1995), drum drying (Valdez et al., 2001) and spray drying (Grabowski et al, 2006). Generally, the choice of a drying technology depends on its efficiency in terms of energy consumption, final food quality, and cost involvement (Humberto et al., 2001). Therefore, it is essential to know the pros and cons of the available dehydration technologies in order to, not only make a right choice for commercial application, but also to study for improvement that may lead to the development of new technologies.

Solar drying is the oldest drying method but it has many disadvantages which limit its use for intensive industrial production. As it is exposed to the outside environment, the material being dried is subject to microbial contamination as well as insect infestation. Moreover, it needs a wide space, high labor inputs and it is difficult to control the drying rate (Yang et al., 1995). Cabinet drying operates in batches and it is difficult to obtain uniform drying rates at different locations within the system. Freeze drying is a slow and expensive process (Liapis et al., 2008). On the other hand, drum drying necessitates food material to be transformed into purees and pastes prior to dehydration that reduces the nutrient retention and possibly cause off flavor and color degradation due to direct contact with high temperature at drum surfaces (Woolfe, 1992). Additionally, all the above mentioned drying technologies have preliminary operations such as peeling, cutting and slicing or pureeing. These processes result in cell breakdown with subsequent increased enzymic activity and microbial growth which, in turn, may affect some of the sensorial qualities such as texture and flavor (Pretel et al., 1998).

The Windhexe dehydration technology is believed to provide a solution to cope with the aforementioned needs. This technology is performed using Windhexe apparatus invented in 2002 by Polifka (2002). In his patent, Polifka (2002) defined Windhexe as a material grinding apparatus in which high velocity compressed air is introduced in a vortex flow to perfom grinding and drying of diverse materials in a one-step process. The materials that can be processed include but not limited to, glass, grain, paper, plastic, aluminum and granite (Polifka, 2002). Since its invention, several researchers have applied the Windhexe to grind several food materials and have filed patents for processing coffee beans (Arora et al., 2005), edible seeds, producing granular chocolate-base materials and manufacture of grated cheese (Shah et al., 2006; Kopp et al. 2007). However, none of these developments have applied to make the sweetpotato powder that can be used as ingredient in food processing industry.

The objective of this study is to investigate the efficacy of using windhexe dehydration technology to process the orange-fleshed sweetpotato into ß-carotene-rich flours as compared to other two drying technologies namely hot air and freeze drying technologies.

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# CHAPTER 2: LITERATURE REVIEW

## 2.1 Drying in food processing

Food drying consists of a partial removal of water to an extent that stops microbial growth and spoilage of the dried food, thereby increasing food shelf-life. At the beginning, drying was conducted traditionally by the use of sun energy. However, scientific improvements have lead to the current and sophisticated drying technologies including, but not limited to, kiln drying, tray drying, spray drying, freeze drying, osmotic drying, microwave drying and Refractance window drying (Humberto et al., 2001). The development of dehydration technologies can be divided into four groups or generations.

### 2.1.1 The first generation

The first generation includes cabinet and bed dryers (i.e., kiln tray, truck, tray, rotary flow conveyor, and tunnel). In this category, solid food products such as sliced fruits and vegetables, and grains are suitable. The hot air flows over the product and removes water on the external surface by evaporation.

#### 2.1.1.1 Cabinet drying

The basic design of cabinet dryers consists of a feeder, a heater, and a collector (Barbosa and Humberto, 1996). This technique is an improvement of solar drying. The solid foodstuffs are exposed to a continuous flow of hot stream of air and evaporate the surface water from the products. The final dried product can have a significantly increased shelf-life, although the quality is significantly reduced comparatively to that of the original fresh food material (Ratti, 2001).

### 2.1.2 Second generation

Spray driers as well as drum dryers are the main dehydration technologies classified in the second generation. They are typically used for dehydration of slurries and purees to produce dehydrated powders and flakes.

#### 2.1.2.1 Spray drying

Spray drying technology is a suspended particle processing operation and consists of four fundamental steps: atomisation, contact between droplets and hot gas, water evaporation and gas-powder separation (Masters, 1991). It is industrially used for drying liquid foods and other heat sensitive materials (Sagar and Suresh, 2010). Additionally, emulsions, gels and colloidal suspensions are perfectly spray dried (Nindo and Tang, 2007), and the main attribute that distinguish spray drier from other drying technologies is its ability of atomizing the liquid into fine droplets and drying (Humberto et al., 2001). The temperature varying between 150$^{o}$C and 240$^{o}$C have been used in spray drying. The output product consists of uniformly sized and spherical powder particles moslty in hollow-bead form (Cohen and Yang, 1995). Spray drying has been used for an extensive range of product such as instant coffe, tea, powdered milk, orange and purple-fleshed sweetpotatoes (Gurkin et al, 1972; Chaveron et al, 1977; Grabowski et al., 2006; Esther et al. 2009; Ahmed et al., 2010).

Some food materials are not easily spray dried. The rapid evaporation conditions created in spray drying, enhance some of puree or sluries rich in carbohydrate to form amorphous materials which lead to the glass-transition state accompanied by stickiness problems (Chen et al., 2007). Additionally, when drying involve high fat, high sugar or high viscosity materials, the low melting point components or the amorphous nature of the food product can cause an immense deposition within the drying chamber (Chen and Patel, 2008).

A special pre-treatment to reduce excessive oil prior to atomization would facilitate the spray drying process. Grabowski et al. (2006) had found out that the increase of processing temperature, coupled with the use of alpha-amylase, worked effectively in reducing the sweetpotato puree viscosity prior to spray drying. Also, they found that in addition of amylase treatment, maltodextrin facilitates the increase of glass transition temperature thus reducing the stickiness and increasing the spray dried sweetpotato yield (Grabowski et al, 2006).

Several researchers have worked on spray drying technology (Masters, 1991; Cohen and Tang, 1995; Nindo and Tang, 2007), and they have found that effective control of product properties, continuous operation, a very short drying time are the main advantages of the spray drying technology. However, the inability to produce high bulk density materials and the high initial capital investment are major disadvantages.

#### 2.1.2.2 Drum drying

In drum drying, hot air stream is introduced inside the drum, either co-currently or counter currently and the wet food material is continuously applied to the surface of the heated drum. Throughout the drying process, three major phenomena take place. First, due to a big difference of temperature between the drum surface and the wet product, the intensive heat is transferred through a thin layer of the wet material and this is called initial heating phase. Second, when the moisture within the wet material reach the boiling temperature, there is an evaporation of a large amount of free water and the product temperature remains constant. This constitutes the constant product temperature phase. Additionally to this phase, there is a decrease of the drum surface temperature caused by an important evaporative cooling.

Finally, in rising product temperature phase, most of free water is removed, there is a dramatic reduction of moisture by evaporation and the heat transferred from the steam progressivelly surpass the required energy for evaporation. Consequently, the drum surface temperature increases.

Drum dryers are designed in single, double or twin and the application of food material differs accordingly. The solid content, viscosity and wetting ability of the product are the factors which determine the appropriate feeding technique. Distinctively, five feeding methods are commonly used. The first method is roll feeding; this technique is used in both single and twin drum dryers and its maximum potential is achieved for viscous and glutious materials. The second method is nip feeding. Considered to be the simplest feeding technique, nip feeding is suitable for thin solutions such as milk and whey applied on double drum dryers. Dipping is the third feeding technique appropriate for suspensions of solids. In this technique, a single rotating drum is immersed on a tray containing the product and the latter adheres to the rotating drum surface. The fourth technique, spraying, consists on the atomization of the product using the nozzle on a single drum surface. Splashing is the fifth drum dryer feeding method and is suitable for high sedimentation rate products (Tang et al., 2003).

The yield of drum dryers is affected by the type of food material, the initial and targeted final moisture content as well as other operating conditions. It was found that its production varies between 5kg and 50kg per meter square (Hall et al., 1986) and the energy use of drum driers ranges from 1.1 kg steam per kg of evaporated water. This corresponds to 60% - 90% of energy efficiency (Moore, 1995; Hall et al., 1986; Nindo and Tang, 2007). Thus, for dehydration of high viscous liquids, drum drying is considered as the most energy efficient technique (Hui et al., 2004).

Some of the drum dried products include milk products, baby foods, breakfast cereal, fruits and vegetable's pulp, mashed potatoes, cooked starch, yeast creams, maltodextrins, (Vallous et al., 2002, Rodrigues et al., 1996), and sweetpotatoes (Walter and Albert., 1976, Manlan et al., 1985, Valdez et al., 2001; Truong and Avula 2010).

The advantages of using drum driers relate to their ability to process high viscosity puree and gelatinized or cooked starch. The drum dried products have demonstrated a good porosity due to boiling evaporation and this results in good rehydration. The operation and maintenance of drum driers are easy and since the whole process takes place at the surface of the drum, they are easy to clean as well. However, their yield is relatively low comparatively to spray drying, and changing drum surface can be costly due to precision engineering required. Also, a potential cook flavor and color degradation caused by a direct contact of the product with high temperature drum surface has been associated with drum drying.

### 2.1.3 Third generation

Third generation of drying technologies includes freeze drying and osmotic drying. While freeze drying was developed to overcome structural damages and minimize losses of heat-sensitive nutrients, flavor and aroma compounds, osmotic dehydration is mainly intended for processing fruits and vegetables by immersion in a hypertonic solution (i.e., sugar, salt, and glycerol)

#### 2.1.3.1 Freeze drying

Also known as lyophilization, freeze drying has various steps including freezing, vacuum, sublimation, and condensation (Ratti, 2001; Wassim et al. 2006) divided the freeze drying process into three steps: freezing (solidification), primary drying (ice sublimation), and secondary drying (desorption of unfrozen water) whereas Krokida et al. (1998) divided freeze drying into two steps: freezing and sublimation. In any case, freeze drying is based on the principle that, under high vacuum, frozen water can be removed from a food and collected without going through a liquid phase (Mujumdar, 2007). Freezing must be rapid to obtain a product with small ice crystals and in an amorphous state (Wassim et al., 2006; Mellor, 1978). Freeze drying is known to be the best drying technology which results in final products of the highest quality (Sagar and Suresh, 2010; Cohen and Yang, 1995). Some of these high-quality characteristics include low bulk density, high porosity, superior taste and aroma retention, as well as better rehydration properties (Krokida et al., 1998). In freeze drying, the product is frozen in the first phase. In the second phase, the ice crystals are removed and leave a porous structure. This preserve the final product’s structure, thus enabling a rapid dehydration and prevent the loss in sensory qualities (Humberto et al., 2001,Cohen and Yang, 1995).

However, freeze drying is slow and additional energy is required to run the compressor and the refrigeration units. This makes it an expensive drying method, suitable for high price products, mostly pharmaceuticals, or those that are very sensitive to sensory deterioration.

### 2.1.4 Fourth generation

Fourth generation dehydration technologies includes microwave drying, fluidized bed drying, refractance window (RW) drying, and other hybrid technologies described by Chou and Chua (2001). Considering the final quality of the product being dried, as well as physico-chemical properties of the raw material to be processed, all these technologies are different from each other. Nevertheless, microwave drying interests have been increased within the research communities and the food industry due to its potential ability of saving energy (Vega-Mercado, 2001; Santos and Silva, 2008).

#### 2.1.4.1 Microwave drying

In microwave drying, a wet solid is exposed to microwave heating and its temperature rise to the boiling point of the liquid. The internal evaporation of moisture generates vapor with a pressure gradient that can rapidly expel the moisture from the interior of the solid (Metaxas and Meredith, 1983). This mechanism of generating heat, is a result of molecular friction within the food product and enables microwave to dry foods, which is a distinct characteristic and advantage of microwave. Other advantages of microwave dehydration include less start up time, faster heating, energy efficiency (Torring et al., 2001), space savings, precise process control, and food product with better nutritional quality (Shams et al., 1999; Sumnu, 2001). Additionally, the moisture content is removed without developing case hardening (Schiffmann, 1986; Walde et al., 2002); this is caused by little solute migration in the liquid phase (Decareau, 1992).

A number of drawbacks are associated to microwave drying and limit its application. One of them is the inherent non-uniformity of the electromagnetic field within a microwave cavity. During the final phase of microwave drying, there is a limited amount of available water within the product. Therefore, temperature control within the product becomes a challenge and a small rise can provoke scorching (Zhang et al., 2006). Also, the penetration depth of the microwave field into the product and a fast mass transfer by microwave energy may result in quality damage or detrimental modification of the food texture by puffing (Nijhuis et al., 1998; Wang and Chen, 2003).

Many food products have been dried using microwave technology. These includes, but not limited to, wheat (Walde et al., 2002), parsley, (Soysal, 2004), potato slices (Bouraoui et al., 1994), spinach (Ozkan et al., 2007), okra (Dadah et al., 2007), apple (Andres et al., 2004), oregano (Soysal et al., 2009), mushrooms (Torring et al., 2001) and pumpkin slices (Alibas, 2007).

#### 2.1.4.2 Refractance window

Refractance window (RW) drying was developed by MCD Technologies, Inc. (Tacoma, Wash., USA). This technology uses circulating water heated at 95$^{o}$C to 97$^{o}$C as a way to transfer sensible heat to the food that is being dried. The food material is processed into puree prior the actual dehydration and is spread on a transparent thin plastic conveyor belt moving over circulating water (Abonyi et al., 2001). The belt is thin (0.2 mm) and its velocity ranges between 0.6 to 3 m/min. The product is deposited on the belt as a thin layer of 0.2 – 1 mm thick. This technology uses conduction and radiation as means of heat transfer. When the food material is still wet, a window serving passage for infrared is opened at all surface areas of the belt containing the food material. Thus, the conduction is coupled with radiation. The radiation works perfectly because the liquid contained in the food material absorbs electromagnetic energy in the wavelength between 3.0 to 15.3 μm. As the moisture content reduces, this window is continuously closing leaving conduction as the principal mean of heat transfer (Kudra and Mujumdar, 2002). The food puree or other liquid biomaterials are processed into sheets, flakes, granules and powders. The drying time is usually 3 – 5 min and the dried product e.g. berries have excellent retention of color, vitamins, and antioxidant (Nindo and Tang, 2007). Refractance window is mostly suitable for dehydration of fruits and vegetables in which the quality and nutrient retention is of great importance (Clarke, 2004).

Several researchers have evaluated the efficacy of RW and reported that ascorbic acid retention in strawberry purees dried with the RW system was comparable to freeze-dried products (Abonyi et al., 2001). Also they realized that total alpha- and beta- carotene retention in carrot purees after RW drying were comparable with freeze-dried samples and much higher than in drum dried products. Caparino et al. (2011) investigated the physical characteristics and microstructures of mango powder produced from RW, freeze drying, drum drying and spray drying. They found out that RW drying can produce mango powder comparable to that obtained via freeze drying, and of better quality than the drum-dried and spray-dried mango powder. In their review, Nindo and Tang (2007) stated that only 9.9% loss of beta-carotene in carrots occurred with RW drying compared to 5.4 and 57% in freeze and drum drying, respectively and the color of RW dried carrot purees was comparable to the fresh puree. However, the overall perception of aroma was altered in RW dried strawberries. The RW technology developer claims that 94% of vitamin C and natural color, flavor, aroma, are retained in dried RW products. Scrambled egg mix, avocado fruits for dips, high carotenoids-containing algae, herbal extracts and nutritional supplements for human use, food ingredients such as herbs, spices, and vegetables have been dried using RW technology (Abonyi et al., 2001, Nindo and Tang, 2007). The consistency and the homogenous spreading of the raw material on the conveyor belt are the key factors determining the efficiency of the RW technology (Nindo and Tang, 2007).

The advantage of RW is that the dried materials are of high quality and the equipment is relatively inexpensive. Kudra and Mujumdar (2002) pointed out that RW equipment is less expensive and less energy consuming as compared to the freeze drying of the similar output capacity, and yet the quality of the dried product is comparable.

## 2.2 Grinding operation in dried food processing

Grinding is an important unit operation in powder processing in the food, pharmaceutical, ceramic and chemical industries. Various techniques are used depending on the nature of the material being ground, the source of energy, and the targeted quality.

The final product is the flour, and the particle size and distribution as well as particle morphology are the key powder properties that determine its quality.

### 2.2.1 Jet Milling

Jet mills are typically used in the industry for grinding solid materials. Particles are subjected to repeated actions of impact between them which result in size reduction (Levy and Halman, 2007). Two main and interdependent phenomena that occur within a jet mill chamber are the comminution and transfer of particles. The solid material is pushed into a chamber by an air-pusher located in the feeding hopper and high pressure air is introduced by nozzles located on the sidewall of the cylindrical chamber. Once reached the chamber, the particle velocity increases up to 200 m/s and the collision between them creates comminution (Gommeren et al., 2000). Depending on their size, the resulting particles are sorted out by a rotating flow of air, and the larger particles are towed to the central outlet. This is how the particle transfer or classification occurs in a jet mill.

Various researchers (Tuunila and Nystrom, 1998, Rajendran et al., 1992, Ramanujam and Venkateswarlu, 1970) have tried to understand jet milling process through different experiments and how to control the parameters that affect its efficiency. They have found that the feed rate and volumetric flow rate of grinding air are the main parameters that influence breakage and chipping of the particles. The increase of air velocity increases the particle velocity, hence the breakage rate increases. However, Katz and Halman (2007) found out that increasing the air flow rate increases the breakage but it takes larger and unbroken particles to the outlet. Also, Katz and Halman (2007) designed an experimental apparatus enabling the inclusion and changing of many parameters which influence the performance of jet mill and they found that a jet mill performance depends on the material size and the total flow rate.

There are many types of jet mills incuding spiral or loop jet mills, impact and counter flow jet mills. All of them use a fluid energy to accomplish grinding and the impact breakage mechanism (Midoux et al., 1999). The pharmaceuticals, chemical and food industries use fine particle powders that are processed using the Jet mill technologies (Molina-Boisseau et al., 2002). Many advantages have been noticed for the Jet mills. Some of them includes the ability to produce micron-sized particles by autogeneous grinding, capability to grind heat sensitive materials, and low noise (Midoux et al., 1999). Nevertheless, the energy consumption of the jet mill remains a major concern for this technology. Mebtoul et al., (2000) stated that only 2% of the energy supplied to jet mill is used for particle breakage.

Other grinding methods includes, mechanical impact mills, classic rotor impact mill, pin mills with two rotating pin discs (desintegrators), long gap mills, fine impact mills with air classifiers, jet mills, spiral jet mill and fluidized-bed jet mills have also been used.

### 2.2.2 Windhexe

Windhexe was invented as a grinding apparatus by Francis K. Polifka (2002). It was designed to efficiently and easily grind, dry and dehydrate various products. Discarded materials in landfills occupy a high volume of space and it was desirable to have an apparatus that could grind different materials disposed in the landfills. This invention uses high velocity compressed and heated air to achieve grinding and drying in one step process.

Windhexe aparatus is made up of different parts; an annular upper enclosure defining an upper chamber, a conical lower enclosure defining a lower chamber, the feeding hopper and the exhaust pipe. The material to be ground is introduced in the upper chamber from above through the feeding hopper and the compressed air is introduced through 2 angled slots located on the sidewall of the upper chamber. The compressed air generates a circular vortex flow which collides with the chamber sidewalls resulting in grinding of the material and consequently drying takes place if the heated compressed air is used. However, the exact mechanism that pulverrizes the materials within the apparatus is not known (Polifka, 2002).

The compressed air introduced into the upper grinding chamber may have a pressure ranging between 10 to 600 psi, with air exchange velocity that falls within a span of 5 to 12,000 cfm. The compressed air temperature may be raised from 5$^{o}$C to 480$^{o}$C to enhance the grinding and drying of the material. If the steam is used to heat the compressed air, its temperature will vary between 100$^{o}$C and 1093$^{o}$C (Polifka, 2002). The air velocity, temperature and material properties have effects of the pulverizing performance of the Windhexe.

Other grinding apparatus which use the compressed air have been patented before, including apparatus for desintegrating pulp, (Stobie, 1914), compressed air insecticide dispenser (Burmeister et al., 1944), anvil grinder (Trost, 1951), rectilinear pulverizer (Chatelain et al., 1954), apparatus for comminuting materials (Kocher, 1962), and comminuting material in a re-entrant circulating stream mill (Andrews, 1981), solids reducing and mixing device (Jackson, 1981), apparatus for forming spheres (Knepprath et al., 1991), and jet mill as well. Each of these apparatus have its own advantages and disadvantages and so does the Windhexe.

Windhexe could potentially have many applications, it performs grinding and drying in one operation, hence reducing dramatically the labor and processing time (Polifka, 2002) Several marerials including glass, grain, paper, plastic, aluminum and granite, animal products, agricultural products, various animal wastes as well as well as their byproducts can be ground and dried using the Windhexe (Polifka, 2002). However, energy consumption as well as the quality of the products processed by this technology need to be evaluated.

## 2.3 Changes in sweetpotato nutrient during dehydration

### 2.3.1 Carotenoids

Woolfe (1992) found that 86.4 – 89.0% of total carotenoids in orange sweetpotato are constituted by β-carotene and their structure is characterized by a large number of double bonds. Food dehydration, as any thermal processing method, affects β-carotene content in sweetpotato. The structural change of carotenoids during dehydration is attributed to oxidative degradation and geometrical isomerisation (Rodriguez amaya and Delia 1997). Exposure to oxygen during dehydration is the main cause of carotene oxidation (Von Elbe and Schwartz, 1996). It occurs through a free radical reaction and results in formation of epoxides, carbonyls and alcohol, loss of color and provitamin A activity. In isomerization, the all *trans* β-carotene with high vitamin A activity change to *cis*- β-carotene, typically 9-cis, 13-cis and 15-cis isomers, with low pro-vitamin A activity.

Research efforts have demonstrated the effect of various dehydration methods on degradation of carotenoids. Lawrence et al. (1988) investigated the isomerization and loss of *trans*-ß carotene in sweet potato during various heat treatments and demonstrated that drum dried flakes contained a great amount of 13-*cis* carotenoids isomers (28.9%) with a substantial oxidative degradation of β-carotene (20.5%). Also, they stated that the quantity of isomers formed is proportional to the intensity and length of heat treatment applied.

In his experiment using hot air drying, Van hal (2000), studied the degradation of β-carotene at three different temperatures; 60°C, 70°C and 80°C. The result showed a less degradation as the temperature was decreasing at any particular time. Woolfe (1992) stated that when small strips of sweetpotato were dried in a cabinet dryer beginning at 70°C and reduced to 50°C over a period of 6 hrs, the loss of carotenoids, mainly β-carotene, was about 20% for each of the two indian cultivars (Woolfe, 1992; Van Hal, 2000).

Bengtsson et al. (2008) analyzed the effect of various tradition processing methods,including hot air drying, on the *all-trans*-β-carotene content of orange-fleshed sweetpotato in Uganda. They found that roots dried at 57°C for 10 hrs lost 12% of *trans*-β-carotene. Also, with solar drying and open air sun drying, the loss was of 9% and 16% respectively. In the same country, Bechoff et al. (2010) studied the effect of open air sun drying on total carotene degradation, and the losses were up to 15%.

In drying studies in Kenya, Hagenimana et al. (1999) investigated an effect of hot air drying of slices from 24 sweetpotato varieties. The slices were dried at 60°C for 12 hrs and total carotene loss was 30%. Similarly, Kósambo et al. (2004) reported an average loss of 35% after drying 13 varieties of orange-fleshed sweetpotato at 58°C for 4 hrs. However, Mdziniso et al. (2006) found a much lower loss of 4.0 – 5.8% in the USA for solar dried OFSP slices, and Bechoff et al. (2009) reported losses of 16% – 23% in France. In producing spray dried OFS flour, Grabowski et al. (2006) reported a significant decrease of total amount of β-carotene due to isomerisation. The *cis* configuration isomers ranged between 8.7% and 42% whereas in freeze drying, Regier et al. (2005), found no degradation or isomerisation of beta-carotene in carrots.

### 2.3.2 Vitamin C

Vitamin C, also known as ascorbic acid, widely varies between different vegetables. For instance, brassicas contain high levels of 50 -100 mg/100gr. Broccoli, citrus, strawberries, and raspberries are reported to be highly rich in vitamin C (Kalt, 2005). Root crops contain relatively lower (< 10 mg/100gr) but sweetpotato varieties, Beauregard and Hernandez; contain 15.4 and 14.7 mg/100 respectively (McConnell, 2005).

In the food industry, ascorbic acid is mostly used as a nutritional additive, a radical scavenger to prevent the oxidative degradation of lipids in foods (Füger, 2009) as well as index of nutrient quality of processes (Santos and Silva, 2008). Negi and Roy (2000) reported that the retention of the vitamin C varies from one product to another and the drying process applied. Generally, the longer the drying time, the lower the retention of vitamin C (Santos and Silva, 2008). In an effort to improve the retention of vitamin C in paprika dehydration, Kim et al. (2006) modified the conventional hot air drying method of drying the whole paprika at 80$^{o}$C for 5 hrs followed by 60$^{o}$C for 18 hrs into three parts at 70$^{o}$C for 6hrs. The short time and low-temperature drying method resulted in a high retention of vitamin C in paprika. Chang et al. (2006) studied the retention for two varieties of tomatoes dried by hot air and freeze drying technologies. The results showed a significant difference in vitamin C retention of 90% and 50% for freeze drying and hot air drying respectively.

The effect of drying method on vitamin C retention in sweetpotato products was reported by several researchers. Arthur and McLemore (1955) observed a total loss of vitamin C spanning from 50% to 70% in drum dried sweetpotato flakes. Orikasa et al. (2010) evaluated the vitamin C degradation in hot air dried sweetpotato. Four set of temperatures namely, 30, 40, 50, and 60$^{o}$C resulted in vitamin C loss of 38, 61, 68 and 80% respectively.

### 2.3.3 Total phenolics

Chlorogenic acid is the main phenolic compound found in sweetpotatoes grown in the USA and its concentration varied from 117 to 467 mg of chlorogenic acid equivalent/kg of fresh weight (Walter and Purcell, 1979). High temperatures applied during steaming and drying can result in degradation of phenolic compounds (Hamama and Nawar, 1991).

The effect of drying temperature has been studied in red grape pomace peels. Drying at 60$^{o}$C did not significantly affect the total phenolic content. However temperature from 100$^{o}$C and 140$^{o}$C significantly reduced about 18.6 and 32.6% total phenolic content, respectively (Larrauri et al., 1997). In the case of strawberries, hot air drying at temperatures of 60$^{o}$C for 220 minutes reduced the total phenolic content by an average of 35% (Böhm et al., 2006). Rozek et al. (2010) conducted an osmotic dehydration of apple, banana, and potato. They reported the phenolic reduction of 3.7% to 9.0% of the samples dried at 55$^{o}$C and an air flow rate of 4m/s. However, in a recent study, Nayak et al., (2011) reported no significant change in total phenolics for purple potato flakes after drum and freeze drying and significant increase of total phenolics for samples dried with RW.

## 2.4 Sweetpotato powder physical characterization

### 2.4.1 Particle size, Particle morphology and Bulk density

Analysis of physical characteristics is essential not only because they define the flour functionalities but also their influence on the inner-changes of the flour during storage, handling, as well as further processing (Teunou et al., 1999). Particle size is considered as the most important physical property of any flour (Schubert, 1987). Along with particle morphology, they affect powder flow ability.

Sweetpotato is converted into flour for preservation purposes and utilization in various food systems as ingredients and/or processing aids. Several studies (Tian et al., 1991, Chen et al., 2003, Jha and Bathacharrya, 2009) have been conducted on the size and morphology of sweetpotato starch granules but limited information is available on these properties of sweetpotato flours. This can be explained by the fact that sweetpotato is rich in starch that provides distinctive functional characteristics of the flour to be incorporated into specific product formulation (Truong and Avula, 2010).

The processing method may influence the properties of the produced flours. For instance, in spray drying, it has been demonstrated that sweetpotato puree pre-treated by amylase and maltodextrin significantly affected the particle size as well as bulk density of the final OFSP flour (Grabowski, 2006). Additionally, Hsu et al., (2003) studied the effect of drying method on the physical properties of three varieties of yams (*Dioscorea alata* and *Dioscorea purpurea*) they reported that freeze-dried and hot air dried yam flours had a significantly higher bulk density compared to drum dried flour. Sing et al. (2006) investigated the particle size of tomato powder obtained from blanched and unblanched tomato subjected to hot air drying at 60$^oC$ for 16 hrs. They reported that the surface area mean diameter is higher for unblanched sample (200.51 μm) compared with blanched tomato powder (158.71 μm). The blanching treatment minimally affected the grinding/milling quality/size-reduction characteristics and results in uniform particle size. Morphologically, most of the food products fell into the skin forming category (Grabowski, et al. 2006). Morphological features of starch granules of drum dried and hot air-dried sweetpotato flours are similar to each other, and the entire granule population seems to be gathered in an aggregated mass containing several small granules especially in drum drying (Truong and Avula, 2010).

There are various techniques used to measure the particle size, but not all of them are suitable for food flour. Evaluation of laser diffraction patterns is among the most commonly used method (Schubert, 1987). The principle behind a laser diffraction particle size analyzer is that the smaller the particle size, the larger the diffraction angle, thus and the focal length establish the measuring range (Singh et al., 2006). Particle morphology is observed using Scanning Electron Microscopy (ESM) technique.

### 2.4.2 Viscosity

Viscosity is one of the properties among the rheological properties of foods. It is defined as a resistance of fluid to flow (Steffe, 1996). Based on rheological properties, foods are classified into liquid, solid and semi-solid. By heat processing, starches, proteins and other substances are interacted to form either gel, dispersion or viscous solutions depending on processing temperature as well as their concentration in food.

There are two types of instruments used to measure viscosity of fluid and semi-solid foods, Brabender Visco-amylograph and Rapid Visco-Analyzer (RVA). RVA was invented by the Australian CSIRO wheat research unit in collaboration with Bread Research Institute to rapidly estimate sprout damage in wheat (Deffenbaugh and walker, 1989). RVA is a rotational viscometer and use a rotating paddle in the sample at a known speed and controlled temperature. The sample viscosity creates a torque in the opposite direction to the paddle rotation which in turn has to create an equal and opposite torque measured and translated to a viscosity interpretation (Bason et al., 2007). During 1986 – 1987 Australian wheat season, RVA was used to identify sprout damage in individual lot of wheat and has proved successful (Deffenbaugh, 1989). Throughout these analyses, it was noticed that RVA is easy to operate, requires a small sample size and the result is obtained in less than 20 min.

Several studies have been conducted on the evaluation of sweetpotato flour viscosity using RVA (Avula et al., 2006; Collado and Corke, 1999). They all have been able to measure peak viscosity, hot and cold paste viscosities for the sweetpotato flour. Collado and corke (1999) analyzed the pasting characteristics of sweetpotato flour in distilled water and in 0.05 mM $AgNO_3$. The results showed overall low pasting viscosities in the RVA amylograph in distilled water. Avula et al., (2006) investigated the pasting behavior of hot air dried and drum dried sweetpotato flour. They reported a relatively low viscosity of the hot air-dried sweetpotato starch paste compared to drum dried material, although the high heat treatment was applied in drum drying.

### 2.4.3 Water activity and water content

Water activity ($a_w$) is a significant constituent of foods and is defined as the ratio of the water vapor pressure (P) in the food product and the vapor pressure of pure water ($P_0$). It is considered as the reference parameter to assess the stability of the foods in storage and processing. Over the years, researchers have realised that water activity ($a_w$) could be much more significant to the quality and stability of the food than the overall moisture content. For instance, Sablani (2008) stated that microbial growth, lipid oxidation, nonenzymatic activity, enzyme activity and texture of foods depend on its water activity. These findings were based on extensively recognized effects, notably: (1) $a_w$ is a determinant for the growth of microorganisms; (2) it is associated with a good number of physical, chemical and enzymatic degradation reactions; (3) moisture migration in multidomain foods obey $a_w$ not MC; (4) the "monolayer" originated from water vapor sorption isotherm provides a suggestion of the optimum moisture content in dried foods and (5) the analysis of $a_w$ is much easier than that of MC, and it does not destroy the sample (Maltini et al., 2003).

Generally, water activity is used to assess the physical, chemical, and microbiological stability of a dried food product. When it ranges between 0.6 – 0.7, the product has the microbial stability, because, below 0.85 – 0.86, there is no growth of pathogenic bacteria.

Nevertheless, molds and yeast can tolerate up to $a_w$ of 0.80. The microbial growth is completely inhibited at 0.62 water activity. Haralampu and Karel (1983) studied mathematical models that describe the effect of water activity on degradation of ascorbic acid and beta carotene in dehydrated sweetpotato systems. They found out that ascorbic acid deteriorates at low water activity whereas beta-carotene can be less degradable at the intermediate and high water activity.

### 2.4.4 Color

Sweetpotato surface color is an important indices of sample quality during drying (Orikasa, 2010). The orange colors of sweetpotato as well as red and yellow colors of other plants are naturally caused by the presence of carotenoids. However, carotenoids are degraded during heat processing thus resulting the loss of their color properties.

Three different color systems are used for color analysis; the CIE system, the Hunter Lab system, and the CIE L*, a*, b* (CIELAB) system. CIELAB system is most commonly used in the food industry for objective color measurements (MacDougall, 2002). CIELAB, is a tridimensional system, and the measurement of three parameters, L*, a*, b* indicate the true color of the product by giving coordinate of color in space. L* indicates the lightness, a* (+/-) value indicates the red /green colors, and b* (+/-) value indicates yellow/blue colors. From these parameters, two values are calculated; hue and chroma, and they refer to perceived color and intensity, respectively.

Orange sweetpotato flour is used as ingredient and provides a natural coloring to the final product. The degradation of carotenoids, not only affects the attractive color of sweetpotatoes flour, but also their nutritive value and flavor.

Several researchers have found that in the most commonly used drying methods, freeze dried sweetpotato flour had low color loss after drying and at different storage temperatures (Çinar, 2004; Ahmed et al., 2010). In their work, Orikasa et al. (2010) investigated changes in color surface of sweetpotato during hot air drying. They noticed that the total color change (ΔE) between the samples processed at high temperature (50 and 60$^{o}$C), were significantly lower than that observed for the low temperature processed samples (30 and 40$^{o}$C). The difference might have been caused by a substantial reduction in drying time for the high temperature treatment. Grabowski et al. (2006) investigated the hue and the color change of reconstituted srpay dried OFSP flour compared to the original puree. They reported that maltodextrin (MD), used to facilitate the spray drying operation, had a significant effect on both (hue, ΔE) values of spray-dried sweetpotato flour.

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# CHAPTER 3: EFFECT OF WINDHEXE DRYING TEMPERATURE ON CAROTENE RETENTION IN SWEETPOTATO FLOUR

## 3. 1 Abstract

Orange-fleshed sweetpotatoes (OFSP) have high beta-carotene content and can be processed into flours for use as functional food ingredients. Current dehydration technologies are time intensive and require additional unit operations such as chipping, blanching or pureeing, and pulverizing. Vortex dehydration technology® (VDT) can simultaneously pulverize and dry the materials using heated, compressed air. This study aims to investigate the efficacy of using VDT, also known as Windhexe (WH), to process OFSP into beta-carotene rich flours and evaluate the effect of temperature on the carotene retention. OFSP cubes were fed to the Windhexe system operated at 110$^{o}$C, 125$^{o}$C, and 140$^{o}$C, with an air flow of 375 cfm, for rapidly converting the material into fine flour. Samples were analyzed for moisture, water activity ($a_w$) and carotene composition. Moisture content of the raw cubes (78.99 %) was instantly reduced to 10.38, 9.21, and 8.22 % ($a_w$= 0.32-0.35) for 110, 125 and 140$^{o}$C, respectively. Raw OFSP had total carotene content of 31.71 mg/100g (db) and 87.78% retained in the flour processed at 110$^{o}$C. Carotene retention was significantly reduced ($p<0.05$) to 76.18 and 66.19% at 125 and 140$^{o}$C, respectively. All-trans-ß-carotene at 110$^{o}$C (23.35 mg/100g) was significantly affected by temperature increases to 125$^{o}$C (18.89 mg/100g) and 140$^{o}$C (15.86 mg/100g). The 13-cis-carotene content increased significantly ($p<0.05$) as the temperature increased from 110 (1.60 mg/100g) to 140ºC (2.68 mg/100g). Other minor cis- isomers, 15-cis and 9-cis were also formed in the flour. These results showed that good quality sweetpotato flours can be produced using Windhexe in its present configuration. A study of the quality of Windhexe produced OFSP flour as compared to freeze drying and hot air drying will be conducted in the second part of this study.

## 3. 2 Introduction

Orange-fleshed sweetpotatoes (OFSP) are rich in carbohydrates, especially starch and beta-carotene. In addition to high starch composition, OFSP are also an important source of carotenoids to the same extent as apricot, carrot and peach (Woolfe, 1992). Carotenoids are known to have high provitamin A activity and antioxidant potential to prevent cancer and degenerative illnesses (Sies 1995). Eating boiled and mashed OFSP improved vitamin A profile of primary school in South Africa (Van Jaarsveld 2006). However, sweetpotato also have high moisture content~~s~~ and their storage becomes difficult. They have been transformed into puree and other dehydrated forms to increase their shelf-life and use as functional ingredients in processed foods (Truong and Avula, 2010). The change in nutrient content during heating treatment and drying is an important factor to control in production of high-quality dried sweetpotato products. It was demonstrated that sweetpotato flour is stable and has various applications such as thickener in soup and gravies, snacks and bakery products (Avula, 2007). Also, sweetpotato flour used in food product as ingredient can enhance color, flavor and provide natural sweetness to the food product (Truong and Avula, 2010). Additionally, drying enables the storage ability of the flour and allows the year round consumption (Avula et al., 2007).

Several studies have been conducted on the application of various dehydration techniques to produce sweetpotato flour, including sun drying, hot air drying, drum drying and spray drying (Agwunobi, 1999; Prabhavat et al., 1995; Valdez et al., 2001; Grabowski et al, 2006). However, all of these drying techniques have demonstrated limitations when used at large scale.

Sun drying exposes sweetpotato material to microbial contamination and insect infestation. It needs a large space and it is difficult to control the drying rate and product quality (Yang et al., 1995). Hot air drying operates in batches and it is difficult to obtain uniform drying rates at different locations within the system. Freeze drying is a slow and expensive process (Liapis et al., 2008). With drum drying and spray drying the materials must first be transformed into purees. Aside from time, labor and energy involved in pre-drying treatments, these processing steps also add to the nutrient losses including beta-carotene in the dried products. Air/sun drying and hot air drying demonstrated a carotene loss of 83% and 28%, respectively (Kósambo, 2004; Bechoff, 2010). In one study, 24 sweetpotato varieties were dried in a hot air dryer at 60$^{o}$C for 12 hours and total carotene content was reduced by 30% (Hagenimana et al., 1999). Bechoff et al. (2009) reported levels of loss between 16 and 34% in trans-β-carotene for an orange-fleshed sweetpotato variety (Bechoff et al. 2009).

Therefore, there is still a need to develop more rapid and efficient drying methods with less labor and energy use. Most importantly, those methods should increase the drying rate while preserving the product quality. Windhexe dehydration technology also known as Vortex dehydration technology comes into that perspective as a potential drying method to produce OFSP flour and preserve its carotenoids and other nutrient content. Windhexe drying technology can perform drying and grinding in one step process using heated compressed air.

It is imperative to improve first the quality of the flour such that the provitamin A content is sufficient to have a nutritional benefit (Van Hal, 2000).

The objective of this study was to produce carotene-rich OFSP flour for nutritional benefits and evaluate the effect of Windhexe drying temperature on carotene isomerization and retention.

## 3. 3 Material and Methods

### 3.3.1 Materials

#### 3.3.1.1 Sweetpotato Flour preparation

Sweetpotato cultivar, Covington, with orange-fleshed roots and rich in β-carotene was grown at the experimental fields of the Sweetpotato Breeding Program (Clinton, NC), North Carolina State University. The harvested roots were cured at 30 °C, 85-90 % relative humidity for 7 days and then stored at 13-16 °C and 80-90% relative humidity as commercially practiced. A batch of raw roots was hand washed and air dried overnight. Five roots were taken and ground using a heavy duty food processor, model RS1 2Y1 (Robo Coupe USA, Inc., Ridgeland, MS) for moisture content and β-carotene analysis. The batch was divided into three parts which were assigned randomly to different Windhexe drying temperatures. The roots were then cut into 1 cm cubes and dried using Windhexe dryer at 110$^{o}$C, 125$^{o}$C, and 140$^{o}$C, with an air flow of 375 cfm. The flour was immediately collected, kept in small jars and stored at -80$^{o}$C for chemical analysis.

### 3.3.2 Methods

#### 3.3.2.1 Windhexe dehydration system

Windhexe dehydration system (Figure 2) is made up of three major components; air compressor, air heater, and Windhexe apparatus (WH) as described by Polifka (2002). The air was generated by air compressor (operating at 375 cfm) and heated at 110, 125, 140ºC by the air heater connected to the WH. The WH consisted of a 61 cm diameter conical unit, with an upper chamber in which the drying and grinding took place, a lower chamber, the feeding hopper and the exhaust pipe (Vortex dehydration technology®, GreenShift CleanTech Corporation, Alpharetta,GA). The material to be processed (1 cm cubes OFSP) was introduced in the upper chamber from above through the feeding hopper at a feeding rate of 1kg/6 min and the compressed air with 78% relative humidity, was introduced through 2 angled slots located on the sidewall of the upper chamber. The compressed air generated a circular vortex flow which collided with the chamber sidewalls resulting in rapid grinding of the material and consequently drying took place prior collecting the fine OFSP flour.

### 3.3.2.2 Moisture Content and water activity

Moisture content of raw sweetpotato samples was determined by drying the samples in a convection oven (Lab-line Instrument, Inc. Melrose Park, IL) at 100$^{o}$C for 24 hrs (A.O.A.C, 1995). The moisture content in dried sweetpotato flour was measured using a DSC 50P moisture analyzer equipped with a result graphic display (DSC 50P moisture analyzer balance, Data Support Co., Inc., Panorama City, CA, U.S.A). Moisture analysis was conducted in duplicate for each sample.

A water activity instrument, Aqua Lab 4TE (Decagon Devices, Inc. Pullman, WA, USA) was used to measure the equilibrium relative humidity of sweetpotato samples. Sample was placed in a temperature controlled chamber equipped with an air circulating fan, a chilled-mirror dew point sensor that is capable of measuring relative humidity from 0% to

100% with an accuracy of ±1.5%, and an infrared temperature sensor measured a temperature of 25$^{o}$C. The water activity meter was continuously displayed until equilibrium was reached. The maximum duration of each test was approximately 15 minutes and each sample was measured in duplicate.

#### 3.3.2.3 Total carotene content

Extraction of total carotenoids from fresh and dried sweetpotato samples was performed as described by Lawrence & Schwartz (1988). Sample (5 g) was mixed with approximately 1 g of diatomaceous earth (celite), and 25ml of methanol. The mixture was ground using a tissuemizer (type SDT – 1810, Tekmar Co., Cincinnati, Ohio, U.S.A). Then, 50 ml of a hexane-acetone (1:1 v/v) mixture was added and stirred. The mixture was vacuum filtered through a funnel with a fritted disk. The residue in the funnel was washed for the second time with 25 ml of methanol and 40 ml of the hexane-acetone (1:1 v/v) mixture and for the third time with 30ml of hexane-acetone (1:1 v/v). All of the extracts were combined in a 250 ml decantation funnel and washed with water. A few drops of saturated sodium chloride solution were added to the funnel to facilitate phase separation. The aqueous phase was removed and the upper layer which constituted the carotene extracts was transferred quantitatively to a 50 ml volumetric flask and made to volume with hexane. The absorbance at 450 nm was measured using a Varian spectrophotometer (Cary WinUV Model 300, Palo Alto, CA) and total carotene content was calculated using β-carotene (Sigma-Aldrich, St. Louis, MO) as a standard. All samples were extracted in duplicate for the analysis and the extraction was conducted under UV-filtered light to minimize degradation of carotenoids.

Total β-carotene retention (TR) was calculated using a slightly modified formula outlined by Murphy et al. (1975):

$$\% \, \mathrm{TR} = \frac{(\text{nutrient content per g of dried OFSPflour} \times \text{g of OFSP flour})}{(\text{nutrient content per g of raw OFSP } \times \text{g of raw OFSP})}$$

#### 3.3.2.4 Quantification of β-carotene isomers

Carotene isomers were analyzed by reverse phase high-performance liquid chromatography using a slightly modified method outlined by Dhuique et al. (2005). The HPLC system (Thermo Quest San Jose, CA) consisted of a P2000 binary pump, AS 3000 autosampler, and SC 1000 degasser. Samples in brown dark vials to minimize light were put in the sample tray cooled to 6$^{o}$C. Samples, 20 μL, were injected onto a Sunfire C30 reverse phase column (4.6 x 250 mm, 5μm, YMC, Co., Ltd., Kyoto, Japan). Separation was conducted at 30$^{o}$C with a mobile phase composed of 75% methanol and 25% methyl tert-butyl ether (MTBE). The flow rate was kept at 2 ml/min. Peaks were monitored at 450nm with a UV 6000 LP Diode Array Detector. Carotene peaks were identified by comparison of retention times with standards and by comparison of peak spectra with published spectra, and were quantified by peak area and external standard solution. The ThermoQuest Chromatography Data Acquisition Software, version 4.1, was used to collect and process the data.

#### 3.3.2.5 Statistical analysis

A completely randomized design with 3 treatments was used for the experiment. The ANOVA and GLM procedures of SAS 9.0 (Statistical Analysis System, Cary, NC) were used for all statistical computations and references. A significant difference between means was determined and independent sample Tukey's test was carried out to determine significant differences between β-carotene compounds before and after drying.

## 3. 4 Results and Discussion

### 3.4.1 Moisture Content and water activity

Raw sweetpotato cubes had a moisture content of 78.99% before feeding into the Windhexe system. After less than a minute of grinding and drying in the chamber with hot air at 110 $^{o}$C, the collected flour had the moisture content of 10.38% (Table 1). This moisture level was significantly decreased to 9.21% and 8.22% ($p < 0.05$) when the air temperature was raised to 125$^{o}$C and 140$^{o}$C, respectively. These results are comparable to the moisture content of 9.8-11.5% reported by Bechoff et al. (2009) for the flour that was obtained from OFSP chips and slices dried at 42$^{o}$C for 2.0 to 7.5 hrs in a convection dryer. For stability in long term storage, sweetpotato flour of less than 11.5% moisture was recommended (Van Hal, 2000). Furthermore, Bechoff et al. (2009) reported that water activity below 0.45 favored the carotenoids stability during storage of OFSP flour. With the moisture content of < 11.5% and water activity values of 0.32-0.35 (Table 1), a slow degradation of carotenoids and microbial stability (Potter, 1998) would be expected for the Windhexe flour. This is important since the Windhexe produced flour is intended to be used as ingredient in food manufacturing, and it may be thus subjected to long term storage.

### 3.4.2 Total carotene retention

Total carotene content of raw Covington sweetpotatoes was 31.70 mg/100g dry weight (Table 2) which was within the range of 0.5 and 45 mg/100g (db) reported for various sweetpotato cultivars (Purcell and Walter, 1968; Lessin et al. 1997; Teow et al. 2007). Carotene content can be affected by drying methods as well as the material preparation prior to dehydration, such as peeling, soaking and blanching (Van Hal, 2000).

Since there are various drying technologies, it is imperative to evaluate the retention of carotene in dried products in relation to that of raw material. In this study, the carotene retention was 87.78 ± 4.62, 76.18 ± 3.18 and 66.19 ± 3.27 % for 110, 125 and 140$^{o}$C treatments, respectively. As shown in Table 2, increase in the Windhexe drying temperature significantly reduced the carotene retention in the OFSP flour ($p < 0.05$). The results demonstrated a good carotene retention in drying sweetpotatoes with the Windhexe system as compared to a retention of 87% in a cross flow dryer, 79% in solar dryer and 67% by direct sun drying (Bechoff et al. 2009). Chandler and Schwartz, (1988) reported a retention of 79.5% during drum drying of sweetpotato puree at 160$^{o}$C. Their results are close to the result obtained at 110 $^{o}$C and 125 $^{o}$C by Windhexe drying. The degradation can be most likely attributed to the oxidation reaction occurred during the cutting step prior dehydration, but also to the isomerization reactions caused by drying temperature.

### 3.4.3 Quantification of carotene isomers

In OFSP, about 80-90% of total carotenoids are all-trans-β-carotene (Bengtsson et al. 2008). Other carotene isomers namely 15-cis-ß-carotene, 13-cis-ß-carotene, and 9-cis-ß-carotene in yellow- and orange-fleshed sweetpotatoes and their processed products have been identified (Ishiguro et al., 2010, Liu et al. 2009). Degradation and isomerization of carotenoids occurs during processing especially at high temperature (Chandler and Schwartz, 1988). This isomeric composition of carotenoids in Windhexe OFSP flour is shown in Figure 2. As expected, the highest peak was identified as all-trans-β-carotene based on a retention time of a corresponding standard. Other minor peaks were identified based on the order of elution, UV-Vis spectra and $\lambda_{max}$ of the isomers reported in the literature (Chandler and Schwartz, 1988; Lessin et al. 1997; Bonnoni, 2002). Previous studies have identified the isomers in sweetpotato products. Chandler and Schwartz (1988) reported 13-cis-β-carotene, all-trans-β-carotene, and 9-cis-β-carotene in pureed, canned and rehydrated flakes extracts of sweetpotato in their HPLC analysis using a C30 column with methanol-MTBE solvent as eluent. It was demonstrated that $C_{30}$ columns have performed a good separation of carotenoids isomers than $C_{18}$ (Rimmer et al. 2005; Emenheiser et al. 1995). Our results are similar to those obtained by Lessin et al. (1997) using a $C_{30}$ stationary phase with similar mobile phase. The effect of Windhexe drying temperature on the quantity of carotene isomers in the Windhexe flour is shown in Table 3. There was a significant decreased ($p<0.05$) to 23.35 mg/100g (83.90%), 18.89 mg/100g (78.18%) and 15.86 mg/100g (82.77%) after processing in the Windhexe system at 110, 125 and 140$^{o}$C respectively.

The effect of Windhexe temperature on the quantity of cis-isomers was also observed. As the temperature increased, the total cis-isomers were increasing from 3.66 mg/100g (13.22%), to 4.58 mg/100g (18.95%) and 4.76 mg/100g (19.75%) at 110, 125 and 140$^{o}$C respectively. There was a significant difference between cis-isomers between 110 and 140$^{o}$C. However, no significant difference ($p>0.05$) was observed between 125 and 140$^{o}$C. The percentage for all cis-isomers was low as compared to drum dried flakes (28.9%) as reported by Chandler and Schwartz (1988). This can be explained by high temperature used in drum drying (160$^{o}$C). They also reported a predominance formation of 13-cis with increasing amount depending on the severity of heat treatment which is in agreement with the results in this study. The low quantity of cis-isomers caused by Windhexe drying can be considered as a positive point, since the isomerization reduced the provitamin A activity of all-trans-beta-carotene about 15- 35% (Sweeney and Marsh, 1971; Chen et al. 1994).

## 3.5 Conclusion

At drying temperature of 110$^{o}$C, the Windhexe technology can produce shelf-stable OFSP flour with high carotene content, minimal labor for material preparation prior to dehydration and short drying time. Since the Windhexe performs drying and grinding in one operation and capable of producing stable OFSP flour, it is important to evaluate the retention of other phytonutrients and physical properties of the produced flour in comparison to the existing drying technologies such as freeze-drying that is known in producing good quality products and hot air drying that has been commonly used in processing of sweetpotato flour.

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**Table 3-1: Effect of Windhexe drying temperature on moisture content and water activity of OFSP flour**

| Treatment | Moisture Content (%) | Water Activity |
|---|---|---|
| Raw OFSP | 78.99 ± 0.06$^a$ | N/A |
| WH 110 | 10.38 ± 0.77$^b$ | 0.35 ± 0.013$^a$ |
| WH 125 | 9.21 ± 0.88$^c$ | 0.34 ± 0.016$^a$ |
| WH 140 | 8.22 ± 1.79$^d$ | 0.32 ± 0.017$^a$ |

Values with different letters are significantly different ($P < 0.05$)

**Table 3-2: Carotene content and retention of Windhexe OFSP flour as affected by drying temperature**

| **Treatment** | **Total Carotene (mg/100g) (db)** | **Retention (%)** |
|---|---|---|
| Raw OFSP | 31.71 ± 0.6$^{a}$ | N/A |
| WH 110 | 27.83 ± 1.55$^{b}$ | 87.78$^{a}$ |
| WH 125 | 24.16 ± 1.14$^{c}$ | 76.18$^{b}$ |
| WH 140 | 19.16 ± 2.71$^{d}$ | 66.19$^{c}$ |

Values with different letters are significantly different ($P < 0.05$)

**Table 3-3: Cis/Trans-ß-Carotene isomers in Windhexe OFSP flour**

| **Carotene isomers** | **WH 110** | | **WH 125** | | **WH 140** | |
|---|---|---|---|---|---|---|
| | **(mg/100g)** | **(%)** | **(mg/100g)** | **(%)** | **(mg/100g)** | **(%)** |
| 15-cis-ß-Carotene | $0.98^{a,b}$ | 3.55 | $1.21^{a}$ | 5.02 | $1.38^{a}$ | 5.18 |
| 13-cis-ß-Carotene | $1.60^{b}$ | 5.75 | $2.01^{a}$ | 8.32 | $2.68^{a}$ | 11.00 |
| Trans-ß-Carotene | $23.35^{a}$ | 83.90 | $18.89^{b}$ | 78.18 | $15.86^{c}$ | 82.77 |
| 9-cis-ß-Carotene | $1.08^{a}$ | 3.92 | $1.36^{a}$ | 5.61 | $0.70^{b}$ | 3.57 |

a: $C_{30}$ column - stationary phase with mobile phase of MTBE-methanol (75:25, v/v)
Superscripts in the same row indicate significant difference ($p < 0.05$)

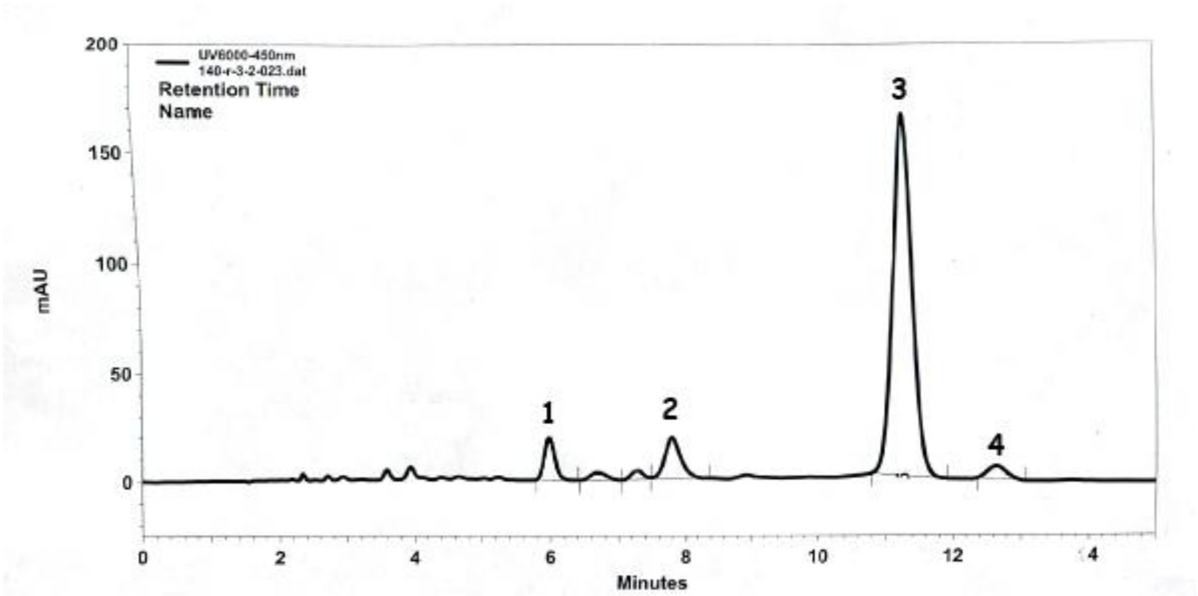

**Figure 3-1:** Typical HPLC Chromatogram of carotene extracts from OFSP flour.

Peak 1: 15-cis-carotene; peak 2: 13-cis-carotene; peak 3; all trans-ß-carotene; peak 4: 9-cis-carotene.

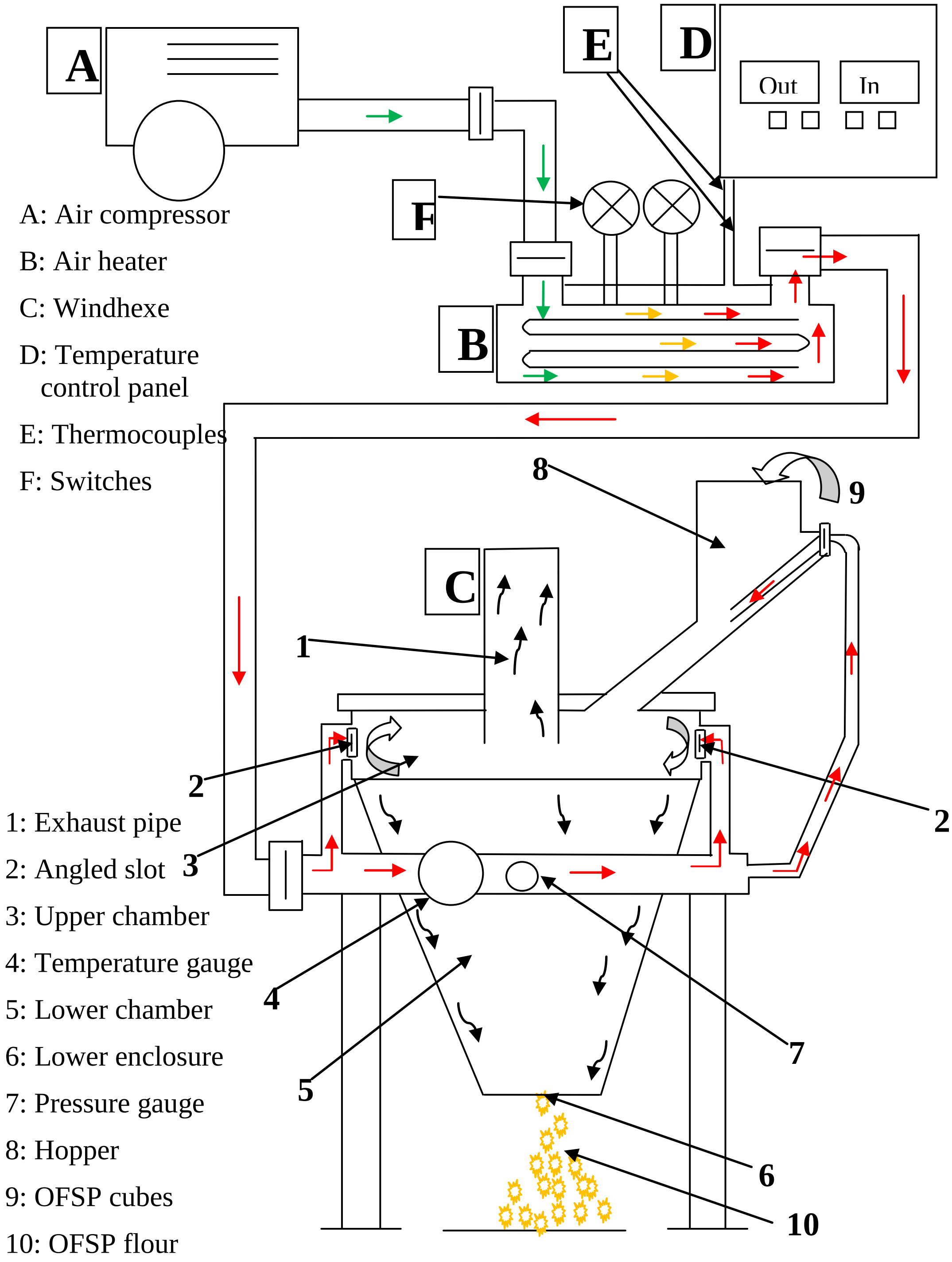

**Figure 3-2:** Schematic Windhexe Dehydration System

# CHAPTER 4:  A COMPARATIVE STUDY ON WINDHEXE, HOT AIR, AND FREEZE DRYING TECHNOLOGIES FOR PRODUCING ORANGE-FLESHED SWEETPOTATOE FLOUR

## 4. 1 Abstract

Processing sweetpotato into flour is an alternative way of preserving the commodity. With the increase in uses of sweetpotato flour as ingredient in various processed food products, there is a need to develop more efficient dehydration technology to produce sweetpotato flour. As shown in the previous chapter, shelf-stable and ß-carotene rich orange-fleshed sweetpotato (OFSP) flour can be produced using Windhexe dehydration. In this second part, the objective was to evaluate the nutrient retention and physical properties of Windhexe OFSP flours as compared to the OFSP flour produced by hot air drying (HD) and freeze-drying (FD). OFSP cubes (1 cm cubes) were processed into flour with the Windhexe system operated at 110$^{o}$C. Unblanched and blanched OFSP slices (0.5 cm) were dried using freeze dryer (-20$^{o}$C) and hot air dried at 65$^{o}$C. The dried materials were then reduced in particle size using a hammer mill and sifted in a 60 mesh screen. All the flour samples dried by the three methods had moisture content of 4.7 – 10.5% and water activity of < 0.45. Higher carotene retention was observed for both blanched (97.21%) and unblanched (94.25%) freeze dried flour, followed by retention of 82.64% and 84.09% by Windhexe and blanched hot air dried flours. Freeze drying retained highest amount of total phenolic and ascorbic acid followed by Windhexe drying. The smaller particle size of 78.59 μm characterized Windhexe dried flour and bigger particle sizes of 142.27 μm characterized hot air dried flour. The particles that escaped from Windhexe lower enclosure are much smaller than the collected flour. Pasting properties showed pre-gelatinized flour was obtained from Windhexe whereas blanching coupled with longtime drying completely gelatinized hot air dried flour. Additionally, the cold paste viscosity for Windhexe dried flour was significantly

different ($p<0.05$) from hot air dried flour. Hot air dried OFSP flours demonstrated significantly higher ($p < 0.05$) bulk density as compared to OFSP flours processed from Windhexe and freeze-drying. The CIE color and hue values showed that Windhexe preserved the orange color better than hot air drying. These results demonstrated that good quality OFSP flour can be produced using Windhexe dehydration technology.

## 4. 2 Introduction

Fruits and vegetables are important sources of essential dietary nutrients such as vitamins, minerals and fiber. Sweetpotato contributes significantly to the nutritional needs of the human diet by providing at least 90% of daily dietary requirements, with the exception of protein and niacin (Bouwkamp, 1985). This is because the root portion of the plant is rich in β-carotene, food fiber, and potassium ions (Lin et al., 2005) as well as antioxidants (Teow et al., 2007). Since the moisture content of fresh fruits and vegetables is more than 80%, they are classified as highly perishable commodities (Orsat et al., 2006). Therefore, in places where refrigerated storage facilities are not available, sweetpotato must be consumed within a few weeks after harvest, or it must be dried to lower the moisture content for storage and uses in various food systems.

Sweetpotato composition differs among cultivars, especially those with varying flesh of color. As various fruits, the orange-fleshed cultivars are rich in β-carotene, and the purple ones are rich in anthocyanins and total phenolics. Sweetpotatoes also have high dietary fiber, ascorbic acid, folic acid and minerals (Woolfe, 1992; Truong and Avula., 2009) this composition – particularly in vitamin A – is comparable to various fruits (Woolfe, 1992). This similarity in composition of SP and fruits served as the basis for development of several food products like candies, jam, ketchup and beverages (Truong, 1992). With high content in carbohydrates and β-carotene, orange fleshed sweetpotatoes (OFSP) can be processed into dehydrated forms and used as an ingredient in processing of food products including breakfast cereals, baked products and baby foods and snack items (Truong, 1992; Truong 1995; Woolfe 1992).

The quality of dried sweetpotatoes and flours is influenced not only by the drying conditions but also by other factors related to processing steps such as washing, peeling, slicing/shredding, soaking and blanching (Van Hal 2000; Woolfe 1992). It has been reported that peeling and slicing as well as shredding have led to nutritional losses (Truong and Avula, 2009). Through dehydration process, starch structure changes. These changes influence its functional characteristics including viscosity and solubility (Avula et al., 2007). The viscosity of the rehydrated sweetpotato flour or reconstituted puree influence the textural quality of the final product in which the flour is incorporated as ingredient. Dehydration also results in degradation of β-carotene pigments and consequently the loss of orange color (Bechoff et al. 2009).

The preservation of fruits and vegetables, including sweetpotato through drying dated back many centuries ago and it is based on sun drying techniques. However, the quality loss mostly caused by oxidation and the product contamination has led to the development of alternate drying technologies (Bezyma and Kutovoy, 2005). Various drying technologies including freeze, vacuum, osmotic, cabinet or tray, fluidized bed, spouted bed and drum drying have been developed. Recently, other heating methods such as infra-red, Refractance window, ohmic, microwave or combinations have also been applied in drying foods (George et al., 2004; Ochoa-Martinez et al. 2012).

Several studies have been conducted on sweetpotato dehydration using cabinet drying technique (Avula et al., 2006; Orikasa et al., 2010; Mais and Brennan, 2008). Avula et al. (2006) dried sweetpotato at 65$^{o}$C for 7-8 hours and obtained suitable flour for baby food. Drum drying was also used for dehydration of sweetpotato purees. Valdez et al., (2001) obtained 0.015 mm thick sheets of dried sweetpotato by drum drying. Spray drying of α-amylase hydrolyzed sweetpotato puree into the maltodextrin encapsulated powder for potential applications in food and nutraceutical products was recently reported (Ameh et al. 2010; Grabowski et al. 2006). Osmotic dehydration was also used in drying sweetpotatoes (Antonio et al., 2008).

All the technologies mentioned above require cutting, blanching and other treatment as pre-drying steps and grinding after drying to produce flours. Aside from energy consumption and labor involved, these operations affect the final product quality. Therefore, any technology that can skip these pre- and post-drying operations would be beneficial to the sweetpotato processing industry. Polifka (2002) have invented the Windhexe apparatus to perform drying and grinding simultaneously thus reducing the time and processing steps. To date, there is no scientific literature available on the application of Windhexe drying technology in food processing specifically in sweetpotato drying. The objective of this study was to evaluate the nutrient content and physical properties of Windhexe OFSP flours as compared to those produced by cabinet drying (CD) and freeze-drying (FD).

## 4. 3 Material and Methods

### 4.3.1 Materials

#### 4.3.1.1 Chemicals

Chlorogenic acid, Folin-Ciocalteau reagent, hexane, metaphosphoric acid, methanol, and ethyl alcohol were analytical grade (Fisher Scientific, Fair lawn, NJ). Ascorbic acid, all-trans-beta carotene for standards were from Sigma-Aldrich, Milwaukee, WI.

#### 4.3.1.2 Sweetpotato flour production

Sweetpotato cultivar, Covington, with orange-fleshed roots and rich in β-carotene was grown at the experimental fields of the Sweetpotato Breeding Program (Clinton, NC), North Carolina State University. The harvested roots were cured at 30 °C, 85-90 % relative humidity for 7 days and then stored at 13-16 °C and 80-90% relative humidity as commercially practiced. Raw roots were hand washed and air dried overnight. Each root was cut longitudinally into fourths and divided into four groups. The first group was used as a raw sample set, the second group used for blanched, non-dried sample, the third group used for blanched, dried sample and the fourth group used for unblanched, dried sample (Figure 1). All groups were immediately cut into slices of about 0.5 cm thickness using Hobart Food processor (Model FP150, Hobart, Troy, OH). Samples were taken from the first group slices for analyzing β-carotene content of the raw sweetpotatoes. The second and third group slices were steam blanched at 100$^{o}$C for 3minutes, whereas the fourth groups were subjected to drying without blanching.

For hot air drying, the slices were dried at 65$^{o}$C for 24 hours. Slices of the third and fourth groups were first frozen at -20$^{o}$C for 24 hours and then freeze dried at -20$^{o}$C for 120 hours. The dried slices of the OFSP samples were ground using a heavy duty CB 10B Food blender (Waring Pro, Torrington, CT) and sifted using a 60 mesh screen (W.S Tyler, Mentor, OH).

For Windhexe drying, a batch of raw and unpeeled OFSP was hand washed and air dried overnight. The roots were then cut into 1 cm cubes and dried at 110$^{o}$C as described in

Chapter 3. The flour was collected immediately, kept in small jugs and stored at -80°C for further analysis of nutrient and physical properties.

### 4.3.2 Methods

#### 4.3.2.1 Moisture content and water activity

Moisture content of raw sweetpotato samples was determined by drying the samples in a convection oven (Lab-line Instrument, Inc. Melrose Park, IL) at 100°C for 24 hrs (A.O.A.C, 1995). The moisture content in dried sweetpotato flour was measured using a DSC 50P moisture analyzer equipped with a result graphic display (DSC 50P moisture analyzer balance, Data Support Co., Inc., Panorama City, CA, U.S.A). Moisture analysis was conducted in duplicate for each sample.

A water activity instrument, Aqua Lab 4TE (Decagon Devices, Inc. Pullman, WA, USA) was used to measure the equilibrium relative humidity of sweetpotato samples. Sample was placed in a temperature controlled chamber equipped with an air circulating fan, a chilled-mirror dew point sensor that is capable of measuring relative humidity from 0% to 100% with an accuracy of ±1.5%, and an infrared temperature sensor measured a temperature of 25°C. The water activity meter was continuously displayed until equilibrium was reached. The maximum duration of each test was approximately 15 minutes and each sample was measured in duplicate.

#### 4.3.2.2 Total carotene

Total carotene extraction in fresh and dried sweetpotato samples was performed as described by Lawrence & Schwartz (1988). Sample (5 g) was mixed with approximately 1 g of diatomaceous earth (celite), and 25ml of methanol. The mixture was ground using a tissuemizer (type SDT – 1810, Tekmar Co., Cincinnati, Ohio, U.S.A). Then, 50 ml of a hexane-acetone (1:1 v/v) mixture was added and stirred. The mixture was vacuum filtered through a funnel with a fritted disk. The residue in the funnel was washed for the second time with 25 ml of methanol and 40 ml of the hexane-acetone (1:1 v/v) mixture and for the third time with 30ml of hexane-acetone (1:1 v/v). All of the extracts were combined in a 250 ml decantation funnel and washed with water. A few drops of saturated sodium chloride solution were added to the funnel to facilitate phase separation. The aqueous phase was removed and the upper layer which constituted the carotene extracts was transferred quantitatively to a 50 ml volumetric flask and made to volume with hexane. The absorbance at 450 nm was measured using a Varian spectrophotometer (Cary WinUV Model 300, Palo Alto, CA) and total carotene content was calculated using β-carotene (Sigma-Aldrich, Milwaukee, WI) as a standard. All samples were extracted in duplicate for the analysis and the extraction was conducted under UV-filtered light to minimize degradation of carotenoids.

#### 4.3.2.3 Ascorbic Acid

Samples of raw sweetpotatoes (10g) or OFSP flour (5g) were blended with 5% metaphosphoric acid using a tissuemizer (type SDT – 1810, Tekmar Co., Cincinnati, Ohio, U.S.A) for 1 minute and then centrifuged in Eppendorf centrifuge (Model 5810 R, 15 amp version, Eppendorf AG, Hamburg, Germany) at 10$^{o}$C and 12,000 rpms for 10 minutes. The aliquot was filtered through glass wool and collected in a 50 ml volumetric flask. The extraction was repeated three times to make up to a 50 ml volume. The AA analysis was conducted using spectrophotometer reading concentration predictions at 725 nm. The AA calculations were conducted based on L-ascorbic acid standard (Sigma-Aldrich, Milwaukee, WI). All samples were analyzed in duplicate.

#### 4.3.2.4 Total phenolics

A sample of 2 g was mixed with 25 ml of boiling 80% ethanol and tissuemized (type SDT – 1810, Tekmar Co., Cincinnati, Ohio, U.S.A) for 1 minute then centrifuged in Eppendorf centrifuge (Model 5810 R, 15 amp version, Eppendorf AG, Hamburg, Germany) at 10$^{o}$C and 8,000 rpms for 10 minutes. The extraction was repeated twice and the extracts were combined, made up to 50 ml volume. Total phenolics were quantified using a modified Folin-Ciocalteau (FC) method with chlorogenic acid (CAE) as standard (Singleton et al., 1999; Steed and Truong, 2008). Samples and standards (0.25 mL) were diluted in 4 mL of water to which 0.5 mL of the FC reagent was added and allowed to react at room temperature for 3 min. Sodium carbonate (1N, 0. 5 mL) was added and the reaction was carried out for 1 h. Sample absorbances were read at 725 nm using a Varian Spectrophotometer, (Cary WinUV Model 300, Palo Alto, CA). The baseline was established by reading a blank that contained 0.25 mL water instead of sample, along with the same amount of water for dilution, FC reagent, and sodium carbonate solution. Total phenolic values were reported in milligrams chlorogenic acid equivalents per 100 g dry weight (mg CAE/100 g db).

#### 4.3.2.5 Particle size

Particle size analyzer using laser diffraction technique, HORIBA LA-300 (HORIBA Jobin Yvon, Inc., Edison, NJ) was used to evaluate OFSP flour particle size. The sample was mixed with ethanol as dispersant as suggested by Schubert (1987) and introduced into the chamber which was equipped with an ultrasonification system to prevent the agglomeration of the particles and a debubbling system to get rid of every air or water bubble that may be in the dispersant. The instrument was connected to a computer equipped with LA-300 software for data acquisition and measurement of particle size (0.1μm - 600μm). The particle size distribution for the sample was automatically calculated by the software providing the mean, median and standard deviation information for the sample. Every sample was analyzed in duplicate.

### 4.3.2.6 Particle morphology

Scanning electron microscopy was used to measure the morphology of the OFSP flour. The powder samples were mounted on double sided adhesive carbon tabs and coated with gold-palladium using a hummer 6.2 (Anatech, LTD, Denver, NC). Scanning electron micrographs were obtained using a JEOL JSM 5900 LV scanning electron microscope (JEOL U. S. A., Peabody, MA) at an accelerating voltage of 10 kV and digital images were captured at various magnifications with JEOL Digital Scan Generator software v2.00.

### 4.3.2.7 Color measurement

The color of the powder was measured using tristimulus colorimeter (Model DP 9000, Hunter Lab, Reston, VA). For each sample, two measurements were conducted and values for L*, a*, and b* were averaged. Hue angle (H*) was calculated using equation outlined by Hutchings (1999): **H*=** Arctan $\frac{(b*)}{(a*)}$

#### 4.3.2.8 RVA-Pasting properties

The viscosity was determined using a Rapid Visco Analyzer (RVA) Super 4 (Newport Scientific Pty Ltd., Warriewood, Australia). The sample was prepared by mixing OFSP flour and distilled water to make a 11% solid content mixture in the sample canister.

A programmed heating and cooling cycle was used at constant shear rate. A 13 minutes profile described by Lockwood et al.(2008) for sweetpotato starch was used. The sample was heated from 50 to 95$^{o}$C at a rate of 12$^{o}$C minutes$^{-1}$ and held at 95$^{o}$C for 2.5 minutes, then cooled to 50$^{o}$C at a ramp of 13$^{o}$C minutes$^{-1}$ and held for 2 minutes. Throughout the process, the rotating speed of the RVA was kept constant at 160 rpm. The data for time, temperature, and viscosity were recorded and analyzed using RVA software to determine the pasting temperature, peak viscosity, and setback viscosity.

#### 4.3.2.9 Bulk density

Sample of OFSP flour (20g) was put in a 50ml graduated cylinder and vortexed for 1 minute. The mass of the flour divided by the volume occupied in the cylinder equals to the bulk density expressed in g/cm$^3$ (Okaka and Potter, 1977).

#### 4.3.2.10 Water Absorption Index and Water Solubility Index

Water solubility index (WSI) and water absorption index (WAI) were determined using the method described by Anderson et al. (1970). A small sample of OFSP powder (2.5 g) was suspended in 30 ml of distilled water at 30$^{o}$C in a 50 ml centrifuge tube and stirred intermittently for 30 minutes. Next, the tubes were centrifuged for 10 minutes at 10,000 rpm. The supernatant was carefully collected in a petri dish and oven dried overnight at 100$^{o}$C.

The amount of solids in the dried supernatant was expressed as a percent of the total dry solids in the original 2.5 g sample gave an indication of solubility index. Water absorption index is calculated as the weight of the solid pellet remaining after centrifugation divided by the amount of dry sample.

#### 4.3.2.11 Statistical analysis

A completely randomized design with five treatments and three replicates was used for the experiment. The ANOVA and GLM procedures of SAS 9.0 (Statistical Analysis System, Cary, NC) were used for all statistical computations and references. A significant difference between means was determined and independent sample Tukey's test was carried out to determine significant differences samples before and after drying.

## 4. 4 Results and Discussion

### 4.4.1 Moisture content and water activity

Moisture content (MC) and water activity ($a_w$) parameters were determined to assess the storability of the flour. As shown in Table 1, raw OFSP had a moisture content of 79.5 – 80.1% and there was no significant among the three sweetpotato batches used in this study ($p > 0.05$). The results are in accordance with the moisture levels in the sweetpotato cultivars reported by Brintley et al. (2008). All the flour samples dried by the three methods had moisture content of 4.7 – 10.5% and water activity of $< 0.45$ that meet the recommended requirements for long-term storage of OFSP flours (Ahrne and Prothon, 2004; Bechoff et al. 2009, Van Hal 2000). The results are similar to those obtained by Bechoff et al. (2009) in drying OFSP slices and chips using hot air, solar and sun drying technologies (9.8 – 11.2 %

MC) and (0.37 – 0.44 $a_w$). The OFSP could be used as a high provitamin A ingredient in several food products (Truong and Avula, 2010). It was demonstrated that sweetpotato flour with water activity from 0.38 to 0.45 has good carotene stability during storage (Bechoff et al. 2009). Other studies showed that water activity of 0.43 (Arya et al. 1979) and between 0.31 – 0.54 (Lavelli et al. 2007) enhanced carotene stability in dehydrated carrots. Low $a_w$ was reported to result in a longer shelf-life of carrots, though carotenoids degrade faster in dehydrated systems through autocatalytic oxidation (Goldman et al. 1983). Blanching apparently resulted in longer drying time and higher moisture content for the samples of both hot air and freeze drying (Table 1). This can be attributed to collapsing of cell structure and starch gelatinization which reduce the mass transfer and water evaporation (Pandey et al. 2008). Regardless of the blanching treatments, it took 120 hrs and 17-24 hrs to dry 3 kg of the OFSP sweetpotatoes by freeze drying and hot air drying to a moisture level below 11.5% under the described conditions in this study, and additional time was required in grinding the dried slices into flour. With the same amount of raw OFSP, a combined operation of grinding and drying in the Windhexe system took less than 10 min to obtain the flour as the finished product (Table 1). This short time drying demonstrates an advantage of windhexe drying over the hot air and freeze drying technologies.

### 4.4.2 Total carotene

Total carotene content in the raw OFSP (Table 2) was higher compared to the results 10.12 -19 mg/100g reported by Fonseca et al. (2008) and Lako et al. (2006). However, they were in agreement with Bengstsson et al. (2008) who obtained carotene content ranging between 10.81 and 31.45 mg/100gr for raw OFSP. A wide range of carotene content (0.5 - 45mg/100g) in various sweetpotato varieties were reported (Kays, 1992; Purcell and Walter, 1968). It is well known that carotenoids are partially isomerized or totally degraded due to heat treatment, including high drying temperatures. The carotene retention reflects the loss caused by drying method during processing in relation to the initial carotene content in the raw OFSP. The results indicated that freeze-drying had a higher retention value and significantly different ($p<0.05$) from both Windhexe and hot air dried flours (Table 3). Blanching slightly increased the retention of total carotene in freeze drying but significantly ($p < 0.05$) increased the retention in hot air dried OFSP flour as compared to the unblanched samples.

The results of carotene retention obtained in this study are in agreement with Van Jaarsveld et al. (2006) who obtained a true retention ranging between 70-80 % after boiling OFSP for 30 min in a pot covered with the lid. Bengstsson et al. (2008) obtained retention of 77% after 30 min steaming of OFSP. Bechoff et al., (2009) have observed a loss of 13, 21 and 33% in hot air, solar and sun dried OFSP chips. Their results for hot air dried sample is lower to the retention values observed with freeze drying and close to the retention values in the hot air and Windhexe dried flours in this study. Fonseca et al, 2008) obtained 38% loss of carotene (about 62% retention). Hagenimana et al. (1999) observed a total carotene loss of about 30% after drying OFSP slices at 65$^{o}$C for 12 hrs using hot air drying.

The OFSP material to be dried using Windhexe are chopped into small pieces of 1 cm$^{3}$, dried at 110$^{o}$C for less than 1 min. The relatively higher retention observed in Windhexe dried flour could be attributed to the fact that a shorter drying time results in higher carotene retention Bengstsson et al. (2008). Usually, the cutting and peeling of fruits and vegetables may expose them to the enzymatic oxidation, hence increasing carotene degradation. However, Van jaarsveld et al. (2006) observed no loss in chopped raw OFSP exposed to room temperature for 4 hrs and indicated that enzymatic oxidation is not a major issue in sweetpotato. Also, it can be anticipated that the higher retention in Windhexe might have been caused by the blanching effect provided by Windhexe due to its high drying temperature. However, a further study is needed to confirm this hypothesis.

Based on the results of total carotene in raw material and total carotene retention in the final flour, it can be argued that the carotene retention was dependent on the type of dryer. Hence, freeze drying come in the first position as best carotene retention technology, and this was expected. Windhexe drying comes in the second position, followed by hot air drying.

### 4.4.3 Ascorbic Acid

The ascorbic acid (AA) content in raw samples (Table 2) was relatively higher than that of 15.4 and 14.7 mg/100g for Beauregard and Hernandez cultivars reported by McConnell et al. (2005). Blanching slightly decreased AA in raw OFSP before drying and significantly ($p<0.05$) after drying due to thermal destruction caused by steam blanching. Steaming raw banana at 100 – 115$^{o}$C for 7 min followed by hot air drying at 60 – 65$^{o}$C reduced significantly the AA content in steamed banana (Muyonga et al. 2001). Additionally, an AA reduction from 24.5 mg/100g (fw) to 7 mg/100g was reported after sweetpotato canning (Purcell et al. 1989).

The results of AA true retention are shown in Table (3). As expected, freeze drying demonstrated higher AA retention which was significantly different ($p<0.05$) from Windhexe and hot air dried samples. The drying temperature in WH (110°C) was almost twice the drying temperature of hot air drying (65°C). However, WH dried flour demonstrated significantly ($p<0.05$) higher retention as compared to hot air blanched (66.08 %) and unblanched (69.74 %) samples. This can be explained by a short drying time applied in Windhexe (< 1 min) as compared to that applied in hot air drying (24 hrs). Generally, the longer the drying time, the lower the retention of vitamin C (Santos and Silva, 2008)

The highest AA loss in this study was observed in hot air drying (up to 33%). However, this loss was lower compare to the loss observed by Arthur and McLemore (1955) ranging from 50 to 70% in drum dried sweetpotato flakes. The AA retention of 90% was reported by Chang et al (2006) in freeze-dried tomatoes and is slightly higher compare to the retention observed in this study for blanched (83.46 %) and unblanched (85.47 %) freeze-dried samples.

### 4.4.4 Total phenolics

The results of total phenolic content of 243.2 - 279.9 mg/100g dry weight (Table 2) are slightly lower than that of 302 mg/100g dry weight of raw Covington sweetpotatoes reported by Truong et al. (2007). The difference can be due to the growing conditions, post harvest handling and the phenolic extraction method. It was observed that steam blanching decreased significantly ($p<0.05$) the total phenolic content in raw roots before freeze drying and hot air drying. Howard et al. (2003) stated growing conditions and extraction method as factors that can cause variation of total phenolic in raw sweetpotato.

The results of retention are shown in Table 3. A significant difference ($p<0.05$) was obtained between flour obtained from three different technologies used in this study. The freeze drying demonstrated a higher total phenolic retention for both blanched (77.08%) and unblanched (81.92%) treatments followed by Windhexe dried flour (75.47%) drying. Hot air drying retained lower amount of total phenolics with 61.54% and 67.71% for blanched and unblanched samples respectively. Blanching decreased total phenolics retention significantly ($p<0.05$) within freeze drying as well as hot air drying. This decrease is attributed to the heat treatment during blanching. Previous studies demonstrated that one minute boiling decreased 14% of total phenolics in spinach and 20% in cabbage (Ismael et al. 2004). Amin et al. (2006) reported a total loss of 71% in *amaranthus gangeticus* after 15 min blanching. It was also observed by Huang et al. (2006) that steaming affected total phenolic content in sweetpotato. A significant difference ($p<0.05$) in retention observed between Windhexe and hot air dried flour can be attributed to the long time heat applied in hot air drying. However, previous studies about the effect of drying temperature on total phenolic content in fruits and vegetables have reported the similar results. Larrauri et al., (1997) observed a total retention of 81.4 and 67.4% (18.6 and 34.6 % loss) in red grape pomace heels dried at 100 and 140 $^{o}$C respectively. Also, the retention of 72 % was observed after hot air drying of strawberries at 60 $^{o}$C for 220 min (Böhm et al. 2006). It is well known that freeze drying is the best drying technology for nutrient retention. Therefore, freeze dried products are used as reference to evaluate the effect of drying method on product quality (Larrauri et al., 1997).

### 4.4.5 Particle size and distribution

The particle size distribution in Figure 2 showed that Windhexe flour had narrower distribution with smaller mean particle size (78.59 μm) as compared to the samples generated from hot air (142.27 μm) and freeze drying (140.23 μm) and the difference was significant ($p<0.05$). The narrow distribution of Windhexe flour indicates that this flour is homogenous in relation to particle size. Blanching reduced the size of particles for both hot air (116.17 μm) and freeze dried (132.12 μm) flours as compared to their unblanched counterpart. Singh et al. (2006) reported that blanching slightly affects grinding/milling quality/size-reduction characteristics of the tomato powder. Grabowski et al. (2006) reported smaller particle sizes of 21.36 and 41.28 μm for spray dried OFSP flour obtained from amylase treated OFSP puree encapsulated with maltodextrin. The particle size influences powder flowability, hence it may impact the use of the OFSP flour as an ingredient in processing of food products. Schubert (1987) stated that the bigger the particle size, the higher the flowability. Additionally, Teunou et al. (1999) stated that larger particles are free flowing whereas smaller particles are subject to cohesion. Therefore, it can be anticipated that hot air dried flour may have higher flowability, therefore, it can be better than Windhexe and freeze dried flour from the processing standpoint. However, flours with smaller particles can be potentially used in food products where uniform dispersion is desirable for acceptable consistency of end product (Singh et al. 2006).

### 4.4.6 Particle morphology

Food powder particle morphology is generally classified in three main categories: crystalline, skin forming and agglomerate (Grabowski, 2005, Walton, 2000). The particle morphology in this study (Figure 2) demonstrated three different categories as well. The freeze dried flour particles were flaky-or plate like particles and the unblanched treatments tended to be much more skin forming than blanched particles. The hot air dried flour particles looks like small crystalline whereas the Windhexe flour particles demonstrated an agglomerated small particles morphology. The observation of particle morphology indicated that hot air dried flour particles were small in size as compared to that of Windhexe dried flour. However, a different observation was shown in the particle size analysis (Figure 1). Schubert (1987) stated that most of dried food powders are much more cohesive when their particle size is less than 100 μm, and this can be the reason of agglomerated morphological aspect appeared in the Windhexe dried flour.

### 4.4.7 Color

The color values (*L*, a*, b** and hue) are presented in Table 4. *L** values varies from blackness (0) to lightness (100), +*a** indicates "redness" whereas the +*b** value indicates the "yellowness". The Winhexe dried flour had the lowest L* value and its redness value was similar to the blanched-freeze dried sample. The hue values were derived from a* and b* and described as spectrum of colors or colors from the rainbow. In this study, the highest hue value was observed in unblanched freeze-dried flour ($71.85^o$) and the lowest hue value was observed in Windhexe dried flour ($67.81^o$). However, there was no significant difference

($p>0.05$) between Windhexe and unblanched freeze dried flour ($68.81^o$). The higher hue value indicates that the color tends to the increase in yellowness, whereas the low hue value indicates the increase towards red color. That explains the more orange color observed for Windhexe dried flour as compared to other treatments. Additionally, the hue value of the Windhexe dried flour are similar to the hue value ($67.0^o$) obtained in the OFSP puree (Grabowski et al. 2006). Blanching significantly decreased ($p<0.05$) the hue value of the freeze dried flour, but it did not affect ($p>0.05$) the hot air dried flour. This difference can be attributable to carotene degradation during blanching coupled with the browning reaction during long time drying with hot air at 65ºC. These reactions could also contribute to the low hue value mentioned above for the Windhexe flour which was processed at 110 ºC.

### 4.4.8 RVA-Pasting properties

Pasting properties (Figure 3) are affected by starch content in the flour, the interaction between other flour components as well as testing conditions (Liu et al. 2006). The highest peak viscosity (PV) was observed in the FD-UF (1857 cP) whereas the lowest PV was observed in HD-BF (142.5 cP). This low PV was attributed to complete gelatinization resulted from blanching coupled with long time drying, and it is similar to the values reported by Collado et al. (1999) and Avula et al. (2006) for hot air dried sweetpotato flours. Windhexe dried flour demonstrated higher peak viscosity (834 cP) and significantly different ($p<0.05$) from FD-BF (408 cP). Blanching significantly ($p<0.05$) decreased the PV for both FD-BF and HD-BF. The results are in accordance with the previous report on the effect of blanching on pasting properties of sweet potato flour and starch (Jangchud et al. 2003).

The cold paste viscosity (CPV) was high in FD-UF (2603 cP). It is relatively close to CPV reported by Avula et al. 2006 (2404 cP) for native sweetpotato starch and CPV for native glutinous and jasmine rice starch obtained by Nakorn et al. 2009. Cold paste viscosity in Windhexe dried flour (1187.5 cP) was close to the values reported by Nakorn et al. 2009 for pre-gelatinized glutinous rich starch. It was significantly different ($p<0.05$) to FD-BF (707.5 cP) and HD-UF (269.5 cP) samples. This indicates a retrogradation of starch molecules in Windhexe dried flour. It was observed that the viscosity of Windhexe sample decreased before the end of heating phase (50 – 95$^{o}$C) and then increased in the cooling phase (95 – 50$^{o}$C). Guha et al. (1998) attribute the increase of viscosity in the cooling phase to gelling caused by retrogradation of starch molecules. This trend is similar to a pre-gelatinized starch solution, and the flour could be suitable thickener in food processing (Truong and Avula, 2010) whereas the low CPV observed for hot air dried samples indicated a high thermal and mechanical stability, which is an important property for the application in baked and frozen foods (Truong and Avula, 2010).

### 4.4.9 Bulk density

Food materials are dried and transformed into flour for preservation, storage, reduction of transportation costs and utilization as ingredients in processed foods. Bulk density is essential since it indicates whether or not a given amount of powder will fill perfectly into its designated package (Goula et al. 2004).

Hot air dried OFSP flours demonstrated significantly higher ($p < 0.05$) bulk density as compared to OFSP flours made from Windhexe and freeze-drying. The bulk density results are shown in Table 5. Freeze drying showed lowest bulk density with no significant difference ($P>0.05$) between blanched (0.35 g/cm$^3$) and unblanched (0.34 g/cm$^3$) treatments. These results are lower compared to the results (0.75 g/cm$^3$) obtained by Hsu et al. (2003) in freeze drying three varieties of yam. However, the bulk density (0.63 g/ cm$^3$) they obtained from hot air dried yam flour were similar to that obtained in unblanched hot air dried flours (0.64 g/ cm$^3$) in this study. The blanched hot air dried results (0.75 g/cm$^3$) obtained in this study are comparable to the results (0.78 g/ml) obtained by Akubor (1997) in producing hot air dried sweetpotato flour.

Windhexe dried flour showed an intermediate bulk density (0.40 g/cm$^3$) between hot air and freeze dried flours. Goula et al. (2005) stated that compressed air affects mean particle size and that smaller particles produced by compressed air get denser and have increased bulk density. Therefore, it was expected that a highest bulk density will be obtained from Windhexe dried flour, since it was the only technology that used compressed air. However, the compressed air effect was not observed in the Windhexe dried samples and it can be explained by high processing temperature (110$^o$C). Walton (1986) reported that an increase in drying temperature results in a decrease of bulk density. The results in this study indicated that Windhexe and freeze drying produced lower bulk density flour than hot air drying. A low bulk density is advantageous in preparation of weaning food formulations (Akubor 1997).

### 4.4.10 Water solubility Index and water absorption index

Water Solubility Index (WSI) indicates the degradation of starch in the flour (Diosady 1985). In this study, the highest WSI was observed in the freeze-dried flours, followed by the hot air dried flours and the lowest WSI was observed in Windhexe dried flours (Table 5). Also, it was observed that blanching increased WSI significantly ($p<0.05$) between blanched and unblanched samples within both hot air and freeze drying samples. This is probably due to the partial degradation of starch during steam blanching.

Generally, the WSI results of 27.94 – 50.60 % in this study were relatively low compared to those obtained by Grabowski et al. (2006) in spray dried OFSP (57.0 – 88.4 %). However, the solubility obtained in hot air dried samples is comparable to the results reported by Avula et al. (2006) for hot air dried sweetpotato. The higher solubility observed in freeze-dried flours can be attributed to its low moisture content. During grinding, low moisture content starch granules are subject to a greater shear resulting in higher solubility. Windhexe dried samples demonstrated lowest solubility (27.94 %). However, given its pre-gelatinized behavior observed with RVA analysis, it was expected to observe a higher solubility in Windhexe dried flour than in freeze dried flour. However, this was not observed. The low solubility in Windhexe dried flour can be attributed to the starch retrodegradation and different level of particle breakdown during the milling step of Windhexe (Whistler and Bemiller, 1997; Kaur et al. 2002).

Water Absorption Index (WAI) reflects the extent of starch gelatinization. The results of WAI are shown in Table 5. Within drying technologies, freeze drying demonstrated lower WAI for blanched and unblanched samples, followed by Windhexe (3.53 g/g) and then hot air drying. There was a significant difference ($p<0.05$) between Windhexe dried flour and blanched as well as unblanched freeze dried flours. However, there was no significant difference ($p>0.05$) between Windhexe dried flour and Hot air dried flours. An increase in water absorption capacity in relation to the increase in drying temperature was observed in this study and it was also reported in previous study characterizing flour and starch from red and white sweetpotato by Osundahunsi et al. (2003).

## 4.5 Conclusion

The first part of this study demonstrated that Windhexe drying technology can potentially produce shelf-stable and beta-carotene rich OFSP flour. This second part compared the Windhexe dried OFSP flour with freeze-dried flour as reference in quality and hot air dying as a commonly used technology in sweetpotato drying industry. It was demonstrated that Windhexe can produce shelf-stable OFSP flour with nutrient retention in between of freeze drying and hot air drying. Smaller particle size of the Windhexe dried flour makes it desirable for use in food products where uniform dispersion is desirable for acceptable consistency of end product. Pasting properties showed that Windhexe produce a pre-gelatinized OFSP flour with a higher cold paste viscosity than hot air dried flour which makes it a suitable thickening ingredient. An overall advantage of Windhexe dehydration technology is its low labor input and simultaneous performance of grinding and drying high moisture content food material in a very short time, into good quality flour. This is the first scientific study conducted to assess the application of Windhexe dehydration in food processing. Further studies are required to evaluate its energy consumption, the effect of feeding rate and relative humidity on Windhexe yield, and process optimization for large scale operations.

## 4.6 References

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**Table 4-1: Moisture content and water activity of raw and OFSP flour samples**

| Treatment | Drying time[a] | Moisture content (%) | Water activity ($a_{w)}$ |
|---|---|---|---|
| Raw-FD | n/a | $79.94 \pm 0.8^a$ | n/a |
| Raw-HD | n/a | $79.45 \pm 1.2^a$ | n/a |
| Raw-WH | n/a | $80.11 \pm 0.4^a$ | n/a |
| FD-BF | 120hrs | $8.2 \pm 0.1^c$ | $0.45 \pm 0.004^a$ |
| FD-UF | 120hrs | $4.7 \pm 0.07^d$ | $0.36 \pm 0.0004^a$ |
| HD-BF | 24hrs | $8.9 \pm 0.7^c$ | $0.46 \pm 0.015^a$ |
| HD-UF | 17hrs | $7.7 \pm 0.1^c$ | $0.38 \pm 0.014^a$ |
| WHF | < 10 min | $10.55 \pm 0.8^b$ | $0.36 \pm 0.04^a$ |

a: for 3000 g of raw materials, FD: Freeze-drying, HD-Hot air drying, WH; Windhexe drying, BF: Blanched Flour, UF: Unblanched Flour. Values with different letters are significantly different
($P < 0.05$)

**Table 4-2: Total carotene, total phenolics, ascorbic acid content of raw and dried OFSP samples**

| Treatment | Total carotene (mg/100g) | Total phenolics (mg CAE/100g) | Ascorbic acid (mg/100g) |
|---|---|---|---|
| Raw-FD | 35.2 ± 1.64$^{c}$ | 243.23 ± 0.96$^{c}$ | 29.38 ± 1.9$^{a}$ |
| Raw-HD | 35.5 ± 8.87$^{c}$ | 268.10 ± 23.9$^{b}$ | 16.18 ± 1.3$^{e}$ |
| Raw-WH | 31.7 ± 0.66$^{d}$ | 279.90 ± 57.8$^{a}$ | 27.93 ± 0.58$^{b}$ |
| BU-FD | 38.97 ± 1.89$^{b}$ | 217.05 ± 0.5$^{e}$ | 27.68 ± 6.15$^{b}$ |
| BU-HD | 42.41 ± 7.9$^{a}$ | 236.81 ± 44.03$^{d}$ | 15.16 ± 1.86$^{e}$ |
| FD-BF | 34.25 ± 1.28$^{c}$ | 187.50 ± 2.5$^{g}$ | 24.52 ± 1.33$^{c}$ |
| FD-UF | 33.20 ± 1.11$^{c,d}$ | 199.27 ± 4.5$^{f}$ | 25.11 ± 2.3$^{b,c}$ |
| HD-BF | 29.01 ± 2.19$^{d,e}$ | 165.012 ± 16.19$^{h}$ | 9.69 ± 2.41$^{g}$ |
| HD-UF | 26.71 ± 2.78$^{f}$ | 181.53 ± 14.59$^{,g}$ | 11.28 ± 0.47$^{f}$ |
| WHF | 25.21 ± 0.55$^{f}$ | 211.25 ± 18.87$^{e,f}$ | 20.79 ± 0.97$^{d}$ |

FD: Freeze-drying, HD-Hot air drying, WH; Windhexe drying, BF: Blanched Flour, UF: Unblanched Flour, BU-HD: Blanched Undried raw samples prior Hot air drying, BU-FD: Blanched Undried raw samples before Freeze drying. Values with different letters are significantly different (P < 0.05)

**Table 4-3: Phytonutrient retention in OFSP flours**

| Treatment | Total carotene retention (%) | Total phenolics retention (%) | Ascorbic acid retention (%) |
|---|---|---|---|
| FD-BF | $97.21^{a}$ | $77.08^{b}$ | $85.47^{a}$ |
| FD-UF | $94.25^{a}$ | $81.92^{a}$ | $83.46^{a}$ |
| HD-BF | $84.09^{b}$ | $61.54^{e}$ | $66.08^{d}$ |
| HD-UF | $77.37^{c}$ | $67.71^{d}$ | $69.74^{c}$ |
| WH-F | $82.64^{b}$ | $75.47^{c}$ | $77.98^{b}$ |

FD-BF: Freeze-dried Blanched Flour, FD-UF: Freeze-dried Unblanched Flour, HD-BF: Hot air dried Blanched Flour, HD-UF: Hot air dried Unblanched Flour, WH; Windhexe dried flour. Values with different letters are significantly different ($P < 0.05$)

**Table 4-4: Color values of OFSP flour samples**

| Treatment | L* | a* | b* | Hue |
|---|---|---|---|---|
| FD-BF | 79.52$^{a}$ | 11.99 | 35.46 | 71.31$^{a}$ |
| FD-UF | 75.96$^{b}$ | 13.15 | 33.69 | 68.81$^{a,b}$ |
| HD-BF | 80.35$^{a}$ | 8.3 | 25.52 | 71.85$^{a}$ |
| HD-UF | 80.84$^{a}$ | 11.15 | 30.70 | 70.03$^{a}$ |
| WHF | 70.50$^{b,c}$ | 11.12 | 27.27 | 67.81$^{b}$ |

FD-BF: Freeze-dried Blanched Flour, FD-UF: Freeze-dried Unblanched Flour, HD-BF: Hot air dried Blanched Flour, HD-UF: Hot air dried Unblanched Flour, WHF; Windhexe dried flour.

**Table 4-5: Bulk density, water absorption index and water solubility index of OFSP flours**

| Treatment | Bulk density (g/cm$^3$) | Water absorption index (g/g) | Water solubility index (%) |
|---|---|---|---|
| FD-BF | 0.35 ± 0.02$^d$ | 2.11 ± 0.2$^b$ | 50.60 ± 2.11$^a$ |
| FD-UF | 0.34 ± 0.07$^d$ | 2.34 ± 0.1$^b$ | 40.63 ± 4.5$^b$ |
| HD-BF | 0.75 ± 0.11$^a$ | 3.60 ± 0.08$^a$ | 38.61 ± 5.6$^c$ |
| HD-UF | 0.64 ± 0.12$^b$ | 3.36 ± 0.24$^a$ | 35.80 ± 3.3$^d$ |
| WHF | 0.40 ± 0.3$^c$ | 3.53 ± 0.4$^a$ | 27. 94 ± 2.5$^e$ |

FD-BF: Freeze-dried Blanched Flour, FD-UF: Freeze-dried Unblanched Flour, HD-BF: Hot air dried Blanched Flour, HD-UF: Hot air dried Unblanched Flour, WHF; Windhexe dried flour.

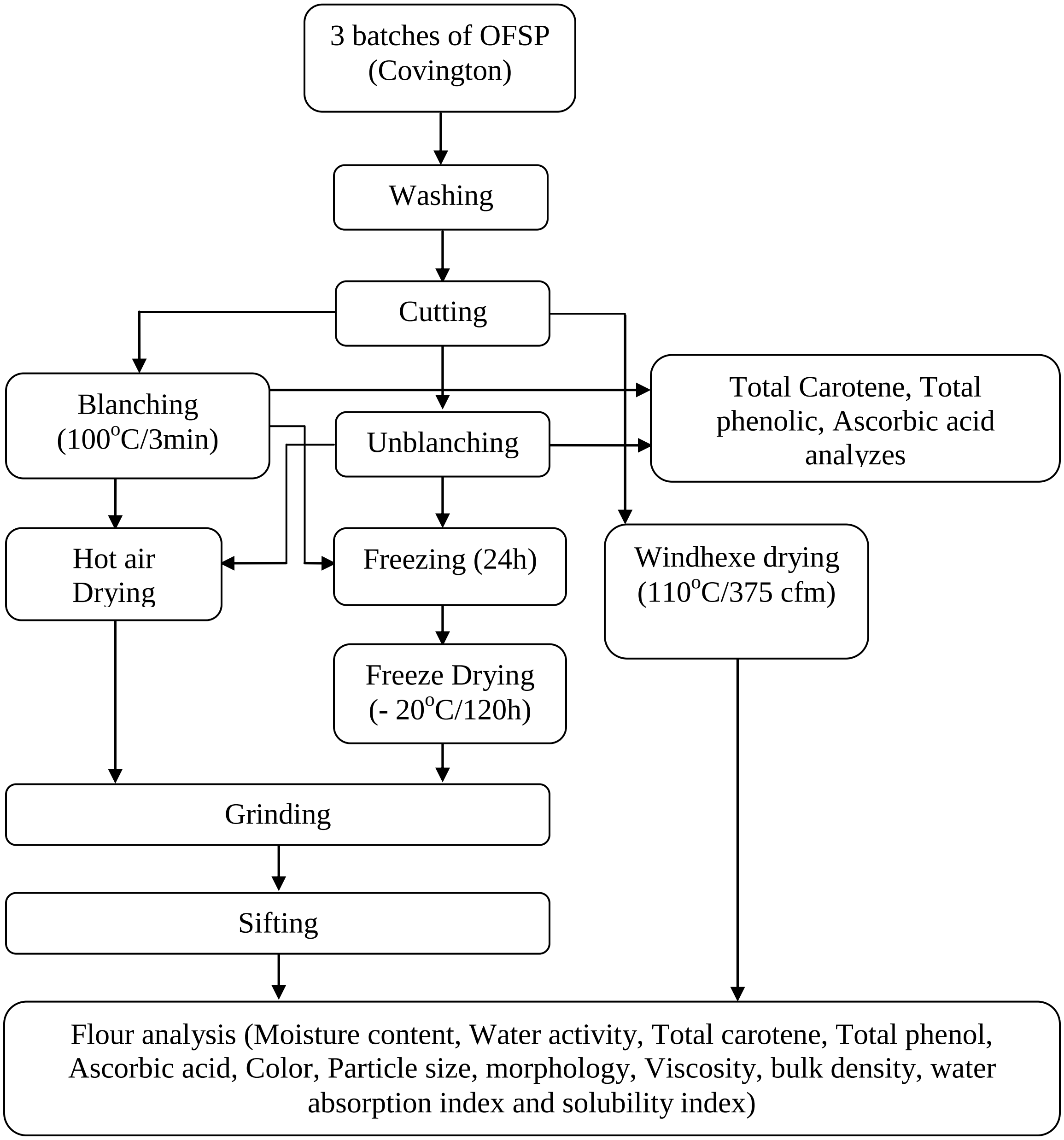

**Figure 4-1:** Diagram of experimental procedure

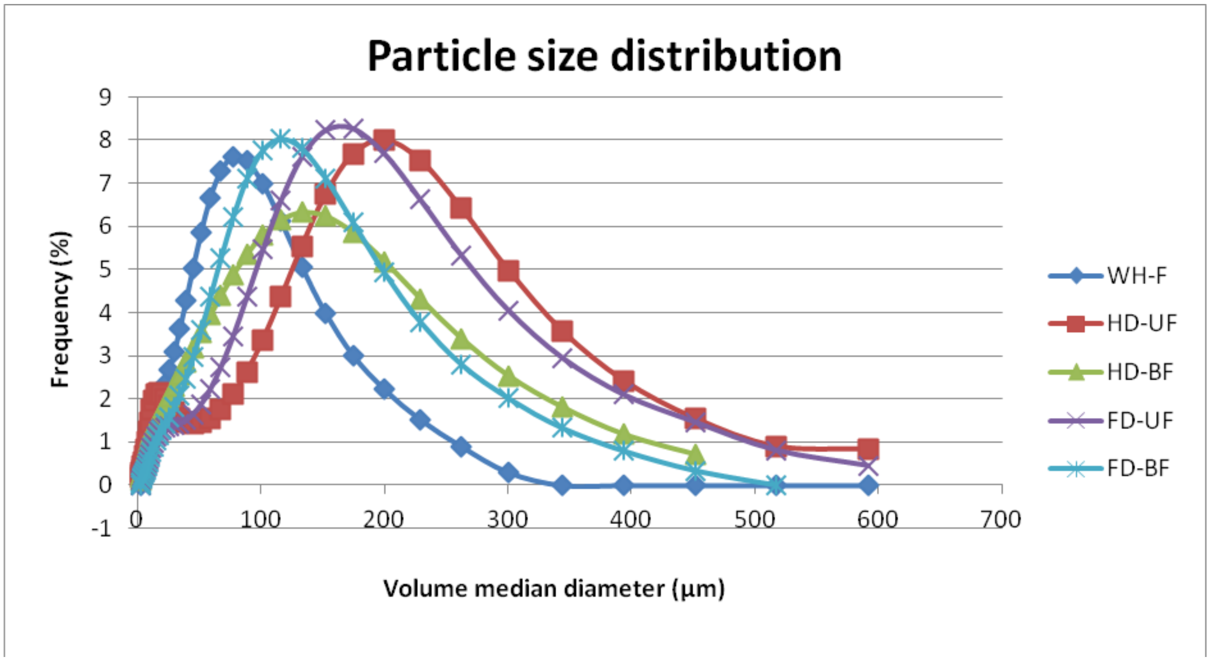

**Figure 4-2:** Particle size distribution for OFSP flour produced by Windhexe, Hot air drying and Freeze drying.

FD-BF: Freeze-dried Blanched Flour, FD-UF: Freeze-dried Unblanched Flour, HD-BF: Hot air dried Blanched Flour, HD-UF: Hot air dried Unblanched Flour, WHF; Windhexe dried flour.

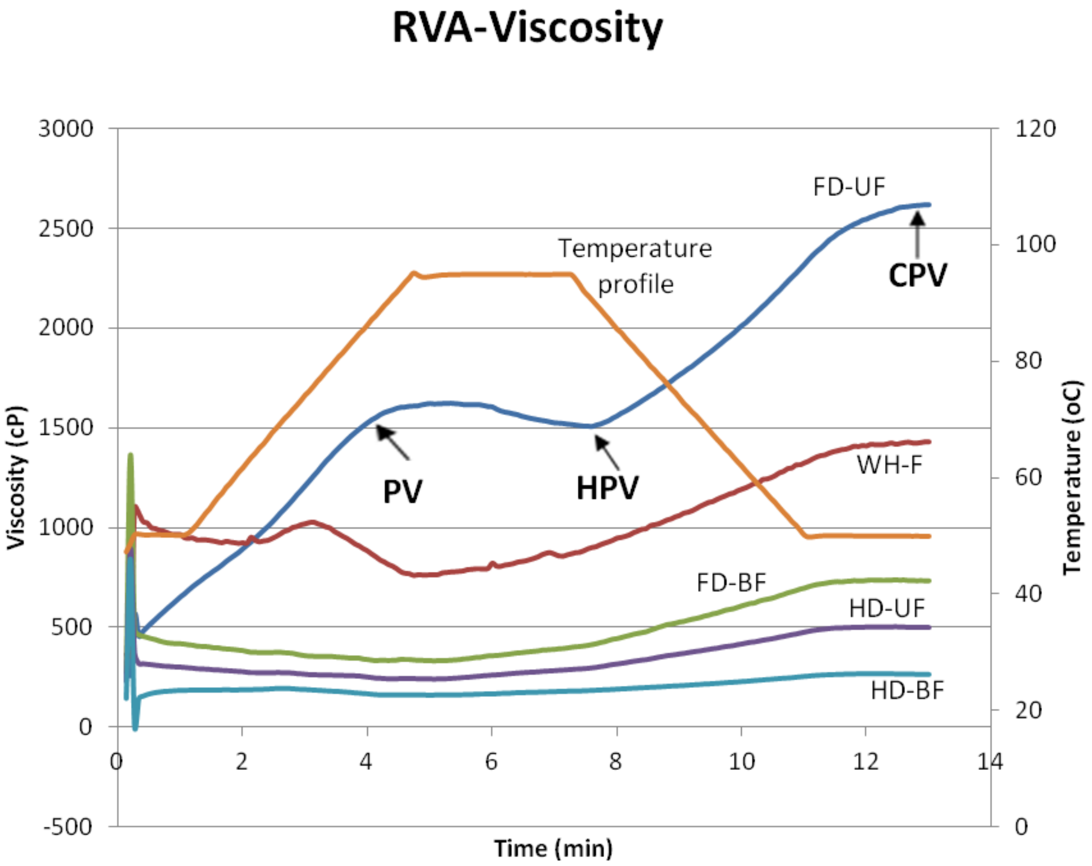

**Figure 4-3:** RVA results for OFSP flours produced by different drying technologies

PV: Peak viscosity, HPV: Hot paste viscosity, CPV: Cold paste viscosity, FD-BF: Freeze-dried Blanched Flour, FD-UF: Freeze-dried Unblanched Flour, HD-BF: Hot air dried Blanched Flour, HD-UF: Hot air dried Unblanched Flour, WH-F; Windhexe dried flour.

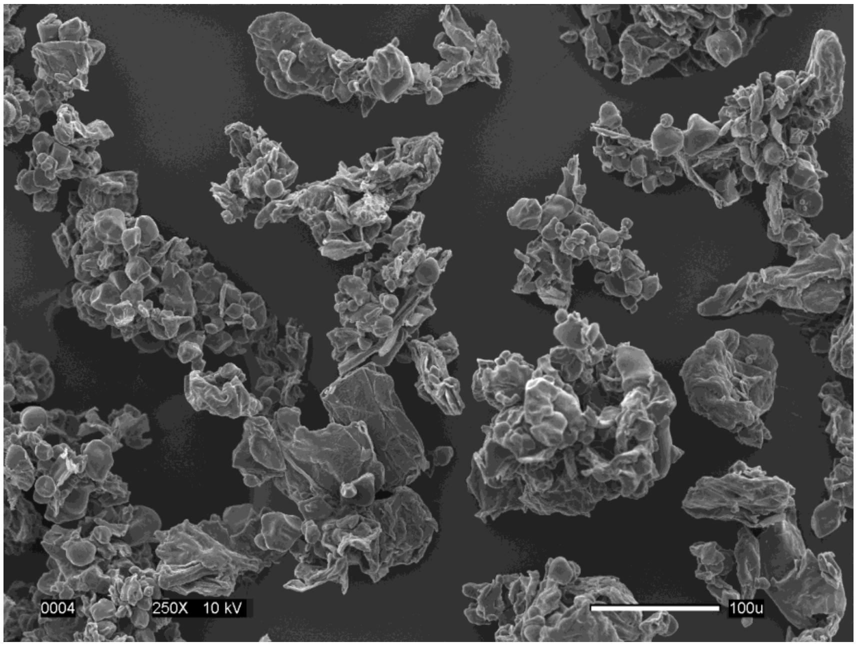

**Figure 4-4: Particle morphology – WH 110**

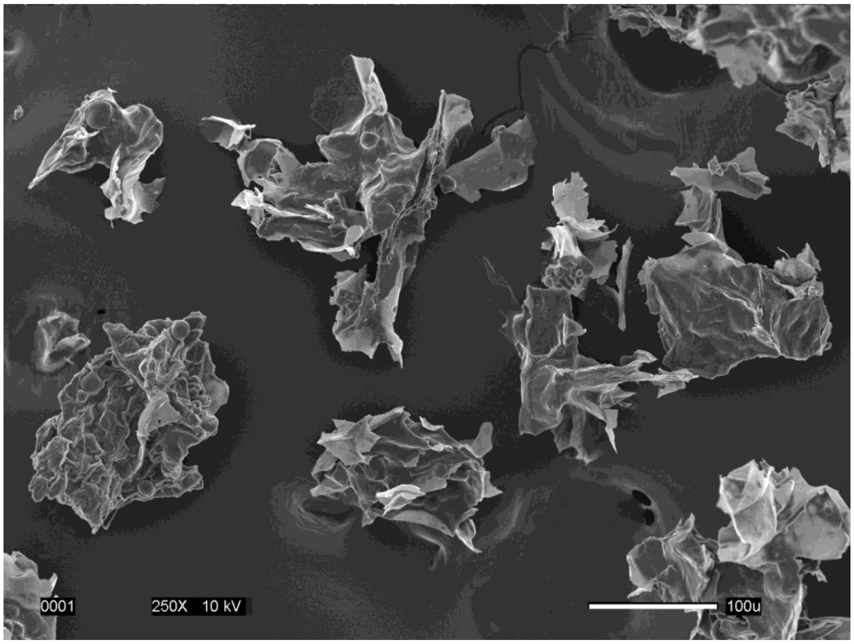

**Figure 4-5: Particle morphology – FD-UF**

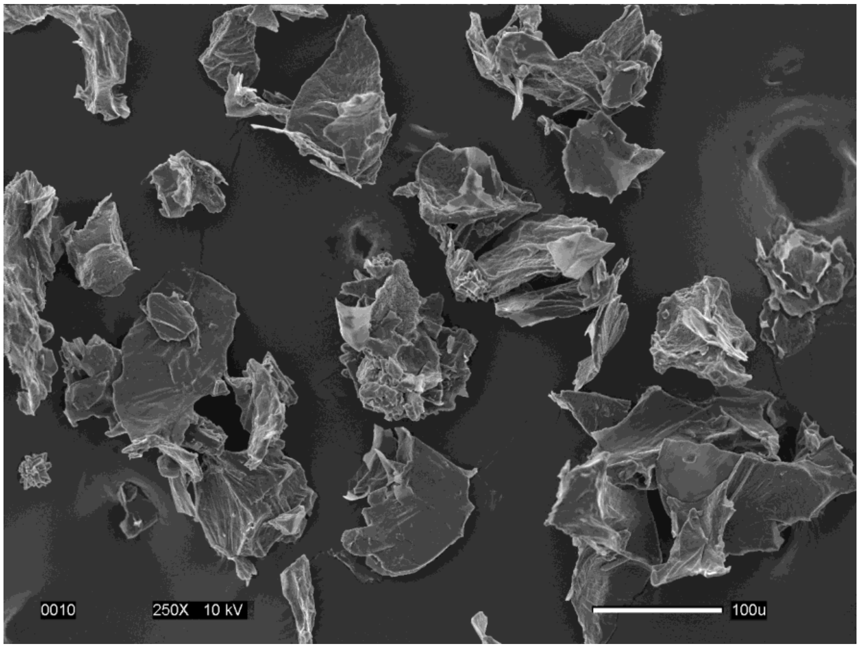

**Figure 4-6: Particle morphology – FD-BF**

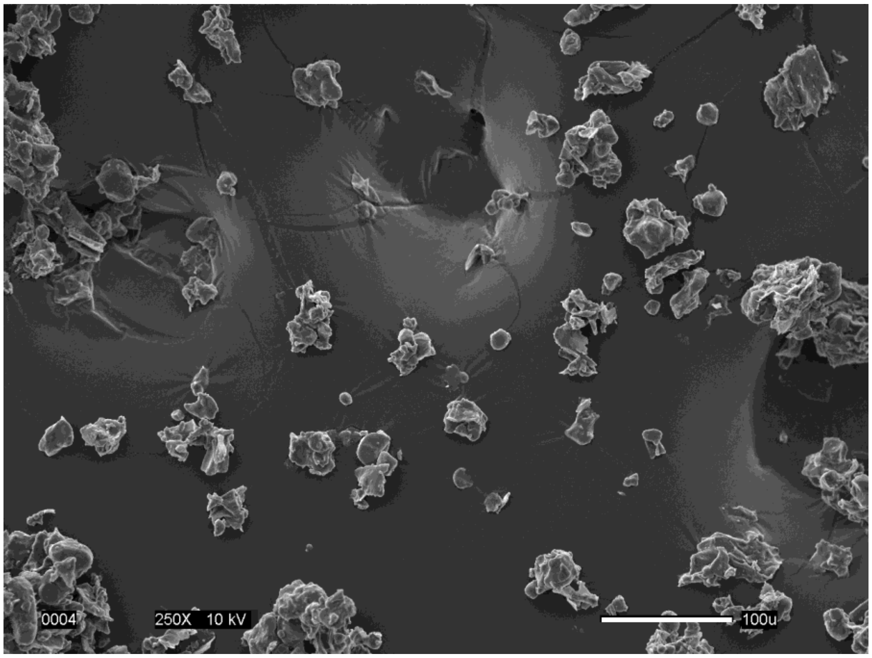

**Figure 4-7: Particle morphology – HD-UF**

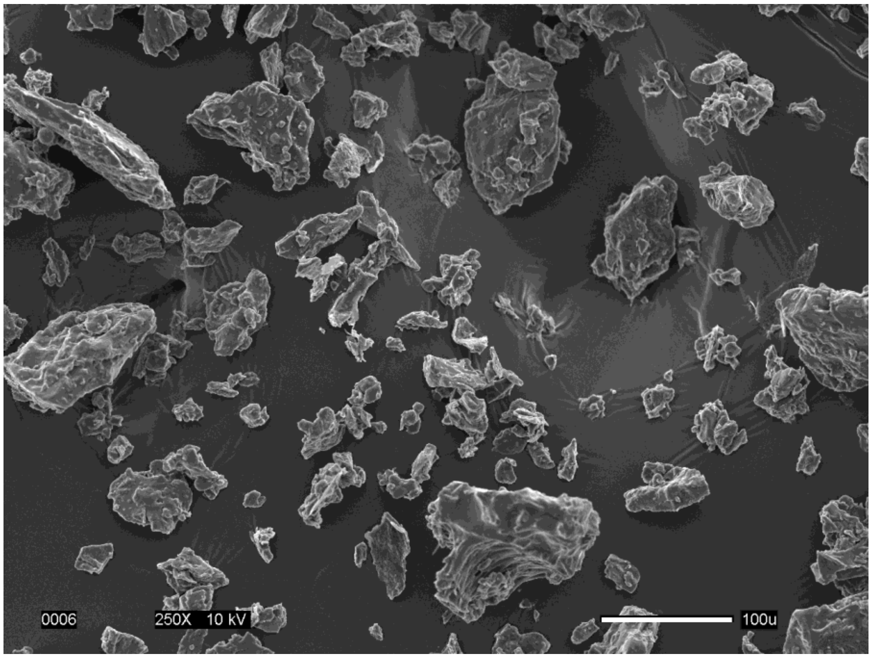

Figure 4-8: Particle morphology – HD-BF