

# **DEVELOP RAPID DRYING TECHNOLOGIES AND INNOVATIVE VALUE-ADDED DRIED NATURAL PRODUCTS FROM RABBITEYE BLUEBERRIES**

by

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(Under the Direction of Yen-Con Hung)

## **ABSTRACT**

Individually Quick Frozen (IQF) rabbiteye blueberries (*Vaccinium ashei*.) were dried in an air-impingement oven using two different configurations (A and B) to a water activity of  $0.55 \pm 0.05$ . Conventional forced air oven (C1) and a jet-zone fluidized bed dryer (C2) were used as control methods. The effect of pretreatment, cultivar (Brightwell and Powderblue), pick time (1 and 2), grade (A and C), drying temperature (85 and 107°C) and drying method on drying time and physico-chemical properties of dried blueberries was investigated. Moderate thawing (~20 min) at room temperature followed by surface scarification increased drying rate. Drying times were lowest for C2 followed by B, A and C1 at both temperatures. Drying method, temperature, cultivar and interactions among them showed significant effect ( $P \leq 0.05$ ) on drying time. Different variables and their interactions showed significant effect on composition, texture, bulk density and color of dried blueberries. Impingement oven showed promise to dry rabbiteye blueberries.

**INDEX WORDS:** Rabbiteye blueberry, drying, impingement oven, physico-chemical properties

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B.Tech. (Food Technology), Osmania University, INDIA, 2004

A Thesis Submitted to the Graduate Faculty of the University of Georgia in Partial  
Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2011

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December 2011

## **DEDICATION**

To my parents Lingamurthy and Vijayalakshmi; and my brother Ramesh for their unconditional love and encouragement in whatever decision I have made.

## **ACKNOWLEDGEMENTS**

I would like to express my profound gratitude to Dr. Yen-Con Hung, my major professor for his invaluable support, guidance and encouragement throughout this program. Thank you Dr. Hung for being my mentor and guiding me to achieve one of my unaccomplished dreams.

I would like to thank our department head Dr. Rakesh Singh for his support during initial adjustments at UGA. My special thanks to Dr. Manjeet Chinnan for all the help provided for the realization of this project. I never forget his support and guidance throughout this project. Also, I would like to thank Dr. Robert Phillips and Dr. William Kerr for serving on my committee.

I should admit that my research would not have been complete without technical help and suggestions from Mr. Glenn Farrell. Glenn, thank you for all the help and encouragement that you provided me during this research. Moreover, my sincere appreciation to Mr. Lary Hitchcock, Ms. Joy Adams, Ms. Sandra Walker and Ms. Sue Ellen McCullough for their help and support.

My sincere thanks to Mr. John Ed. Smith for providing blueberries to my research and helping me to conduct experiments on dryer at Alma, GA and Mr. Jerry Davis for helping me with statistical analysis of research data. I would like to thank my research group Dr. Pangloli, Dr. Hamanaka, Dr. Mi-Jeong, Brian and Sailaja for their encouragement.

Finally, I would like to thank Vijay Suvarnam and Venu Boppa for their support. In addition, I would like to extend my thanks to all my friends for their encouragement and moral support throughout this journey.

This study was supported by a grant from the U.S. Department of Agriculture Specialty Crop Block Grant Program to the state of Georgia and by the State and Hatch funds allocated to the University of Georgia Agricultural Experiment Station, Griffin Campus.

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**CHAPTER 1**  
**INTRODUCTION**

The Blueberry, genus *Vaccinium* belongs to the family *Ericaceae* is a perennial crop and native to the North America and gaining popularity in other parts of the world as well. In recent years, blueberries have been included in a category of functional foods called super fruits because of their favorable combination of nutrient richness, antioxidant strength, and emerging evidence of health benefits (U.S. Highbush Blueberry Council, 2010).

Blueberries are almost spherical, depending on the species and cultivar between 7 mm to 15 mm in diameter with a purple-blue to blue-black epidermis or skin that is covered by a waxy or slivery sheen called a “bloom”, giving fruit a light blue appearance. The flesh is creamy-white to green in color and juicy. They contain up to 100 very small seeds in a central core (Stuckrath and Petzold, 2007).

U.S. cultivated and wild blueberry production reached around 456 million pounds, which was, valued around 508 million dollars (National Agricultural Statistical Services (NASS), U.S. Department of Agriculture (USDA), 2009). Rabbiteye blueberry (*Vaccinium ashei*) is highly productive in south eastern region of the USA. It is tolerant to high summer temperatures and has only moderate chilling requirement making it ideally suitable for southeastern states, particularly Georgia, Florida and Alabama (Basiouny, 1996). In Georgia, rabbiteye blueberry production increased rapidly from several years and is reached 43 million pounds with a value of 55.6 million dollars (NASS, USDA 2009).

Blueberries have brief harvest season and short shelf-life. The keeping quality of fresh form can be extended up to two weeks at -0.5 to 0°C with >90% RH, for lowbush and highbush blueberries ( Perkins-Veazie and others 1995), and up to four weeks for

rabbiteye blueberries (Miller and others 1988). Under controlled atmosphere 10-15% CO<sub>2</sub>, 1-10% O<sub>2</sub> and at below 5°C, shelf life can be extended up to six weeks (Miller and others 1988, Prange and Asiedu 1995). High perishability and short shelf-life is a concern to many blueberry growers and processors. Increase in production and rapid machine harvesting aggravated the problem further.

Drying blueberries is a common practice to increase the shelf-life, to preserve overall quality, and to reduce packaging, transportation and storage costs. Several drying methods are available for drying blueberries. However, most of the existing methods are relatively expensive, complicated or time consuming. Also, very limited information is available on the effect of cultivar, harvest time and grade on drying characteristics and final product quality. Any study to address the issues related to drying blueberries would be very useful for growers and processors.

Hence there is a need to develop efficient drying technologies and innovated value added dried natural products to increase market potential of this wonder fruit.

This research work focuses on two major objectives:

1. To study the effect of pretreatment, cultivar, grade and drying temperature on drying characteristics of individually quick frozen (IQF) rabbiteye blueberries.
2. To determine the effect of drying method on drying time and physico- chemical properties of previously frozen rabbiteye blueberries.

The present thesis includes five chapters. The first chapter is an Introduction. The second chapter presents theory and literature related to blueberries, production statistics, composition, health benefits, drying methods, and methods for measuring physical and chemical properties. The third chapter discusses the effect of blueberry cultivar, grade,

drying temperature on drying characteristics of rabbiteye blueberries. The fourth chapter presents the effect of cultivar, pick time, grade, drying temperature and drying method on drying time and physico-chemical properties of dried blueberries. The fifth chapter summarizes chapter 3 and 4 and presents general conclusions.

## References

- Basiouny, F. M. (1996). "Blueberry fruit quality and storability influenced by post-harvest application of polyamines and heat treatments." Proc.Fla.State Hort.Soc 109: 269-272.
- Miller, W.R., McDonald, R.E., and Crocker, T.E., (1988). "Fruit quality of rabbiteye blueberries as influenced by weekly harvests, cultivars, and storage duration." Hort.Science 23: 182-184.
- NASS, 2009. Agricultural Statistics Board, United States Department of Agriculture, Noncitrus Fruits and Nuts 2009 Summary. Retrieved November 25, 2010 from the World Wide Web  
[http://usda.mannlib.cornell.edu/usda/nass/NoncFruiNu//2010s/2010/NoncFruiNu-07-07-2010\\_new\\_format.pdf](http://usda.mannlib.cornell.edu/usda/nass/NoncFruiNu//2010s/2010/NoncFruiNu-07-07-2010_new_format.pdf)
- Prange, R. K., Asiedu, S. K et al. (1995). "Quality of Fundy and Blomidon Lowbush Blueberries - Effects of Storage Atmosphere, Duration and Fungal Inoculation." Canadian Journal of Plant Science 75(2): 479-483.
- Perkins-Veazie, P., Clark, J. R., Collins, J.K. and Magee, J. (1995). "Southern highbush blueberry clones differ in postharvest fruit quality." Fruit Var.J. 49: 46-52.
- Stückrath, R., and Petzold, G., 2007. Formulación de una pasta gelificada a partir del descarte de arándanos (*Vaccinium corymbosum*). Inf. Tecnol. 18:53-60.
- USHBC, 2010. United States Highbush Blueberry Council, Folsom, California, U.S.A. Blueberry information. Retrieved December, 2010 from the World Wide Web  
<http://www.blueberry.org>
- Vega-Galvez, A., Lemus-Mondaca, R., et al. (2009). "Kinetic Study of Convective Drying of Blueberry Variety O'neil (*Vaccinium corymbosum* L.)." Chilean Journal of Agricultural Research 69(2): 171-178.

**CHAPTER 2**  
**THEORY AND LITERATURE REVIEW**

## **Blueberry**

Blueberries are native to the North America and over the years blueberry cultivation spread into various other parts of the world as well. From 1995 to 2007 world blueberry acreage grew by 254 percent, from 57,122 acres to 144,807 (U.S. Highbush Blueberry Council (USHBC), 2007). United States of America and Canada are the leading blueberry producers in the world, accounting for ~90% of the production and rest of the contribution is mainly from Europe, Australia, New Zealand, China and South American countries. With new countries like Philippines, Japan, South Korea and some African countries adding to the list; world production is projected to increase from 494 million pounds in 2009 to more than 800 million pounds by 2012-13 (USHBC, 2007).

Blueberries are popular in USA owing to their high nutritional quality. The production and utilization of blueberries in USA increased rapidly from last couple of years and it reached around 456 million pounds (81% cultivated, 19% wild) with a value of 508 million dollars (USHBC, 2007). Region wise contribution of cultivated blueberries can be divided into Mid-west 28%, North West 30.5%, East 15% and South 26.5%. In southern states, Georgia is the leading producer (44%) of blueberries which are native to this region (U.S. Department of Agriculture, National Agricultural Statistics Service (NASS), 2009). There are hundreds of different varieties of blueberries around the world with various botanical names. Initially, blueberries are grown as wild “highbush” and “lowbush”; later due to the development of agricultural research wild highbush varieties are successfully cultivated as per the commercial and consumer needs. In the U.S. blueberries can be divided into three commercial varieties (USHBC) as follows:

**1. Northern Highbush** (*Vaccinium corymbosum*), also called as modern highbush which is cultivated from wild highbush. The highbush varieties survive in the cooler climates and native to the North American regions and mostly sold in fresh market during the season.

**2. Southern Rabbiteye** blueberries (*Vaccinium ashei*) are cultivated from wild highbush to suit the southern high temperatures and named after the berry calyx resembles eye of a rabbit. Mostly, these berries are marketed as fresh and surplus berries are frozen stored for later use and value addition.

**3. Lowbush or Wild** blueberries (*Vaccinium angustifolium*) are widely grown in the northeastern states of United States and eastern provinces of Canada. The berry size is very small and is widely used for food processing applications.

### **Rabbiteye blueberries**

Rabbiteye blueberry (*Vaccinium ashei*) (Fig.2.1) is popular in southeastern region of the USA. It is tolerant to high summer temperatures, high drought resistance and has only moderate chilling requirement making it ideally suitable for southeastern states, particularly Georgia, Florida and Alabama (Basiouny, 1996). Georgia's blueberry industry has experienced remarkable growth from zero in 1995 to 10,500 acres in 2009. More than 90% of the blueberry acreage in Georgia is contributed by Rabbiteye blueberries (Scherm and Krewer 2003).

Harvesting southern highbush blueberries (*Vaccinium corymbosum* L.) begin in May and Rabbiteye blueberries (*Vaccinium ashei*) from late May. When rabbiteye blueberries are ready for harvest, the fresh market is already saturated with northern and southern highbush blueberries (Su and Chein 2007). Hence, significant amount of Rabbiteye

blueberry production were frozen stored for later usage and value addition. Among rabbiteye cultivars, Windy, Snowflake, Savory, Backyblue, Aliceblue, Veron\*, Premier\*, Alapaha\*, Climax, Austin\*, and Bonita are early season varieties (mid -May to mid-June); Bluegem, Ira, Brightwell\*, Woodard and Chauca are mid-season varieties (mid-June to mid-July); Bluebelle, Delite, Briteblue, Tifblue, Choice, Columbus, Yadkin, Powderblue\*, Baldwin, Ochlockonee and Centurion are late season varieties (mid- June to early August). The cultivars with asterisk mark (\*) are identified as commercially most promising cultivars in south Georgia (Krewer and NeSmith 2006). Depending on weather conditions, the harvesting time may vary few weeks earlier or later. Due to variability in harvesting times, mid and late harvests of Rabbiteye blueberries have higher potential for value addition.

### ***Cultivars of Research Interest***

#### **Brightwell**

Brightwell is released by University of Georgia Coastal Plain Experiment Station, U.S.A. in 1983 (Fig.2.2) and in recent times it is becoming one of the highly productive cultivars in south Georgia. It is also reported as one of the reliable cropping cultivars. In south Georgia, harvesting time may vary from early-mid June to mid-July and it last for about 35 days. The berries are medium to large in size, have small, dry stem scars, and have good flavor and color. The berries are very firm and round and ideal for packing on a mechanical packaging line. Fruits are susceptible to severe cracking under wet conditions during maturation stage (Krewer and NeSmith 2006).

### **Powderblue**

Powderblue is released by NC State University, U.S.A. in 1978 (Fig.2.3).

Approximate ripening time in south Georgia is late June to early August. Berries are medium in size and with very light blue in color. Powderblue berries have a small, dry stem scar, and have average firmness and flavor. Powderblue is regarded as an improved version of commercially successful Tifblue and resembles very closely in appearance, quality, and other characteristics (Krewer and NeSmith 2006).

### ***Harvesting and Grading***

Highbush and rabbiteye blueberries are cultivated in long straight rows and the plants are pruned into shapes that facilitate harvesting. Highbush varieties can tolerate high chilling temperatures and rabbiteye varieties can tolerate wide range of temperatures and require moderate chilling conditions. Blueberries can be hand-picked or machine harvested. For commercial applications, majority of the blueberries are mechanically harvested with specially designed blueberry harvesters. Most of the mechanical harvesters are driven by vertical bars perpendicularly attached with several fish scale rods or paddles. These rods and paddles will rotate and vibrate when passing through a blueberry bush and shake loss the ripened berries onto conveyor belts underneath for collection (Fig.2.4). Harvesting is done several times in a season on a single field allowing sufficient time for the immature fruits to ripen.

Sugar content of fruit will increase during maturation to about 15% when fruit is ripe. Accumulation of sugars during ripening will increase sweetness. Sugar content will not increase after harvest but acids will break down which reduce tartness. Size of the berry will increase during maturation due to continuous uptake of water. Based on time of

harvesting; fruit is designated as Pick-1, Pick-2, Pick-3 etc. Even though cost of mechanical harvesting is low (approximately 10 cents per pound) compared to manual harvesting (which is around 80 cents per pound) as per Georgia growers information, it can reduce fruit storage life by half due to bruising and rough handling compared to hand harvesting (Perkins-Veazie, 2004). High quality blueberries should be free of injury, decay, sunscald, and are fully blue in color with little or no red at the stem end, and appear, as well as feel, turgid (Perkins-Veazie, 2004). Postharvest shelf-life of blueberries can be increased by rapidly cooling fruit after harvest. Frozen blueberries are segregated into different market grades. As per United States Department of Agriculture (USDA) Standards, frozen blueberries are graded as A, B, C and D on a 100 point scale based on color (20 points) absence of defects (green berries, cap stems and clusters, 40 points) and character (whole, firm, fleshy and intact, 40 points). U.S. Grade A or U.S. Fancy should have not less than 90 points with good color, practically free from defects and good character. U.S. Grade B or U.S. Choice and U.S. Grade C or U.S. Standard should have a total score of not less than 80 and 70 points respectively. The frozen berries which fail to meet the requirements of U.S. Grade C are considered as U.S. Grade D or Substandard.

### **Composition**

Type of cultivar, growing conditions, fruit maturity and other variables affect composition of blueberries. As per USDA National Nutrient Database (For standard reference, Release 17 (2004)), 100g of fresh blueberries consists 84.21% Water, 2.4% Dietary fiber, 0.74% Protein, 0.33% Fat and 0.24% Ash and 12.08% carbohydrates.

Blueberries are also a potential source of micro nutrients like minerals (Ca, Cu, Fe, Mg,

Mn, P, K, Se, Na and Zn) and vitamins (Vitamin C, Thiamin, Riboflavin, Niacin, Pantathenic acid, Vitamin B6, Folate, Vitamin A and Vitamin E).

Blueberries are known for their strong antioxidant activity (Wang, Cao and others 1996) which may be attributed to the presence of flavonoids (polyphenols, anthocyanins) and ascorbic acid. Anthocyanins are widely distributed among many fruits and vegetables including blueberries. Anthocyanins are also natural pigments and responsible for the blue, purple, violet and red colors of fruit (Wang and Cao 1997, Prior and Cao 1998). Anthocyanins are one of the main classes of water-soluble flavonoids and contribute significantly to the antioxidant activity (Lapidot, Harel and others 1999). Among various fruits and vegetables studied, blueberries exhibit one of the highest in vitro antioxidant capacities (Francis, 1989, Gao and Mazza 1995, Wang, Cao and others 1996). Wild lowbush and cultivated highbush blueberries have been reported to have very high antioxidant activity (Prior and Cao 1998, Kalt, Ryan and others 2001). The average content of total anthocyanins, total polyphenols and antioxidant capacity of rabbiteye blueberries were higher than those of southern highbush (Sellappan, Akoh and others 2002). Late harvests of rabbiteye blueberry cultivars (Tifblue and Brightwell) were reported to have higher antioxidant activity than early harvests, as determined by their oxygen radical absorbance capacity (ORAC) (Prior and Cao 1998). In a study conducted by Lohachoompol and others (2008), rabbiteye cultivars of Climax, Powderblue and Brightwell found to have significantly higher anthocyanin content than highbush cultivars of Crunchie, Star and Sharpe and concluded that environmental factors play significant role in the development of anthocyanin fractions. Among different berry types, blueberries are well known for their complex anthocyanin pattern and high total

anthocyanin content. Besides anthocyanins, blueberries are excellent source of proanthocyanidins. Specific benefits associated with these components in blueberries were reported by Garcia-Viguera and others 1997, Kalt and others, 1999, Zheng and Wang, 2003.

### **Health benefits**

Blueberries are good source of various health-promoting bioactive substances (Lila, 2004, Wang and Chang 2005) like flavonoids (such as flavonols, Hakkinen and Torrenon, 2000), Polyphenols (anthocyanins and proanthocyanins) and others (Cao, Booth and others 1998). These compounds exhibit excellent antioxidant properties which help in cardiovascular protection, antidiabetic properties, vision improvement, inhibition of carcinogenesis and mutagenesis (Camire, 2000), neuroprotective properties (Yodium and others 2000), anti-adhesion activity (Schmidt, Erdman and others 2000), and antimicrobial activities against human pathogens (Puupponen-Pimia and others 2001). Treatments with extracts from blueberries reduced oxidative stress and age-related declines in normal function in vitro and in vivo (Joseph, Shukitt-Hale and others 1998). Lowbush blueberries are reported to contain a range of compounds that protect against the initiation, promotion and progression stages of carcinogenesis (Kraft and others 2005). Rats pre-treated with blueberry, spinach and spirulina diets for four weeks had neuroprotective effects against transient focal ischemia (Wang, Chang and others 2005). These bioactive compounds are free radical-scavengers and can potentially interact with biological systems, conferring enzyme-inhibiting, anti-bacterial and antioxidant effects (Cowan 1999, Parthasarathy 1998, Serafini and others 1998).

## **Blueberry products**

Growing awareness of health benefits on consuming blueberries contributed to an increase interest in both fresh and processed blueberries of various forms. Blueberry consumption in the United States increased 13% in the year 2009 compared to the previous year (North American Blueberry Council (NABC) Statistical Report, 2009) and per capita consumption of blueberries in the United States increased more than 70% in last ten years (USHBC). More than 50% of the cultivated blueberries are sold in fresh market and surplus amount is frozen to retain flavor and ensure overall quality for further processing and usage. Cultivated highbush and rabbiteye varieties are bigger in size and sold as both fresh and frozen blueberries whereas characteristics of lowbush or wild blueberries are more suitable for commercial food processing applications and hence they are sold mostly as frozen blueberries. Freezing of fresh blueberries can be done in several different ways. Generally blueberries are Individually Quick Frozen (IQF), case frozen and block frozen to maintain quality. According to USHBC reports, blueberries are utilized in several different food processing applications throughout the world and in 2008, more than 1300 new blueberry containing products were introduced in the USA with sector wise breakdown as bakery 22%, non-alcoholic beverages 17%, snacks 12%, dairy 11%, sweet spreads 8%, sugar and gum confectionery 7%, desserts and ice creams 6%, breakfast cereals 4%, chocolate confectionery 4%, fruits and vegetable products 3%. An estimated 16% of North America blueberries are exported in 2009 and Japan is the most popular export market for blueberries and related products (USHBC).

## **Processing effects**

Consumers are well informed with the health benefits of eating diet rich in fruits and vegetables. However, issues related to seasonal availability, market accessibility, cost, and time restraints may limit consumption of fresh fruits and vegetables on daily basis. Frozen, canned or dried products may be selected over fresh products because of convenience and shelf life. These products undergo a wide variety of processing steps, which could alter or diminish nutritional and bioactive components (Schmidt and others 2004). Table 2.1 is a list from US Highbush Blueberry Council on a range of different formats of processed blueberry for food applications. Freezing and drying are two possible methods to preserve blueberries but the severity of both processes might destroy phenolics, anthocyanins and their antioxidant properties (Lohachoompol and others 2008, Talcott and others 2003). In blueberries and other small fruit, the effects of food processing have been studied from the standpoint of color quality as affected by pigment stability under various conditions. Heat, pH, oxygen and various storage conditions are known to have marked effects on anthocyanin stability (Kalt, McDonald and others 2000, Skrede, Wrolstad and others 2000). Heat treated blueberry products suffered significant losses in antiproliferative activity even in products in which total phenols and in vitro antioxidant activity were maintained (Schmidt and others 2004). A study reported that processing of blueberries caused an overall loss in total procyanidins, and their retention in processed samples stored for six months was better with canning (22-30%) as opposed to juices (8-11%) or puree (7%) (Brownmiller and others 2009). Factors like fruit maturity, genetic differences, preharvest environmental conditions, postharvest storage conditions, and processing may also impact antioxidant activity. Storage at ambient or

above ambient temperatures will positively affect phenolic metabolism to enhance the antioxidant capacity and therefore the functionality of some fruit crops (Kalt and others 1999a). Blueberry skins were higher in anthocyanins, polyphenolics and antioxidant activity compared to the flesh or seed fraction. Combination of heat, SO<sub>2</sub> and citric acid treatments increased anthocyanin and polyphenolics extraction from blueberries and blueberry skin (Lee and others 2004). A study reported that juice processing of highbush blueberries resulted in recoveries of only 32, 35, 43 and 53% of anthocyanins, flavonols, procyanidin and chlorogenic acid respectively. These losses occurred during milling and depectinization and are attributed to polyphenol oxidase (Skrede and others 2000). Hence processing of blueberries for preservation and value addition in different ways will have marked effect on nutritional components.

## **Drying**

### *History*

Drying is a process in which water is removed from the foods to halt or slowdown the growth of spoilage microorganisms and occurrence of deteriorative chemical and enzymatic reactions. It is one of the oldest and most common form of food preservation. Since prehistoric time, fruits, vegetables, fish and meats have been known to be preserved by drying. Drying fruits is an age-old practice which was in use in Biblical times by Persians, Greeks, and Egyptians. The first known record of drying involved vegetables and appeared in the 18th century (Van-Arsdel and Copley 1973). Sun drying was the method used in those early times. Thereafter, development of the drying industry was closely related to war scenarios but use of dried foods was not very popular among the domestic consumers. In the latter part of 19th century, attempts were first made to use

other sources of heat to commercialize drying process. Many years of experience and trial-and-error methods as well as research done during the last hundred years resulted in development of variety of drying methods and drying equipment (Lewicki, 2006).

### ***Mechanism and Consequences of drying***

Dehydration is also used in synonymous to drying but there is slight distinction between them. Drying implies, the process of moisture removal due to simultaneous heat and mass transfer. It is primarily removal of moisture in the vapor phase, whereas dehydration includes moisture removal that can be done without addition of heat like compression, pressing, filtration etc., (Venkatachalapathy and Raghavan 1998). The United States Department of Agriculture (USDA) lists dehydrated foods as those with no more than 2.5% water (dry basis), while dried foods apply to any food product with more than 2.5% water (dry basis) (Vega-Mercado, Gongora-Nieto and others 2001).

Drying involves the use of artificial heats; which imparts energy to the water molecule or changes the environment so that the molecule has sufficient latent energy to vaporize, and removed from the food as a water vapor by special means in the dryer. Drying not only affects the water content of the product, but also other physical and chemical characteristics such as water activity, sorption isotherms, microbial spoilage, enzymatic and non-enzymatic reactions, and destruction of nutrients and flavor (Vega-Mercado and others 2001). Removal of water increases concentration of soluble solids and reduces thermodynamic water activity thus prevent the growth of microorganisms that cause spoilage reactions (Babalís and Belessiotis 2004), so that the food will be shelf stable for extended period of time. At the same time increased concentration of solubles can promote chemical and enzymatic reactions due to higher concentration of reagents

and catalysts. Changes of pH, redox potential and solubility as a result of moisture removal may affect structure and functionality of biopolymers. Depending upon the porous nature of the food product, water removed from the material is, at least in part, replaced by air and contact with oxygen is substantially increased. Shrinkage and shape distortions, fading of natural color or discoloration, decreased flavor and unappetizing texture and poor rehydration characteristics are the most evident defects of dried products. Drying will extend the shelf-life of the product under proper storage conditions, because high degree of inhibition of bacterial, enzymatic, and mold actions is achieved. Dried foods have substantially lower transportation, handling, and storage costs and do not require costly refrigeration during transport and storage (Somogyi and Luh 1986). It also reduces the food weight and sometimes the volume (Vega-Mercado and others 2001). Seasonality, market accessibility and costs commonly limit the consumption of fresh fruits and vegetables, so dehydrated products are preferred over fresh products for their convenience, availability and shelf-life (Azzouz, Guizani and others 2002). Drying hardly affects the main calorie-providing constituents of fruits. It leaves the mineral content virtually unchanged and vitamin losses are no greater with drying than with other preservation methods (Luh and Woodroof 1988). Drying provide a consistent product and that can be sized, shaped, formed to fit almost any requirement (Somogyi and Luh 1986).

### **Drying methods**

Several drying techniques have been used for the purpose of drying foods however; the most common and widely used drying methods for fruits and vegetables were discussed in this section.

***Sun or Solar Drying:*** Sun or Solar drying is the most primitive and common method of drying under the sun light and natural wind flow. It is the most inexpensive method of drying and large quantities of product can be dried together at a time as batches. The quality of sun dried product is a major concern and the drying process is uncontrollable. Drying of fruit at different temperatures and over extended times leads to color deterioration as a result of enzymatic and non-enzymatic browning and destruction of natural fruit pigments (Toribio and others, 1986). The non-uniform and variable texture of sun dried product is also a major problem. In general, sun drying will not lower the moisture content of fruit below 15%; therefore, the shelf life of such fruit products does not exceed 1 year, unless they are held in cold storage.

***Kiln and Tower Driers:*** Gould (1907) reported that non-commercial small dehydrators (cook-stove or portable evaporators) are used in olden days which relied on natural draft from rising heated air brings about the drying small amount of fruit at one time. Later improved versions of dehydrators known as Kiln and Tower driers are came into existence. Kiln driers generally have two levels. A furnace or burner is located at the bottom part of the kiln and heated air and/or combustion gases rise through the slotted floor and through the fruit slices in upper part. Tower driers also works under same principle but fruit pieces are stacked in trays along the tower. As the fruits on the bottom trays of the stack become dry, they removed and replaced with freshly loaded trays on the top of the stack.

***Cabinet and Tunnel Driers:*** Modifications to Kiln driers by Ridley (1921) resulted in tunnel and cabinet dryers which are in wide commercial use until now. Eidt (1938) discovered two stage short tunnel dryer with a finishing chamber for dehydrating apples.

This kind of dryer produced dried product with good overall quality by effective fuel utilization. Mark and Perry (1946), Kilpatrick and others (1975) experimented with direction of air flow (cross-flow, parallel-flow, countercurrent, and through-flow) with respect to the movement and position of fruit to increase drying rate. A cabinet drier is similar in operation to a stack/tower drier, except heat is supplied in steam coils that are located in between the trays. Tunnel drier allows continuous movement of tray-loaded trucks along a rectangular tunnel; otherwise it is same as cabinet drier. Both of these driers are very convenient for drying fruit and vegetable pieces. The duration of drying depends on type of fruit or vegetable and their characteristics.

***Continuous belt drier:*** A continuous belt (conveyor) drier replaces trays in a tunnel drier with a conveyor or a belt else there is no difference between both. It reduces difficulty and cost of handling products on trays before and after drying. The dimensions and speed of conveyor belt is variable and suit both the product and heat conditions. Process conditions are controlled by designing the drier into sections thus allowing different flow rates, humidities, and temperatures to be set in each section. An improved version of belt drier by forcing heated air upward across the belt and the product is known as belt-trough drier which keeps the food pieces in continuous motion throughout the drying process. However, belt-trough driers are not a good choice for drying fruits with high sugar content as they exude sugar and tend to stick together and clump with the tumbling motion.

***Fluidized bed drier:*** In a fluidized bed drier, airflow from beneath is sufficient to lift particles of food and at the same time convey them towards the outlet. The process is continuous, and the length of time particles remain in the drier can be regulated by the

depth of the bed and other means. They offer uniform drying due to better contact of product with the drying medium. However, higher air velocities channeling will occur and most of the air will escape without contact with product and particles may escape from the bed (Brown and others 1972). There are different variations in fluidized bed driers depending on its mode of action.

***Vacuum drying:*** It is a method of drying in a vacuum chamber under reduced atmospheric pressure to remove water from the food at below its boiling point under ambient or refrigerated temperatures. The drying time varies, depending on the kind of fruit, initial moisture, and size. The dried product will be of good quality and retaining most heat sensitive volatiles thus flavor of the dried product is preserved.

***Spray drying:*** Spray drying is mostly used in dehydration of slurries and purees into fruit powders. It involves both particle formation and drying, which makes it a special type of drying process. The feed is transformed from a fluid state into particles by spraying it continuously into a hot drying medium. It is not an useful drying method for solid foods.

***Drum drying:*** Drum dryers conduct an indirect heat transfer through a solid surface; they are generally used to produce powdered and flaked ingredients for bakery, beverages, cereal, granola and dairy foods. They consist of hollow metal cylinders that rotate on horizontal axes while heated internally by steam, hot water, or other heating medium.

***Freeze drying:*** Freeze drying or lyophilization has been used for drying heat-sensitive products at freezing temperatures under high vacuum. This method was introduced in 1940's and widely used for the production of dry plasma and blood products (Rey, 1975). Products that decompose or undergo changes in structure, texture, appearance, and/or flavor as a consequence of high temperature can be freeze dried under vacuum with

minimum damage. Freeze drying has been shown to be an attractive method for extending the shelf life of foods (Ma and Arsem 1982). Freeze dried products have the quality of being readily reconstituted and are of excellent flavor when dehydrated, however this method is not cost effective for commercial dehydration of fruits.

***Osmotic drying:*** The concentration of food products by means of product immersion in a hypertonic solution (i.e., sugar, salt, sorbitol or glycerol) is known as osmotic dehydration (Raoult- Wack and others 1989) and water removal in this process can be aided with the use of vacuum (Fito and others 1994). Application of this method for partial dehydration of fruits by osmosis in sugar or syrup has been investigated by Ponting and others (1966). The fruit is reduced to about 50% of its original weight by osmosis, after that the product can be dehydrated to the required level with other drying methods like freeze, fluidized, air or vacuum drier.

***Microwave drying:*** Microwave drying is a relatively new method. In this method microwave energy is converted into thermal energy which raise the temperature of the moist product and starts lose moisture once the vapor pressure in the food is above that of the environment. Microwave drying is very rapid and gives acceptable quality products. However, high capital investments, energy costs, uneven heating, possible texture damage are the major concerns for its wide applicability for fruit dehydration. Feng and Tang (1999) reported the advantages of combining hot air drying and microwaves in drying diced fruits (apples and blueberries) to overcome some of the constraints of microwave drying alone.

***Radio frequency (RF) drying:*** Radio frequency is being used for precooking, sterilization, tempering, and baking processes in the food industry. Radio frequency uses

electromagnetic energy to heat products; heating occurs instantly inside the product (Vega-Mercado and others 2001). This method is very rapid, uniform and gives good quality end product. This method is now widely under consideration for drying agricultural products.

***Refractance window drying:*** This is a new technology in which water is used to transmit heat into the product being dried. The product is evenly applied to the surface of a conveyor belt and infrared heat passes directly into the product. This method prevents color and flavor degradation of product because of its drying mechanism (Vega-Mercado and others 2001).

***Impingement drying:*** In this method of drying, air or super-heated steam impinges at high velocity on the product surface removing the boundary layer of moisture and cold air thus greatly accelerating heat transfer and reducing process time (Moreira, 2001). The air is continuously reheated and recirculated for moisture removal thus conserves energy. Impingement drying technique has been used successfully in the paper and textile industries. In food industries, it is used for baking and cooking products like tortilla and potato chips, pizza crust, pretzels, crackers, cookies, bread, cakes etc (Rickard, 1993). This method has also been used for drying granular products such as coffee beans, cocoa beans, rice and nuts (Moreira, 2001). Some special features of impingement drying involve rapid and more uniform convectional type of drying. Generally impingement drier consists of single gas or air jet or an array of such jets, impinging directly onto product surfaces. Some driers will be configured to impinge air or gas from both directions (impinge from top and bottom surface of product). There is a great variety of nozzle shapes and air ducts that are available and selection of the nozzle geometry and

multinozzle configuration will play crucial role in operating costs, efficiency of dryer and final quality of product. Based on the type of configuration the temperature and jet velocity, impingement drying may range from 100°C to 350°C and 10 to 100 m/s respectively. Xiao and others (2010) investigated the effect of drying temperature and air velocity on the drying kinetics and quality of monukka seedless grapes, which are subjected to thin-layer air impingement drying and concluded that compared to air velocity; the effect of drying temperature on the drying time was more significant. However, feasibility of using impingement dryer for drying different fruits and vegetables especially blueberries at different operating conditions need to be studied.

### **Blueberry drying**

Blueberries have very thin skin and small size compared to most of the fruits hence it is a difficult task to produce raisin like dried blueberries. However, over the last 70 years many researchers worked on developing various drying methods for blueberries. Few of the most notable studies are outlined below.

Friar and Mark (1943) reported a drying time of 13hr on conventional air drier for untreated blueberries. Eidt and others (1944), pretreated the berries with a hot lye dip prior to dehydration and reduced the drying time to 4hrs. However, the conventional air drying produced hard blueberries with poor rehydration characteristics. Eisenhardt and others (1964 and 1967) reported that batch explosion-puffing of high bush blueberries created rapid drying and quick rehydration characteristics. Heiland and others (1977) improved costly and labor intensive batch explosion-puffing suggested by Eisenhardt and others to make it as a continuous process and introduced the continuous explosion-puffing system (CEPS). Later Sullivan and others (1977, 1980 and 1981) successfully

processed potatoes, carrots and apples in CEPS. Sullivan and others (1982) adapted CEPS and optimized this method to process Rabbiteye blueberry cultivar Tifblue. In their study they compared the effect of pre-treatment with lye dips, mild detergent wash, steam blanch to increase the drying rate but failed to do so. However, they successfully produced dehydrated Rabbiteye blueberries with good rehydration properties using CEPS, which was believed to save 40% of energy compared to conventional air drying. The product is suitable to use in dry pastry mixes but is too hard, woody, and sour when eaten in the dry form directly.

Rahman (1972) used freeze drying method to produce densely packed blueberries for military use. Hammond (1967) reported that the freeze drying method is not commercially feasible due to long drying times and high operating costs. Guadagni and others (1975) reported that the on-the-vine drying method suggested by Petrucci and others (1974) which involves spraying ethyl ester on fruits may not be suitable to the lowbush blueberries due to a different fruit growing pattern and strong taste thresholds of ethyl ester against mild aroma of wild blueberries. The traditional sun drying process to produce raisin type blueberries is not suitable as it requires minimum 3 weeks in the field of warm weather, any inclement weather during this period can cause serious losses to the growers in terms of lower quality product and reduced yield (Somogyi and Luh, 1986). Stafford and Guadagni (1977) reported that drying blueberries using tunnel drying method will result in sticky products and consume considerable amount of energy.

Yang and others (1985) studied the effect of forced air oven, vacuum oven, micro-convection oven and freeze drying methods on the quality of intermediate moisture lowbush blueberries. Their results showed forced air and micro-convection drying

methods resulted in poor quality products when compared to freeze and vacuum drying methods. They suggested that vacuum oven combined with freeze drying may be an ideal combination for drying blueberries of better overall quality. However, Freeze and vacuum drying deemed to be too costly for large scale production (Azoubel and Murr 2003, Grabowski and others 2002).

Kim and Toledo (1987) studied the effect of osmotic dehydration and high temperature fluidized bed (HTFB) dryer on the drying time and properties of dehydrated rabbiteye blueberries. They concluded that HTFB drying reduced drying time compared to conventional air drying and also the dried product has lower bulk density with raisin like texture. Combination of osmotic dehydration and HTFB drying resulted in a product with a raisin –like texture and would be suitable for consumption in the dry state. Yang and others (1987) used combination of osmotic dehydration and freeze drying to produce raisin type lowbush blueberry product. Their studies revealed frozen blueberries are preferred to fresh blueberries as raw material for drying. Using berry to sugar ratio of 3:1 or 4:1 for osmotic dehydration followed by rinsing, freeze drying with abrupt release of vacuum, and thermal conditioning; it is feasible to produce a raisin-type blueberry product with good texture, flavor and overall acceptability. Venkatachalapathy and Raghavan (1998) used combined osmotic and microwave drying for strawberries and blueberries which were pretreated in a solution of ethyl oleate and sodium hydroxide to increase drying rate. Results indicated that the berries which were pretreated and then osmotically dehydrated for 24hr in sucrose solution followed by microwave drying reduced the final drying time. The product quality is comparable to freeze-dried product. They suggested this method was an alternative to freeze drying method. Ramaswamy and

Nsonzi (1998) worked on convective air-drying kinetics of osmotically pretreated blueberries and found that the temperature and sucrose concentration during pretreatment significantly influenced drying time and the effect of contact time was not significant.

Feng and Tang (1999) used microwave and spouted bed combined dryer (MWSB) for drying frozen blueberries. The effect of pre-treatment using a 2.5% ethyl oleate and 0.2% NaOH dipping solution followed by sucrose osmotic treatment was investigated. The physical properties of the dried product were compared with freeze, tray and spouted bed (SB) drying. They concluded that MWSB drying method substantially decreased drying time by about five times compared to tray drying at a temperature of 70°C and improved product quality. Pretreatment methods prevented bursting when microwaved but increased bulk density and resulted in low rehydration ratio.

MacGregor (2005) conducted experiments on forced air packed bed drier at air temperatures up to 65°C and studied effects of air velocity, air temperature and berry diameter on dried IQF wild blueberries. The experiments suggested that increasing air velocity would increase both drying rate and yield than increasing temperature. Drying times for all size berries reduced by 25 to 50% with increasing air velocities. Under similar drying conditions, it took longer to reach the final moisture content for larger blueberries than smaller ones, but the larger berries had a higher mass-losing rate than smaller ones.

Stojanovic and Silva (2007) evaluated the effects of air dehydration, osmotic concentration (12hrs at 21°C, 3hrs at 21°C) plus air dehydration, osmotic concentration and ultra sound plus air dehydration on nutritional and chemical properties of rabbiteye blueberries. Longer osmotic concentration time, continuous high frequency ultra sound

(CHFV) increased loss of phyto-nutrients. Decreased time of osmotic concentration, processing under reduced oxygen environment or vacuum and reuse of sucrose solution could be a good alternative to preserve nutritional properties with lower drying costs. Their results suggested that the air drying at 70°C for 10hrs with or without pretreatment can be used to produce good quality dehydrated blueberries with high nutritional value compared with treatment under high temperature, high sugar concentration and oxygen availability. Mejia-Meza and others (2008) used microwave-vacuum, hot air drying and freeze drying technologies to improve nutritional quality of dried blueberries. Hot air drying showed more negative impact on retention of some chemical components. Combined process of hot air, microwave-vacuum led to lower loss of antioxidants and their activity than hot air drying. Freeze drying resulted in a higher retention of total polyphenols and anthocyanins.

Shi and others (2008) reported drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation (IR) heating. IR drying tests were conducted at four different product temperatures (60, 70, 80 and 90°C) on catalytic infrared dryer (CIR) at 4000 W/m<sup>2</sup>. IR drying produced much firmer-texture product with much increased drying efficiency for fresh and sugar-infused blueberries compared to conventional air-drying. Increasing drying temperature from 60 to 80°C increased drying rate and decreased drying time without causing significant negative influence on the quality of dried products.

### **Pretreatment methods**

Pretreatment is an important step in designing a successful drying process. Pre-drying processing depends on the kind of material (liquid or solid) to be processed. In case of

liquids the pre-drying steps may involve but not limited to water evaporation, vacuum evaporation, membrane separation, cryo concentration, enzyme treatment and whipping etc. Solid foods can be pretreated in a number of ways which are divided into chemical, mechanical and thermal pretreatments (Lewicki, 2006).

Fruits and vegetables are subjected to certain pretreatment methods in order to facilitate drying and minimize adverse changes during drying and subsequent storage of the products (Venkatachalapathy and Raghavan 1998). Blueberries have a shining waxy outer layer which offers protection to the fruit from environmental and external factors like parasites (Grabowski and others 2002). The waxy outer layer also affects the flow of moisture from inside the fruit to its surface which is a crucial process in drying.

Pretreatment methods employing chemical dipping, mechanical methods, and thermal treatments have been used to overcome wax barrier in several applications (Azoubel and Murr 2003, Grabowski and others 2002, Yang and others 1987, Feng and Tang, 1999).

### ***Chemical pretreatments***

The chemical pretreatment of the material before drying include sulfiting, dipping in sodium chloride, calcium chloride or sugars, use of surfactants and impregnation with biopolymers (Lewicki, 2006).

### **Sulfiting**

Sulfiting is a well-known pretreatment for many solid foods especially for drying fruits. Research work in this area reported that sulfiting retard non-enzymatic browning (Burr and Reeve 1973, Ozkan and Cameroglu 2002); inhibit pectin esterase activity (Levi and others 1980). Immersion in solutions containing sulfites disinfect surface and reduces oxidation of labile food components (Jayaraman and Das Gupta 1995, Negi and Roy

2000, Sian and Soleha-Ishak 1991). It facilitates drying due to reaction with proteins and breaking disulfide bonds (Kaymak-Ertekin, 2002, Levi and others 1977), which also results in reduced firmness of the material (Riva and Masi 1988) and improved rehydration characteristics of dried materials (Barbanti and others 1991, Kaymak-Ertekin, 2002). Sulfiting causes bleaching of anthocyanins and affect color of some fruits subjected to dehydration (Sian and Soleha-Ishak 1991, Lewicki, 2006). Hence this method of pretreatment may not be ideal choice for anthocyanin rich fruits like blueberries prior to drying.

### **Salt solutions**

Soaking in sodium chloride solution prior to drying cause dewatering of the tissue. Dewatered material dries faster and better preserves color during drying (Baroni and Hubinger 1998); with improved rehydration properties (Kaymak-Ertekin, 2002). Pretreatment with calcium salts before drying retards non-enzymatic browning of fruits and vegetables (Burr and Reeve, 1973). Calcium binds to the plant cell walls and cross-links with pectins of the middle lamella (Ahmed and others 1991) hence affect the texture of dried product (Lewicki and Michaluk 2004). However, pretreatment with salt solutions prior to drying fruits adversely affects the taste of final product.

### **Sugar solutions**

Pretreatment with sugars will depend upon several factors like concentration of sugar solution (°brix), temperature, contact time etc. Extensive research has been done by many researchers on this method of pretreatment. The most important findings were that the dipping plant tissues in sugar solutions prior to drying improves rehydration characteristics of dried material, preserves its microscopic structure, reduces shrinkage,

protects color, reduces oxidation of carotenoids. The notable adverse effects include softening of the tissue, ultra structural damage and prolonged drying time (Lewicki, 2006).

### **Acid solutions**

Acid treatment prior to drying showed positive effect on reducing microbial population in many fruits and vegetables. Yohan-Yoon and others (2004) reported that immersion in ascorbic acid (3.4%) or citric acid (0.21%) reduced bacterial load of tomatoes subjected to dehydration and rendered bacterial population below detectable levels after drying and storage. Ascorbic acid solution (3.4%) reduced *E.coli* counts substantially on apple slices when subjected to hot air drying (Burnham and others 2001, Lewicki, 2006).

### **Surfactants and alkali solutions**

Surfactants widely used for fruits and vegetable pretreatment. Spraying grapes on the vine with a commercial ethyl ester mixture containing an emulsifier and added potassium carbonate allowed grapes to dry faster than the conventional sun drying procedures (Petrucci and Canata 1974) and produced light colored raisins of acceptable quality. Dipping grapes in ethyl oleate containing  $K_2CO_3$ , reduced drying time by half (Masi and Riva 1988); similar results were also observed while drying plums (Cinquanta and others 2002); apricots treated with ethyl oleate containing metabisulphite decreased drying time (Mahmutoglu and others 1995). Surfactant pre-treatment of basil leaves increased drying rate by a factor of 14 (Rocha and others 1993). Dipping in high temperature NaOH solution and ethyl oleate in boiling water increased drying rates in cranberries and blueberries (Feng and Tang 1999, Grabowski and others 2002). Blueberries dipped in

0.1% NaOH solution at 75°C, followed with a quickly rinsed under water for 30 s and wiped before IR drying increased the drying rate and moisture diffusivity, and significantly reduced the number of broken berries at high drying temperatures (Shi and others 2008).

### **Biopolymers**

Infiltration of porous structure with biopolymers can increase mechanical strength and reduce shrinkage during dehydration, as well as improve texture of the dry material (Lewicki, 2006). Dextrans provided superior texture to dehydrated carrot and potato (Mudahar and others 1990, 1991). In some cases, application of biopolymers on the surface of the processed material facilitates drying and improves quality of the final product (Lewicki and others 1998, Tripathi and Nath, 1989).

### ***Mechanical pretreatments***

Di-Matteo and others (2000) abraded the surface of seedless grapes using a shaker with abrasive wall before convection oven drying at 50°C and found that the abrasion was as effective as the traditional chemical dipping method with reduced risk of using chemicals. Grabowski and others (2007) tried 13 different pretreatment methods including chemical, thermal, combined chemical and thermal, and mechanical (perforating ten holes (1mm diameter) per berry, halving) prior to osmotic drying of cranberries. They found halving cranberries increased mass diffusion from the open-by-cut area approximately 100 times faster than that through the surface skin and provided best pre-treatment compared to other chemical and thermal methods. They also suggested that the average thickness of the wax layer on cranberries was about 5-10 times that of blueberries, and additionally freezing and thawing produced more pronounced cracks on

the blueberry surface wax layer so the resistance to mass transfer is greatly reduced and hence no pretreatment is necessary for blueberries.

Mechanical cutting of blueberries and tomatoes is not possible due to the softness of these fruit. Grabowski and Marcotte (2003) perforated the skin of cranberries before drying and found that the perforations should represent 20 to 30% of the total surface area of the berry in order the drying method to be effective. Azoubel and Murr (2003) washed and perforated cherry tomatoes with needles (1mm in diameter) to a pinhole density of 16 holes/cm<sup>2</sup>, prior to osmotic pretreatment and they are successful in increasing the uptake of salt solution and hence drying rate.

### ***Thermal pretreatments***

Yang and others (1987) reported that freezing blueberries with individual quick frozen (IQF) method directly after harvest can also be used as a pre-treatment method since slow defrost for at least 5 hrs in a 4°C resulted in slight breakdown of the waxy layer and it may be enough to increase the rate of drying without extra pre-treatment. Frozen fruits and vegetables prior to dehydration showed superior rehydration (Kompany and others 1991). Freezing disrupts tissue structure and results in better diffusion and shorter drying times (Estiaghi and others 1994). However freezing as a pre-treatment is not a cost effective method (Lewicki, 2006).

Blanching is also widely used thermal pre-treatment method. Depending on the requirement it can be done as high temperature short time (HTST) or low temperature long time (LTLT). Several researchers reported HTST method has advantages like inactivation of enzymes, changes in tissue structure which facilitate drying process, decrease microbial load, better color retention and improve puffing. At the same time it

has some adverse effects like shrinkage, loss of solubles and volatiles. Blanching adversely affected quality of the dried apricots (Prian and others 1994). On the other hand LTLT blanching results in increased firmness, reduced shrinkage, reduced tissue softening and improved mechanical strength as reported by several studies (Lewicki, 2006). High pressure treatment resulted in good color retention but incomplete rehydration (Eshtiagi and others 1994). Microwave treatment reduced water content by 10-20% in raisins and resulted in faster drying and better color of final product and it affected drying rate to the same degree as blanching in boiling water (Kostaropoulos and others 1995).

## **Quality analysis**

### ***Moisture and Water activity***

The moisture content of a product can be defined as the percentage weight of water in relation to the dry weight of the product. Based on the moisture content, products can be classified into hygroscopic (which readily absorb water) and non-hygroscopic (which do not absorb water readily). Under the conditions of static equilibrium, the moisture content of hygroscopic product will depend on the nature of the product, the temperature of the product and the partial pressure of water vapor in the immediate environment of the product. Based on absorption process, water is bound to the hygroscopic product with more or less strength as an, active (free) and inactive (bound or immobilized) forms. Water activity reflects the active part (which supports biological and chemical reactions) of moisture content which under normal circumstances can be exchanged between the product and its environment.

Water activity is defined as the ratio of the vapor pressure of water in a material to the vapor pressure of pure water at the same temperature. Under the conditions of static equilibrium water activity of the sample is equal to the relative humidity of air surrounding the sample.

$$\text{Water activity } (a_w) = P/P_0 = \%ERH / 100$$

Where P= Vapor pressure of water in a material

$P_0$ = Vapor pressure of pure water

%ERH= Equilibrium relative humidity

Water activity is also temperature dependent. The effect of temperature on the water activity of a food is product specific. Some products increase  $a_w$  with increasing temperature, others decrease  $a_w$  with increasing temperature. Dried products are shelf stable for longer duration due to controlled water activity. Water activity plays major role in determining the quality of dried product. At normal temperatures most bacteria require a water activity in the range of 0.90-1.00 for growth, some yeasts and molds grow slowly at a water activity as low as 0.65 (Potter, 2007). Hence products dried to a water activity level below 0.65 arrests the growth of microorganisms and are shelf stable under normal storage temperatures.

### ***Physical properties***

#### **Texture**

Texture, appearance, and flavor are the three major components associated with food acceptability (Bourne, 1978). Food texture has been defined as “the sensory and functional manifestation of the structural, mechanical, and surface properties of foods detected through the senses of vision, hearing, touch and kinesthetics” (Szczesniak,

2002). Texture of food can be determined by both subjective (human response) and objective (Instrumental) measurements. A vast array of instruments has been developed for measuring mechanical properties of foods, which can be related to texture of foods (Bourne, 1978). Accurate textural determinations are accomplished by measuring resistance of the product to applied force under carefully controlled conditions such as rate of applied force, temperature, and humidity. Test samples are subjected to shear, compression, extrusion, tension or other modes of action according to textural parameters of interest (Hung and Chinnan 1989).

A graduate student at Kansas State College by the name of Lyman Bratzler was assigned by his advisor, Professor Warner, a research problem involving toughness of meat. He developed a mechanical shearing device whose principle of operation is well known today as Warner-Bratzler Shear (Bourne, 1980). The test cell can be mounted on an Instron universal testing machine capable of recording motion of the crosshead and force required to shear an uniform piece of product. The Warner-Bratzler jig consists of a rigid frame supporting a shear bar and interchangeable variable shape blades fit into the frame. The force to shear the core sample using the slotted blade in compression mode is then measured by recording the resistance of the food to shearing as a function of time in a force-deformation plot. The maximum shear force is the highest peak of this curve. Although this method was developed for meat tenderness measurement; it is successfully applied to correlate texture characteristics of other food products like peanuts and dried blueberries (Hung and Chinnan 1989, Kim and Toledo 1987).

## Color

Color is one of the most important aspects of foods. Although color does not indicate whether a food is safe, a food whose color is unappealing will likely not be purchased or consumed. Products may change in color over time because of changes in ingredient source, changes over the growing season, effect of processing method and storage conditions. Color measurement ranges from subjective visual comparisons involving color chips or liquids to objective analytical tests based on physical reflectance or transmittance measurement (Mermelstein, 2010).

Objective color measurements can be performed by using colorimeters and spectrophotometers. Colorimeters measure the light reflected from or transmitted through a sample and convert the measurement into colorimetric values using filtered detectors. Both methods express color in CIE L\*, a\*, b\* or Hunter L, a, b values that represent three primary color components of light (Mermelstein, 2010). The Hunter L, a, b color space is organized in a cube form. The L axis runs from the top to bottom. The maximum for L is 100, which would be a perfect reflecting diffuser. The minimum for L would be zero, which would be black. The a and b axes have no specific numerical limits. Positive a is red, negative a is green. Positive b is yellow and negative b is blue.  $\Delta L$ ,  $\Delta a$  and  $\Delta b$  values indicate how much a standard and sample differ from one another in L, a and b. The total color difference  $\Delta E$  is a single value that takes into account the difference between the L, a, and b of the sample and standard (Mermelstein, 2010).

$$\Delta L = L_{\text{sample}} - L_{\text{standard}} ; +\Delta L \text{ means sample is lighter than standard}$$

$$-\Delta L \text{ means sample is darker than standard}$$

$$\Delta a = a_{\text{sample}} - a_{\text{standard}}$$

$$\Delta b = b_{\text{sample}} - b_{\text{standard}}$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

$$\text{Hue angle (H)} = \tan^{-1}(b/a)$$

$$\text{Chroma (C)} = (a^2 + b^2)^{1/2}$$

### **Bulk density**

The structural properties of dried food materials are significant for the characterization and prediction of the quality. The structure of food material can be characterized by density (apparent and true), porosity, pore size distribution, specific volume, particle density shrinkage etc. Density and porosity are vital for product characterization and in the design of process equipment (Boukouvalas and others 2006)

Density of foods can be expressed as apparent density and true density. True density is the density excluding all pores and it is determined by mass of the sample and its true volume. Apparent density concerns powdered and porous materials and it is determined by the mass of the sample and its apparent volume. Bulk density is a term used to express apparent density of granular materials. Bulk density depends on the packing of granular materials and can be varied by pressure or vibration (Boukouvalas and others 2006). The bulk density of a dried product can be determined by a glass beads displacement method in a known volume of cylindrical container (Hwang and Hayakawa 1980, Ali and Hanna 1997).

Bulk density is calculated as follows:

$$\rho_{\text{ds}} = W_{\text{ds}} / V_{\text{ds}} = W_{\text{ds}} / (V_{\text{c}} - \{W_{\text{gb+ds}} - W_{\text{ds}}\} / \rho_{\text{gb}})$$

Where

$\rho_{\text{ds}}$  is bulk density of the dried sample (g/ml)

$W_{ds}$  is weight of the dried sample (g)

$V_{ds}$  is volume of the dried sample (ml)

$V_c$  is volume of the cylindrical container (ml)

$W_{gb+ds}$  is weight of glass beads along with dried sample in cylindrical container (g)

$\rho_{gb}$  is the density of glass beads (g/ml)

## References

- Ahmed, E.M., Mirza, S and Arreola, A.G. Ultrastructural and textural changes in processed carrot tissue. Journal of Food Quality, 14 (1991), pp. 321–330.
- Azoubel, P. M. and F. E. X. Murr (2003). "Optimisation of osmotic dehydration of cashew apple (*Anacardium occidentale* L.) in sugar solutions." Food Science and Technology International 9(6): 427-433.
- Azzouz, S., A. Guizani, et al. (2002). "Moisture diffusivity and drying kinetic equation of convective drying of grapes." Journal of Food Engineering 55(4): 323-330.
- Babaliz, S. J. and V. G. Belessiotis (2004). "Influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs." Journal of Food Engineering 65(3): 449-458.
- Barbanti, D. Mastrocola, G. Pinnavaia, C. Severini and M. Dalla Rosa, Air drying of fruits: Effects of different pretreatments on drying rate and product quality, A.S. Mujumdar, I. Filkova, Editors , Drying '91, Elsevier, Amsterdam (1991), pp. 471–482.
- Baroni A.F. and Hubinger M.D., Drying of onion: Effects of pretreatment on moisture transport. Drying Technology, 16 (1998), pp. 2083–2094.
- Basiouny, F. M. (1996). "Blueberry fruit quality and storability influenced by post-harvest application of polyamines and heat treatments." Proc.Fla.State Hort.Soc 109: 269-272.
- Boukouvalas, C. J., M. K. Krokida, et al. (2006). "Density and porosity: Literature data compilation for foodstuffs." International Journal of Food Properties 9(4): 715-746.
- Brown, G. E. and E. S. Marchena (1972). "Centrifugal fluidized-bed - blanches, dries, and puffs piece-form foods." Food Technology 26(12): 23-28.
- Brownmiller, C., L. R. Howard, et al. (2009). "Processing and Storage Effects on Procyandin Composition and Concentration of Processed Blueberry Products." Journal of Agricultural and Food Chemistry 57(5): 1896-1902.
- Bourne, M. C. (1978). "Texture Profile Analysis." Food Technology 32(7): 62.
- Bourne, M. C. (1980). "Texture Evaluation Of Horticultural Crops." Hortscience 15(1): 51-57.
- Burnham, J.A, Kendall, P.A. and Sofos, J.N. (2001) "Ascorbic acid enhances destruction of *Escherichia coli* 0157:H7 during home-type drying of apple slices." Journal of Food Protection, 64, pp. 1244–1248.

- Burr, H. K., and Reeve, R. M. (1973). Potatoes. In W. B. Van Arsdell, M. J. Copley, and A. I. Morgan (Eds), Food dehydration (Vol. 2) (pp. 83-157). Westport, CT: The AVI Publishing Co.
- Camire, ME. (2000). Bilberries and blueberries as functional foods and nutraceuticals. In: Mazza G, Oomah BD, eds. Functional Foods: Herbs, Botanicals and Teas. Lancaster: Technomic Publishing pp:289-319.
- Cao, G. H., S. L. Booth, et al. (1998). "Increases in human plasma antioxidant capacity after consumption of controlled diets high in fruit and vegetables." American Journal of Clinical Nutrition 68(5): 1081-1087.
- Cinquanta, M. Di Mattco and M. Esti, Physical pretreatment of plums (*Prunus domestica*) part 2. Effect on the quality characteristics of different prune cultivars. Food Chemistry, 79 (2002), pp. 233–238.
- Cowan, M. M. (1999). "Plant products as antimicrobial agents." Clinical Microbiology Reviews 12(4): 564-582.
- Di-Matteo, M., L. Cinquanta, et al. (2000). "Effect of a novel physical pretreatment process on the drying kinetics of seedless grapes." Journal of Food Engineering 46(2): 83-89.
- Eidt, C. C. (1938). Principles and methods involved in the dehydration of apples. Canoe Dept. Agr. Tech. bull. 18.
- Eidt, C. C. (1944). Dehydration of lowbush blueberries. Food in Canada. 4: 22.
- Eisenhardt, N. H., Eskew, R. K., Cording, J. (1964). Explosive puffing applied to apples and blueberries. Food Engng. 53-55.
- Eshtiaghi, M.N, Stute R. and Knorr, D. (1994). "High-pressure and freezing pretreatment effects on drying, rehydration, texture and color of green beans, carrots and potatoes." Journal of Food Science. (59): 1168–1170.
- Feng, H., J. M. Tang, et al. (1999). "Microwave and spouted bed drying of frozen blueberries: The effect of drying and pretreatment methods on physical properties and retention of flavor volatiles." Journal of Food Processing and Preservation 23(6): 463-479.
- Fito, P. (1994). "Modeling of Vacuum Osmotic Dehydration of Food." Journal of Food Engineering 22(1-4): 313-328.
- Francis, F. J. (1989). "Food Colorants - Anthocyanins." Critical Reviews in Food Science and Nutrition 28(4): 273-314.

- Friar, H., Mark, C. M. (1943). Dehydration of blueberries. Fruit Prod. J. 22: 138.
- GarciaViguera, C., P. Zafrilla, et al. (1997). "Determination of authenticity of fruit jams by HPLC analysis of anthocyanins." Journal of the Science of Food and Agriculture 73(2): 207-213.
- Gao, L. and G. Mazza (1995). "Characterization of Acetylated Anthocyanins in Lowbush Blueberries." Journal of Liquid Chromatography 18(2): 245-259.
- Guadagni, D. G., A. E. Stafford, et al. (1975). "Taste thresholds of fatty-acid esters in raisins and raisin paste." Journal of Food Science 40(4): 780-783.
- Gerard Krewer and Scott NeSmith. (2006). "Blueberry cultivars for Georgia" (Accessed on December, 2010) from World Wide Web  
[http://www.smallfruits.org/Blueberries/production/06bbcvproc\\_Nov0206.pdf](http://www.smallfruits.org/Blueberries/production/06bbcvproc_Nov0206.pdf).
- Grabowski, S., M. Marcotte, et al. (2002). "Drying characteristics of osmotically pretreated cranberries - Energy and quality aspects." Drying Technology 20(10): 1989-2004.
- Grabowski, S., M. Marcotte, et al. (2007). "Kinetics and quality aspects of Canadian blueberries and cranberries dried by osmo-convective method." Drying Technology 25(1-3): 367-374.
- Gould, H. P. (1907). Evaporation of apples, G.P.O. Agri. Farmers bulletin 291.
- Hakkinen, S. H. and A. R. Torronen (2000). "Content of flavonols and selected phenolic acids in strawberries and Vaccinium species: influence of cultivar, cultivation site and technique." Food Research International 33(6): 517-524.
- Heiland, W. K., J. F. Sullivan, et al. (1977). "Continuous explosion puffing system." Food Technology 31(11): 32.
- Hammond, L. H. (1967). "Economic evaluation of UHF dielectric Vs radiant heating for Freeze-drying." Food Technology 21(5): 735.
- Hung, Y.-C., Chinnan, M.S. (1989). "Mechanical texture measurement of whole and chopped peanuts." Peanut Science 16:32-37.
- Hwang, M. P. and K. I. Hayakawa (1980). "Bulk densities of cookies undergoing commercial baking processes." Journal of Food Science 45(5): 1400.
- Jayaraman, K. S., and Das Gupta, D. K. (1995) Drying fruits and vegetables. In A. S. Mujumdar (Ed.), Handbook of industrial drying (Vol.1) New York: Marcel Dekker. Pp. 643-690.

- Joseph, J. A., B. Shukitt-Hale, et al. (1999). "Reversals of age-related declines in neuronal signal transduction, cognitive, and motor behavioral deficits with blueberry, spinach, or strawberry dietary supplementation." Journal of Neuroscience 19(18): 8114-8121.
- Kalt, W., C. F. Forney, et al. (1999). "Antioxidant capacity, vitamin C, phenolics, and anthocyanins after fresh storage of small fruits." Journal of Agricultural and Food Chemistry 47(11): 4638-4644.
- Kalt, W., J. E. McDonald, et al. (2000). "Anthocyanins, phenolics, and antioxidant capacity of processed lowbush blueberry products." Journal of Food Science 65(3): 390-393.
- Kalt, W., D. A. J. Ryan, et al. (2001). "Interspecific variation in anthocyanins, phenolics, and antioxidant capacity among genotypes of highbush and lowbush blueberries (*Vaccinium* section *cyanococcus* spp.)." Journal of Agricultural and Food Chemistry 49(10): 4761-4767.
- Kaymak-Ertekin, F. (2002), Drying and rehydrating kinetics of green and red peppers. Journal of Food Science. (67):168–175.
- Kilpatrick, P.W, E. Lowe and W.B. Van Arsdel, (1975) Tunnel dehydration for fruit and vegetables. Adv. Food Res. 50: p. 385.
- Kim, M. H. and R. T. Toledo (1987). "Effect of osmotic dehydration and high-temperature fluidized-bed drying on properties of dehydrated rabbiteye blueberries." Journal of Food Science 52(4): 980-984.
- Kostaropoulos and G. Saravacos, (1995). "Microwave pre-treatment for sun dried raisins." Journal of Food Science. (60): 344–347.
- Kraft, T. E. B., B. M. Schmidt, et al. (2005). "Chemopreventive potential of wild lowbush blueberry fruits in multiple stages of carcinogenesis." Journal of Food Science 70(3): S159-S166.
- Kompany, K. Allaf, J.M. Bouvier, P. Guigon and A. Maureaux, A new drying method of fruits and vegetables—Quality improvement of the final product, A.S. Mujumdar, I. Filkova, Editors , Drying '91, Elsevier, Amsterdam (1991), pp. 499–506.
- Lapidot, T., S. Harel, et al. (1999). "pH-dependent forms of red wine anthocyanins as antioxidants." Journal of Agricultural and Food Chemistry 47(1): 67-70.
- Lee, J. and R. E. Wrolstad (2004). "Extraction of anthocyanins and polyphenolics from blueberry-processing waste." Journal of Food Science 69(7): C564-C573.

- Levi, A., J. R. Ramirezmartinez, et al. (1980). "Influence of heat and sulfur-dioxide treatments on some quality characteristics of intermediate-moisture banana." Journal of Food Technology 15(5): 557-566.
- Lewicki, P. P. (2006). "Design of hot air drying for better foods." Trends in Food Science & Technology 17(4): 153-163.
- Lila, M.A. (2004). "Anthocyanidins and human health: an invitro investigative approach". Journal of Biomedical and Biotechnology 5: 306-313.
- Lohachoompol, V., G. Srzednicki, et al. (2004). "The change of total anthocyanins in blueberries and their antioxidant effect after drying and freezing." Journal of Biomedicine and Biotechnology(5): 248-252.
- Luh, B. S. and J. G. Woodroof (1988). Commercial Vegetable Processing Second Edition. New York: Van Nostrand Reinhold, pp 387-473.
- Ma, Y.H., and Arsem, H. (1982). Low pressure sublimation in combined radiant and microwave freeze drying. In A. S. Mujumdar (Ed.), Drying'82. New York: McGraw-Hill.
- MacGregor, W. (2005). "Effects of air velocity, air temperature, and berry diameter on wild blueberry drying." Drying Technology 23(1-2): 387-396.
- Mejia-Meza, E. I., J. A. Yanez, et al. (2008). "Improving Nutritional Value of Dried Blueberries (*Vaccinium corymbosum* L.) Combining Microwave-Vacuum, Hot-Air Drying and Freeze Drying Technologies." International Journal of Food Engineering 4(5).
- Mermelstein, N. H. (2010). "Measuring Food and Beverage Color." Food Technology 64(4): 67-71.
- Moreira, R. G. (2001). "Impingement drying of foods using hot air and superheated steam." Journal of Food Engineering 49(4): 291-295.
- Mahmutoglu, M. Pala and M. Unal, (1995). "Mathematical modeling of moisture, volume and temperature changes during drying of pretreated apricots." Journal of Food Processing and Preservation. (19): 467-490.
- Mudahar, G.S, J.R. Buhr and J.J. Jen, (1991). "Infiltrated biopolymers effect on quality of dehydrated carrot." Journal of Food Science. (57): 526-529.
- Mudahar, G.S, Toledo R.T. and Jen, J.J. (1990). "A response surface methodology approach to optimize potato dehydration process." Journal of Food Processing and Preservation. (14): 93-106.

- NASS, 2009. Agricultural Statistics Board, United States Department of Agriculture, Noncitrus Fruits and Nuts 2009 Summary. Retrieved on November 25, 2010 from the World Wide Web  
[http://usda.mannlib.cornell.edu/usda/nass/NoncFruNu//2010s/2010/NoncFruNu-07-07-2010\\_new\\_format.pdf](http://usda.mannlib.cornell.edu/usda/nass/NoncFruNu//2010s/2010/NoncFruNu-07-07-2010_new_format.pdf).
- Negi, P. S. and S. K. Roy (2000). "Effect of blanching and drying methods on beta-carotene, ascorbic acid and chlorophyll retention of leafy vegetables." Lebensmittel-Wissenschaft Und-Technologie-Food Science and Technology 33(4): 295-298.
- North American Highbush Blueberry Council, Annual meeting, March 2007, Vancouver, Canada. (Accessed December 2010) "Fruit Growers News Magazine".
- Ozkan, M. and B. Cemeroglu (2002). "Desulphiting dried apricots by exposure to hot air flow." Journal of the Science of Food and Agriculture 82(15): 1823-1828.
- Parthasarathy, S. (1998). Mechanisms by which dietary antioxidants may prevent cardiovascular diseases. Journal of Medicinal Food 1: 45-51.
- Petrucci, V., N. Canata, et al. (1974). "Use of oleic acid-derivatives to accelerate drying of thompson seedless grapes." Journal of the American Oil Chemists Society 51(3): 77-80.
- Perkins-Veazie, P. (2004). Blueberry. "The commercial storage of fruits, vegetables and florist and nursery stocks". USDA Agr. Handbook. Nr 66. Available from [www.ba.ars.usda.gov/hb66/039blueberry.pdf](http://www.ba.ars.usda.gov/hb66/039blueberry.pdf). (Accessed December 2010).
- Perry, R. L., E. M. Mrak, H. J. Pfaff, G. L. Marsh, C. D. Fisher. (1946). Fruit dehydration I. Principles and equipment. Berkeley: California Agricultural Experiment Station bulletin 698.
- Ponting, J. D., G. G. Watters, et al. (1966). "Osmotic Dehydration of Fruits." Food Technology 20(10): 1365-1368.
- Prior, R. L., G. H. Cao, et al. (1998). "Antioxidant capacity as influenced by total phenolic and anthocyanin content, maturity, and variety of Vaccinium species." Journal of Agricultural and Food Chemistry 46(7): 2686-2693.
- Puupponen-Pimia, R., L. Nohynek, et al. (2001). "Antimicrobial properties of phenolic compounds from berries." Journal of Applied Microbiology 90(4): 494-507.
- Rahman, A.R. (1972) "Increased density for military foods", Tech. Rpt. No. Ad-750-368. U.S. Army Natick Labs, Natick, MA.
- Ramaswamy, H. S. and F. Nsonzi (1998). "Convective-air drying kinetics of osmotically pre-treated blueberries." Drying Technology 16(3-5): 743-759.

Raoult-Wack, A.L., Lafont, F., Rios, G., and Guilbert, S. (1989). Osmotic dehydration. Study of mass transfer in terms of engineering properties. In A.S. Mujumdar and M. Roques (Eds.), *Drying'89*. New York: Hemisphere.

Rey, L. (1975). "Freezing and Freeze-drying." Proceedings of the Royal Society of London Series B-Biological Sciences 191(1102): 9-19.

Rickard, A., Wuerthner, J., Barret, G. (1993). Corn Snacks: Full speed ahead, Snack World (3): 278-300.

Ridley G.B. and others (1921). The symposium on drying. Jour. Indus. and Engin. Chem. 13: 427-460.

Riva, M., and Masi, P. (1988). The influence of the blanching procedure on the quality and shelf-life of dried apples. In Progress in food preservation processes (Vol. 1) (pp. 31–38).

Rocha, A. Lebert and C. Marty-Andonin (1993). "Effect of pretreatments and drying conditions on drying rate and color retention of basil (*Ocinum basilicum*)." Lebensmittel Wissenschaft und Technologie. (26): 456–463.

Rossi, M., E. Giussani, et al. (2003). "Effect of fruit blanching on phenolics and radical scavenging activity of highbush blueberry juice." Food Research International 36(9-10): 999-1005.

Scherm, H., and Krewer, G (2003). "Blueberry production in Georgia: Historical overview and recent trends." Small Fruits Review 2(4): 83-91.

Schmidt, B. M., A. B. Howell, et al. (2004). "Effective separation of potent anti proliferation and antiadhesion components from wild blueberry (*Vaccinium angustifolium* ait.) fruits." Journal of Agricultural and Food Chemistry 52(21): 6433-6442.

Schmidt, B. M., J. W. Erdman, et al. (2005). "Effects of food processing on blueberry antiproliferation and antioxidant activity." Journal of Food Science 70(6): S389-S394.

Sellappan, S., C. C. Akoh, et al. (2002). "Phenolic compounds and antioxidant capacity of Georgia-grown blueberries and blackberries." Journal of Agricultural and Food Chemistry 50(8): 2432-2438.

Serafini, M., G. Maiani, et al. (1998). "Alcohol-free red wine enhances plasma antioxidant capacity in humans." Journal of Nutrition 128(6): 1003-1007.

- Shi, J., Z. Pan, et al. (2008). "Drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation heating." Lwt-Food Science and Technology 41(10): 1962-1972.
- Shi, J., Z. Pan, et al. (2008). "Effect of berry size and sodium hydroxide pretreatment on the drying characteristics of blueberries under infrared radiation heating." Journal of Food Science 73(6): E259-E265.
- Skrede, G., R. E. Wrolstad, et al. (2000). "Changes in anthocyanins and polyphenolics during juice processing of highbush blueberries (*Vaccinium corymbosum* L.)." Journal of Food Science 65(2): 357-364.
- Smith, M. A. L., K. A. Marley, et al. (2000). "Bioactive properties of wild blueberry fruits." Journal of Food Science 65(2): 352-356.
- Sian and Soleha Ishak (1991). "Carotenoid and anthocyanin contents of papaya and pineapple: Influence of blanching and predrying treatments." Food Chemistry. (39): 175–185.
- Somogyi, L. P. and B. S. Luh (1986). In: S Luh, JG Woodroof, eds. Commercial Fruit Processing, 2d ed. AVI Publ., Westport, Conn., pp 353-405.
- Stojanovic, J. and J. L. Silva (2007). "Influence of osmotic concentration, continuous high frequency ultrasound and dehydration on antioxidants, colour and chemical properties of rabbiteye blueberries." Food Chemistry 101(3): 898-906.
- Stafford, A. E. and D. G. Guadagni (1977). "Storage stability of raisins dried by different procedures." Journal of Food Science 42(2): 547-548.
- Su, M.-S. and P.-J. Chien (2007). "Antioxidant activity, anthocyanins, and phenolics of rabbiteye blueberry (*Vaccinium ashei*) fluid products as affected by fermentation." Food Chemistry 104(1): 182-187.
- Sullivan, J. F., R. P. Konstance, et al. (1977). "Continuous Explosion-Puffing of Potatoes." Journal of Food Science 42(6): 1462.
- Sullivan, J. F., J. C. Craig, et al. (1980). "Continuous Explosion-Puffing of Apples." Journal of Food Science 45(6): 1550.
- Sullivan, J. F., J. C. Craig, et al. (1982). "Dehydrated Blueberries by The Continuous Explosion-Puffing Process." Journal of Food Science 47(2): 445-448.
- Sullivan, J. F., R. P. Konstance, et al. (1981). "Carrot Dehydration Optimization Process Studies on the Explosion-Puffing Process." Journal of Food Science 46(5): 1537-1542.

- Szczesniak, A. S. (2002). "Texture is a sensory property." Food Quality and Preference 13(4): 215-225.
- Talcott, S. T., C. H. Brenes, et al. (2003). "Phytochemical stability and color retention of copigmented and processed muscadine grape juice." Journal of Agricultural and Food Chemistry 51(4): 957-963.
- Toribio, J. L. and J. E. Lozano (1986). "Heat-Induced Browning of Clarified Apple Juice at High-Temperatures." Journal of Food Science 51(1): 172- 175.
- Tripathi R.N, and Nath, N. (1989) "Effect of starch dipping on quality of dehydrated tomato slices." Journal of Food Science and Technology. 26:137–141.
- USHBC, 2010. United States Highbush Blueberry Council, Folsom, California, U.S.A. Blueberry information. Retrieved December, 2010 from the World Wide Web <http://www.blueberry.org>
- VanArsdel, W.B. 1973. Drying phenomena. In "Food Dehydration", V. 1(Ed.) W.B. Van Arsdel, M. Copley, and A. Morgan, P.22 AVI Pub. Co., Westport, CT.
- Vega-Galvez, A., R. Lemus-Mondaca, et al. (2009). "Kinetic Study of Convective Drying of Blueberry Variety O'neil (*Vaccinium corymbosum* L.)." Chilean Journal of Agricultural Research 69(2): 171-178.
- Vega-Mercado, H., M. M. Gongora-Nieto, et al. (2001). "Advances in dehydration of foods." Journal of Food Engineering 49(4): 271-289.
- Venkatachalapathy, K. and G. S. V. Raghavan (1998). "Microwave drying of osmotically dehydrated blueberries." Journal of Microwave Power and Electromagnetic Energy 33(2): 95-102.
- Wang, H., G. H. Cao, et al. (1996). "Total antioxidant capacity of fruits." Journal of Agricultural and Food Chemistry 44(3): 701-705.
- Wang, H., G. H. Cao, et al. (1997). "Oxygen radical absorbing capacity of anthocyanins." Journal of Agricultural and Food Chemistry 45(2): 304-309.
- Wang, Y., C. F. Chang, et al. (2005). "Dietary supplementation with blueberries, spinach, or spirulina reduces ischemic brain damage." Experimental Neurology 193(1): 75-84.
- Xiao, H.-W., C.-L. Pang, et al. (2010). "Drying kinetics and quality of Monukka seedless grapes dried in an air-impingement jet dryer." Biosystems Engineering 105(2): 233-240.
- Yang, A. P. P., C. Wills, et al. (1987). "Use of a Combination Process of Osmotic Dehydration and Freeze-Drying to Produce a Raisin-Type Lowbush Blueberry Product." Journal of Food Science 52(6): 1651-1664.

Yang, C. S. T. and W. A. Atallah (1985). "Effect of 4 Drying Methods on The Quality of Intermediate Moisture Lowbush Blueberries." Journal of Food Science 50(5): 1233-1237.

Yohan-Yoon, J.D. Stopforth, P.A. Kendall and J.N. Sofos, Inactivation of *Salmonella* during drying and storage of Roma tomatoes exposed to predrying treatments including peeling, blanching and dipping in organic acid solutions. Journal of Food Protection, 67 (2004), pp. 1344–1352.

Youdim, K. A., B. Shukitt-Hale, et al. (2000). "Short-term dietary supplementation of blueberry polyphenolics: Beneficial effects on aging brain performance and peripheral tissue function." Nutritional Neuroscience 3(6): 383-397.

Zheng, W. and S. Y. Wang (2003). "Oxygen radical absorbing capacity of phenolics in blueberries, cranberries, chokeberries, and lingonberries." Journal of Agricultural and Food Chemistry 51(2): 502-509.

Fig 2.1: Rabbiteye blueberry



Source: <http://www.southwoodnursery.com/berries.shtml>

Fig 2.2: Brightwell blueberry



Source: [http://www.extension.org/pages/Brightwell:\\_Rabbiteye\\_Blueberry\\_Variety](http://www.extension.org/pages/Brightwell:_Rabbiteye_Blueberry_Variety)

Fig 2.3: Powderblue blueberry



Source: [http://www.extension.org/pages/Powderblue:\\_Rabbiteye\\_Blueberry\\_Variety](http://www.extension.org/pages/Powderblue:_Rabbiteye_Blueberry_Variety)

Fig 2.4: Mechanical Harvester



Table 2.1: Blueberry formats for commercial applications

**Blueberry Formats to Meet Manufacturer Needs** (For USHBC suppliers list go to <http://www.blueberry.org/suppliers.htm>)

Product	Process	Typical Packaging	Characteristic/ Application	Storage
<b>FRESH</b>				
Fresh	Fresh blueberries > packaged	Consumer packs; plastic clam shells, cello packs; Cartons: 2-1/2 lb, 5 lb (2.3 kg), 10 lb (4.5 kg), 20 lb.	Available almost year round.	32° to 34°F (-0.6° to 1°C) 90-95% relative humidity
<b>FROZEN</b>				
IQF (Individually Quick Frozen)	*>Fresh blueberries>individually quick frozen> packaged.	Consumer packs: poly bags. Bulk: Poly lined corrugated cartons 10-50 lb (4.5 - 22.7 kg), poly-lined metal drums: 270 lb (122.5 kg)	Individual fresh fruit identity. Any formulation where fruit identity is important.	0° to -10°F (-18° to -23°C)
Straight Pack or Block Frozen	*>Fresh Blueberries> packaged> flash frozen.	Poly-lined corrugated cartons: 30-50 lb (13.6 - 22.7 kg); poly-lined metal drums: 350 lb (158.8 kg)	High amount of fruit in a box, base ingredient for toppings, syrups fillings and soups.	0° to -10°F (-18° to -23°C)
<b>DRIED</b>				
Dehydrated	*>Fresh or frozen blueberries > air dehydrated to around 11-18 % moisture > further processed to dried fruit specs: i.e. oil coated, diced etc.	Poly-lined corrugated boxes: 5, 10, 25 lb.	Moisture: 11-18 % Water Activity: 0.5-0.6	Shelf stable in a cool, dry place.
Dehydrated Infused	*>Fresh or frozen blueberries are infused with a syrup>dehydrated to 11-18% moisture> further processed to dried fruit specs: eg. oil coated, diced	Poly-lined corrugated boxes 5, 10, 25 lb.	Moisture: 11-18 % Water Activity: 0.5-0.6	Shelf stable in a cool, dry place.
Freeze Dried	*>Fresh or frozen blueberries > flash frozen > moisture removed in vacuum chamber > sealed in moisture proof bags.	Poly lined corrugated boxes (10 lb) and other custom sizes.	Moisture (unsweetened): 0-2 % Moisture (sweetened): 9-14%	Stable at room temperature 3 mo., after that store at 40°F.
Osmotically Preserved	*>Fresh or frozen blueberries >placed in vacuum chamber>undergo slow natural infusion process with syrup solution and stabilizers> carefully dried to preserve color and flavor	Poly lined corrugated boxes (25 lb) and other custom sizes.	Moisture: 40% maximum Water Activity: 0.5 - 0.87	Shelf stable in cool, dry place. Best used within 10 months.
Drum Dried/Powders	*>Fresh or frozen blueberries or purée > drum dried > ground into powder or flakes to specifications	Poly lined corrugated boxes (10 lb) and other custom sizes.	Moisture Content: 3-5% Various screen sizes and granule consistency available.	Stable at room temp. for 3 months, after that store at 40°F.
<b>LIQUID</b>				
Single Strength Purée	*>Fresh blueberries> crushed>finished> pasteurized or cold filled in containers> frozen.	Plastic pails: 28, 30 lb (12.7, 13.6 kg) Poly lined corrugated cartons: 25, 30 lb (12.7, 13.6 kg); Poly lined metal drums: 55 gal (208 l) 400 lb. (181 kg)	Brix: 8.0 -13.0 pH: 2.8 -3.5 >Used in, sauces, flavorings and fillings.	0° to -10°F (-18° to -23°C)
Purée Concentrate	*>Fresh blueberries> crushed > heat/enzyme treated> vacuum concentrated > pasteurized > packaged > frozen.	Plastic pails: 4, 6 gal (15.1, 22.7 l) 28, 30, 60 lb (12.7, 13.6, 27.2 kg) Poly-lined metal drums	Brix Ranges: 20,37, 40 pH: 2.8 - 3.4 >Juices, sauces, blends.	0° to -10°F (-18° to -23°C)
Single Strength Juice	*>Fresh berries > crushed > pressed > filtered > pasteurized > packaged > frozen	Plastic pails: 5,6 gal (18.9, 22.7 l) 28,30,60 lb (12.7,13.6, 27.2 kg) Poly-lined metal drums	Brix: 8.0 - 12.0 pH: 2.8 - 3.4 >All natural fruit juices.	0° to -10°F (-18° to -23°C)
Juice Concentrate	*>Fresh blueberries > crushed > heat/enzyme treated > vacuum concentrated > packaged > frozen.	Plastic pails: 5,6 gal (18.9, 22.7 l) 50,66 lb (22.7, 29.9 kg) Poly-lined metal drums/	Brix: 45.0, 65.0 pH: 2.1 - 2.7 >Fruit juices and sauce flavor.	0° to -10°F (-18° to -23°C)
<b>OTHER FORMATS</b>				
Canned (Packed in Syrup) (Packed in Water)	*>Fresh or frozen blueberries > placed in cans > light or heavy syrup added > sealed > heated. Fresh or frozen blueberries> placed in cans>water added >sealed>heated.	Cans: #2, #2-1/2, #10, other sizes.	Various levels of fruit content depending on supplier and application.	Shelf stable in a cool, dry place.
Bakery fruit fillings	*>Fresh or frozen blueberries and/or other forms > sweetener and starch/gum based slurry added > heated > packaged to specifications. (differs from supplier to supplier)	Plastic and foil pouches, 5 gal plastic pails (18.9 l) and 55 gal drums (208.2 l).	Various levels of fruit content depending upon supplier and end use	Shelf stable in a cool, dry place.
Essence	+ >volatile flavor components distilled off from juice and concentrate process > packaged.	Plastic pails: 5, 6 gal (18.9, 22.7 l) and other sizes.	Intensive blueberry flavor found in no artificial flavoring.	Tightly closed container at 40°F (4°C) or lower
Other	Real fruit bits and chips are formulated out of a blend of purée and other ingredients.	10 lb boxes and other custom sizes.	Fruit Content: 30-40 % >Baking/snack applications.	Shelf stable in a cool, dry place.

**CHAPTER 3**  
**DRYING CHARACTERISTICS OF INDIVIDUALLY QUICK FROZEN**  
**(IQF) RABBITEYE BLUEBERRIES**

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<sup>1</sup> Yemmireddy, V and Hung, Y. –C. To be submitted to the Transactions of the ASABE.

## **Abstract**

Frozen storage of rabbiteye blueberries and subsequent value addition in the form of drying is a common practice in the U.S.A. The knowledge of desorption characteristics of previously frozen blueberries is vital for the design and management of efficient drying processes. In this study, the drying rate of partially thawed and mechanically scarified individually quick frozen (IQF) rabbiteye blueberries were investigated during forced air oven drying at 85 and 107°C. The effect of cultivar, grade and drying temperature on drying characteristics was investigated. Drying temperature was found to be the most influential factor on the drying rate under tested conditions and most of the drying occurred during the falling rate period. Several isotherm equations including BET, Modified Halsey, Kuhn and Oswin were used to predict rabbiteye blueberry desorption isotherm. The modified Halsey equation best fitted the experimental data based on the goodness of fit. The developed desorption isotherm model and the drying curves would help to optimize the drying process for rabbiteye blueberries.

**Keywords:** Rabbiteye blueberry, desorption isotherms, drying, modeling.

## **Introduction**

Rabbiteye blueberries (*Vaccinium ashei*) are native to the southeastern region of United States and Georgia is the leading producer of this variety in this region. As per United States Department of Agriculture, National Agricultural Statistics Service (USDA-NASS) reports, Georgia produced 43 million pounds of blueberries (all varieties) in 2009, of which 23 million pounds sold in fresh market and 20 million pounds were utilized for further processing and value addition. As most of the fresh market is usually saturated with northern and southern high bush blueberries, most of the rabbiteye blueberries were frozen stored for later usage and value addition. In view of raising demand for the value-added blueberry products in the domestic and international markets (US Highbush Blueberry Council, 2010), understanding drying characteristics of frozen stored blueberries is critical to develop efficient and cost effective processing technologies like drying.

Reduction of moisture content of foods to a stable water activity level will increase the shelf life of food products by inhibiting the growth of spoilage microorganisms (Scott, 1957). Stable water activity levels also control certain enzymatic, non-enzymatic reactions and lipid oxidation (Rockland and Beuchat, 1986., Rockland, 1980). Drying is the most common method used to reduce the moisture content or lower the water activity of foods to a shelf-stable level. The end point of any drying process is generally determined by the desired water activity of finished product (Luh and Woodroof, 1988). Predicting the drying time to achieve desired water activity level is very complicated.

The water sorption isotherms of foods show the equilibrium relationship between the moisture content of foods and the water activity at constant temperature and pressure

(Labuza, 1968). The isotherms are unique to the individual foods and the relationship between moisture content and water activity is important to predict the physical, chemical and biological changes that might take place during processing and subsequent storage of foods (Moreira and others 2009). Besides predicting microbial or physico-chemical stability of foods, moisture sorption isotherms are useful for the analysis and design of various food processes such as drying, mixing, and storage (Zhang and others 1995).

Moisture sorption isotherms can be determined by experimental methods or by mathematical equations. Experimental methods can be divided into gravimetric, manometric and hygrometric methods. Several experimental isotherms are reported in the literature based on the determination of three physical properties: equilibrium moisture content, water activity and temperature (Moreira and others 2009). There are empirical and semi-empirical equations to establish mathematical relationships among these three variables (Iglesias and Chirife, 1978), which are usually evaluated by adjustment of experimental data. Conventional experimental methods for determination of moisture sorption isotherms are time consuming and sometimes may lead to inaccurate determinations. Determination of sorption characteristics using dynamic gravimetric analysis is based on measuring weight changes during the drying and rapid determination of change in water activities. This method might help to address the problems associated with conventional methods and to rapidly obtain desorption data.

Most drying methods involve a pretreatment step to increase the drying rate of fruits and vegetables including blueberries. Several researchers in the past studied the effect of various drying methods involving a pretreatment step on the drying characteristics of blueberries. These pretreatment methods include abrasion, dipping in NaOH, ethyl

oleate, hot water, osmotic pretreatment using various concentrations of sugar solutions and ultra sound treatment to crack open the waxy surface layer of blueberries (Grabowski and others 2007, Shi and others 2008, Stojanovic and Silva 2007). They noticed significant influence of pretreatment on the drying characteristics of blueberries. However, desorption characteristics of IQF rabbiteye blueberries involving a pretreatment step is not readily available. The objectives of this study were to: (1) determine the desorption characteristics of individually quick frozen (IQF) rabbiteye blueberries during hot-air drying; (2) test the possibility of using four popular isotherm equations to predict the desorption isotherm of rabbiteye blueberries; (3) determine the effect of pretreatment, cultivar, grade and drying temperature on desorption isotherms of rabbiteye blueberries.

## **Materials and Methods**

### ***Test samples***

IQF rabbiteye blueberries (*Vaccinium ashei*) for all experiments were obtained in 30 lb boxes from Alma Pak Industries (Alma, GA). Pretreatment experiments were conducted with berries harvested in 2009. For drying experiments, IQF rabbiteye blueberry cultivars Brightwell and Powderblue of grades A and C were used and were harvested in 2010. According to USDA-Agricultural Marketing Services ( 22 FR 3535 §52.613), on a 100 point scale based on color (20 points), absence of defects (40 points) and character (firm, fleshy and intact, 40 points); frozen blueberries whose total score is not less than 90 and 70 are graded as A and C, respectively. The samples were stored at below -18°C until used.

### ***Blueberry pretreatment***

To facilitate drying process, blueberry skin was punctured with a mechanical scarifier. Pretreatment protocol was developed based on several preliminary experiments. In the first experiment, equal quantity of frozen blueberries were thawed for 0, 15, 20, 25, 30 and 60 min at room temperature and placed in a rectangular tray (30 x 9 cm<sup>2</sup>) with a stainless steel base having square shaped openings to hold the berries stable. The surface of the berries was abraded using an in-house fabricated hand-held scarifier with a series of serrated rollers; to a fixed depth by a fixed number of to-and-fro motions. The weight loss due to scarification was recorded by weight change during scarification and then dried in an impingement oven (Lincoln<sup>®</sup>, Model 1452, Food Service Products, Inc., Fort Wayne, IN 46804, U.S.A) at two temperatures 85°C and 107°C (selected based on previous research not published yet) for 60 min in duplicates and measured the final water activities of all samples. The results from these experiments indicated that the weight loss due to scarification is negligible when thawed for 0-60 min intervals. However, the hand-held scarifier was ineffective to achieve uniform and desirable degree of drying and this may be due to the fact that not sufficient scarification was achieved. The hand-held scarifier was not used for further experiments.

In the second experiment, hand-held scarifier was replaced by a mechanical scarifier which was equipped with a continuous conveyor belt system to transport thawed blueberries and an adjustable clearance between the conveyor belt and the roller blades (Fig.3.1). In this way we were able to fix the depth of scarification as desired. Frozen blueberries were thawed for 0, 15, 20, 25, 30 and 60 min and mechanically scarified to variable scarification depths (4, 5 and 6 mm). Scarification depth was defined as the

clearance between the serrated rollers and the conveyor belt of mechanical scarifier with an average blueberry diameter of 12 mm. It was observed that the scarification depth of 6 mm allowed most of the berries escape without puncture and 4 mm resulted in excessive compression and shearing of blueberries under the spiked rollers. Hence a fixed scarification depth of 5 mm was used for further experiments. Scarified berries were then dried at both 85°C and 107°C using an impingement oven and the final water activity values after 60 min drying were measured. The moisture content of thawed and scarified blueberries was 83% (wb).

***Water activity measurement***

Water activity of pretreated berries was measured with a calibrated Aqua Lab water activity meter (Series 3, Decagon Devices, Inc. Pullman, WA, USA) at room temperature. The moisture content of the same samples was determined using a vacuum oven according to the AACC method 44-40 (AACC 2000).

To account for the deviations in the water activity measurement, the water activity meter was calibrated using different relative humidity standards (Etalons D’humidite Calibration Standards, Rotronic ag, Badenerstrasse 435, Postfach, CH-8040 Zurich). Based on the measured and target water activity values, a regression equation (Fig 3.1) was developed to correct for the deviations in the measurement of water activity value by the meter using equation 1.

$$X = (Y - 0.0042) / 0.9315 \dots \dots \dots [1]$$

Where Y is the measured water activity value

X is the corrected water activity value

### ***Drying experiment***

Drying experiments were conducted in a forced air oven (Lindberg/Blue M mechanical oven, Asheville, N.C., U.S.A) at two drying conditions 85 and 107°C using 500 g of pretreated blueberries as a batch. The berries were contained in a stainless steel screen (20x8 cm<sup>2</sup>) with a same dimension screen as top cover. Desorption data was collected by using a dynamic method. A ~2 g sample was collected every 30 min during drying and chopped into small pieces using a stainless steel knife. The chopped sample was measured for water activity using the water activity meter described above and stored in an air-tight desiccator for moisture content determination using vacuum oven drying method described earlier. The moisture content was expressed in dry basis and the values above 150% were not considered for the isotherm. The sample collection stopped once the water activity values reached below 0.6; which is considered as the shelf-stable water activity level for dried blueberries. Desorption isotherm (Water activity vs Moisture content) as well as drying curve (Time vs Moisture content) was then constructed.

### ***Experimental design***

Drying experiments were conducted for both cultivar (Brightwell and Powderblue) and for both grade (A and C) at two different drying temperatures (85°C and 107°C). Factorial design based on cultivar\*grade\*temperature (2\*2\*2) was conducted in duplicates.

### ***Modeling of desorption isotherms***

Each set of desorption data with respect to cultivar, grade and drying temperature (Table 3.1) was analyzed using a non-linear regression procedure (the NLIN procedure, SAS, 2009). The Gauss-Newton method which minimizes the sum of squares of errors in a series of iterative stages was used to estimate the parameters A and B for the isotherm

equations. Also, the desorption data for each set of drying experiment was fitted to the four popular isotherm equations representing models that are commonly used in agricultural products. The mathematical models used in this study are listed below:

The BET equation (Brunauer et al., 1938).

$$M = \frac{A \cdot B \cdot a_w}{(1 - a_w) [1 + (B-1) a_w]} \quad \text{-----} [2]$$

The modified Halsey equation (Iglesias and Chirife, 1976).

$$M = \left[ 1 - \frac{A}{\ln(a_w)} \right]^{1/B} \quad \text{-----} [3]$$

The Kuhn equation (Kuhn, 1964).

$$M = \frac{A}{\ln(1/a_w)} + B \quad \text{-----} [4]$$

The Oswin equation (Oswin, 1948).

$$M = A \left[ \frac{a_w}{1-a_w} \right]^B \quad \text{-----} [5]$$

Where M is the equilibrium moisture content (EMC) (% db),  $a_w$  is the water activity, and A and B are the constants associated with each equation.

The estimated coefficient of determination ( $R^2$ ) to measure the goodness of fit of a non-linear model was calculated as follows:

$$R^2 = 1 - \frac{\text{Residual Sum of Squares}}{\text{Uncorrected Total Sum of Squares}} \quad \text{-----} [6]$$

The model which fits the data best should have a higher  $R^2$  value.

## **Results and Discussion**

### ***Effect of pretreatment***

The results of thawing experiments are showed in Fig 3.3. Blueberries thawed for up to 60 min and single pass scarification resulted in incomplete drying ( $a_w$  around 0.8) at 85°C for 60 min. Drying time (60 min) is too short at 85°C to estimate the effect of thawing and scarification. Longer thawing times ( $\geq 30$  min) resulted in incomplete drying of blueberries ( $a_w$  around 0.6) for drying at 107°C for 60 min with single pass scarification. At these thawing times, the berries were too soft and skin did not get punctured sufficiently during scarification. Shorter thawing time helped the blueberry to maintain its integrity and hence achieve better scarification (more and even puncture by serrated roller). Too short thawing times ( $\leq 10$  min) resulted in blueberries to split into halves or broken into pieces. Hence berries lost their structural integrity resulted in too much moisture loss during drying ( $a_w$  below 0.5).

Based on the results in Fig 3.3, it is clearly evident that the thawing time is critical to achieve effective scarification on blueberries. Thawing time of 15-30 min also showed better scarification by allowing the berries to roll around the spiked rollers at a spiked roller speed of 33 rpm and conveyor belt speed of 11.5 rpm. Average diameter of blueberries for this study was about 12 mm. The scarification depth of 5 mm achieved effective drying and maintained the integrity of the blueberries after drying.

Partial thawing of frozen blueberries for 20 min followed by mechanical scarification to a depth of 5 mm helped to reduce drying time significantly. Similar results were observed by Jazini and others (2010) when plums were pierced with needles dried faster

than chemical pretreatment with hot NaOH solution (1%). Thakur and others (2010) reported that superficial abrasion of grape skin by rough surface increased drying rate and concluded it is also safer than traditional chemical pretreatments. In the same study the authors reported that cutting the grapes into two halves increased drying rate but affected the overall quality especially ascorbic acid. Similar results were observed by Matteo and others (2000).

Blueberries have thin layer of waxy cuticle which is very sensitive to physical pretreatment. Shi and others (2008) reported that blueberries pretreated with hot NaOH solution increased the drying rate and moisture diffusivity and reduced the number of broken berries during IR heating ( $>80\text{ }^{\circ}\text{C}$ ) due to the changes in the surface and cell microstructure of blueberries. The physical pretreatment (scarification) used for the current blueberry drying study reduced drying time when compared with the blueberries without subjected to pretreatment and avoid chemical pretreatment methods and hence produce more natural dried berries. This pretreatment helped the moisture to diffuse out through the random pin holes formed on the surface of the partially thawed frozen berries.

### ***Blueberry drying***

Moisture content and water activity data for the blueberries dried in a forced air oven at 85 and 107°C is reported in Table 3.1. The drying time(s) to achieve a shelf stable water activity of less than 0.6 is around 420 min at 85°C. The drying time was found to be least (390 min) for Powderblue, Grade-A combination and highest (480 min) for Brightwell, Grade-C combination at 85°C. Similarly, the drying time(s) were around 240

min at 107°C and drying time for Powderblue, Grade-C combination was found to be highest at 300 min and Brightwell, Grade-A to be fastest at 180 min.

Drying rate curves for each set of drying data was plotted (not reported). Also, Statistical analysis of the drying data revealed that the parameter estimates of individual drying curves at a particular temperature for each data set were not significantly different from each other at 95% confidence level (data not shown). As a result at a particular temperature (either 85°C or 107°C) the confidence intervals of parameter estimates overlapped each other. Hence drying curves for a cumulative data at 85 and 107°C were plotted (Fig. 3.4). The drying curves moved closer to the origin as the drying temperature increased, which mean that the higher the drying temperature the faster the drying process. As a result drying is more rapid at 107°C compared to 85°C. Similar results were observed during convective drying of blueberry variety O'Neil (Vega-Galvez and others 2009) and tray drying of mulberries (Maskan and Gogus 1998) at 60, 70 and 80°C. Under current conditions, no constant rate drying period was observed and the falling rate drying period occurred immediately. This kind of behavior is very common in fruits and vegetable drying (Togul and Pehlivan 2003, Kingsly and others 2007).

As discussed earlier physical pretreatment significantly influenced the drying rate of blueberries. Matteo and others (2000) found an increase in drying rate when plums subjected to mechanical (abrasion) and chemical (ethyl oleate) pretreatments. They concluded that the mass transfer coefficients were higher in mechanical pretreated plums followed by chemical and untreated plums. The same reasoning may be applicable for the IQF rabbiteye blueberries as well. The blueberry cultivar and grade showed only slight differences in drying time. However, the difference is statistically

not significant. Ihns and others (2010) reported that the drying times for two apricot varieties (Southern Red and Moonpark) at different temperature (60, 80 and 100°C) were very similar at a constant air velocity of 0.20 m/s. Similarly in this study the two rabbiteye blueberry cultivars Brightwell and Powderblue did not show much variation in the drying time during forced air oven drying. Among the different variables tested, drying temperature was found to be a major factor affecting the drying time of mechanically pretreated IQF rabbiteye blueberries.

### ***Desorption isotherms***

The desorption isotherm of IQF rabbiteye blueberries (for both cultivars and grades) at 85 and 107°C are shown in Fig. 3.5. The isotherms showed a curvilinear pattern. However, as the water activity values goes beyond 0.5 it may trace a path of sigmoid shape which is typical for a Type-II moisture isotherms; characteristic of dehydrated foods (Labuza, 1984). Equilibrium moisture content increases slowly at low water activity (around  $a_w = 0.55$  to 0.75) and shows a steep rise at high water activities (after  $a_w = 0.75$  onwards), which is typical behavior for high sugar substances (Maskan and Gogus 1998). The isotherm slightly shifted towards the right as the temperature increased from 85 to 107°C. The difference in the EMC diminished as the water activity reduced to a lower values (<0.6). This behavior is typical for many of the agricultural products (Iguaz and Virseda 2007, Goneli and others 2010). Similar behavior of moisture desorption isotherms were observed by Vega-Galvez and others (2008) for Chilean papaya at 5, 20 and 45°C and Oliver and others (2009) for sweet corn at 30, 40, 50 and 60°C .

Statistical analysis of the moisture and water activity data (Table 3.1) was performed using NLIN procedure with Gauss-Newton approximation. The parameter estimates (A and B) of the regression equations generated from each data set presented in Table 3.2. The mean parameter estimates for all the data sets ranged from 0.0118 to 2.5347 for A (Intercept) and 9.169 to 3.8155 for B (slope). The comparison of 95% confidence intervals for parameter estimates A and B across each data set shows that the confidence limits overlapped each other. It means that the parameter estimates from each data set were not significantly different from each other. As a result a combined data was used to develop the desorption isotherm of IQF rabbiteye blueberry. The isotherm equation from the combined data was found to have a parameter estimate of 1.1078, 4.7144 for A and B respectively. This predicted isotherm is regarded as a representative desorption isotherm for IQF rabbiteye blueberries dried in a forced air oven at 85 and 107°C.

The empirical model fitted the experimental data and the goodness of fit is estimated based on coefficient of determination ( $R^2$ ). The parameter estimates and the  $R^2$  values obtained from the empirical model is compared with other common isotherm equations (Table 3.3). The empirical model and the modified Halsey model best fitted the data with higher  $R^2$  values of 0.97 and 0.94 respectively. Fig 3.6. compares the closeness of predicted isotherms using modified Halsey model and empirical model with the experimental data. The predicted data points from the modified Halsey model closely traced the path of experimental data points with slight deviation at the lower water activity values ( $< 0.70$ ). The analysis of residual plot (not reported) revealed that the random errors distributed around the horizontal band centered around the zero and the residuals showed no apparent pattern. Whereas BET, Kuhn and Oswin model not

successful in fitting the experimental data and predicting desorption behavior of IQF rabbiteye blueberries. Hence under current testing conditions, the empirical model and the modified Halsey equation are the most reliable model(s) in describing the desorption behavior of IQF rabbiteye blueberries.

### **Conclusions**

Based on the results of this study the mechanical pretreatment method showed promise to decrease the drying time of IQF rabbiteye blueberries. Under tested conditions, the effect of cultivar and grade on drying curve was not significant whereas temperature showed marked influence on the drying time. The effect of cultivar, grade and temperature on the desorption isotherm of IQF rabbiteye blueberries is not significant. An empirical equation to predict the desorption characteristics of IQF rabbiteye blueberries was proposed. Among the tested mathematical models, the modified Halsey equation showed good fit of experimental data. This study helped to identify the drying characteristics of individually quick frozen (IQF) rabbiteye blueberries.

## **Acknowledgements**

This research was supported by a grant from the USDA Specialty Crop Block Grant Program to the state of Georgia and by the State and Hatch funds allocated to the University of Georgia Agricultural Experiment Station, Griffin Campus.

The authors would also like to thank Mr. Glenn Farrel for all the technical help, Mr. Phil Tyre of The Alma-Bacon County Economic Development Authority for providing materials and financial support, and Mr. Jerry Davis for helping with statistical analysis of data.

## References

2000. AACC method 44-40. Approved Methods of the American Association of Cereal Chemists. 10<sup>th</sup> ed. St.Paul, MN: AACC International.
2009. SAS/STAT 9.1 User's Guide. Cary, NC: SAS Institute, Inc.
- Branauer, S., Emmett, P.H. and Teller, E. 1938. Adsorption of gases in multimolecular layers. *J. Am. Chem. Soc.* 60:309.
- Grabowski, S., M. Marcotte., D. Qua., A.R. Tahéria., M.R. Zareifard., M. Poirier and T. Kundra 2007. Kinetics and quality aspects of Canadian blueberries and cranberries dried by osmo-convective method. *Drying Technology* 25(1-3): 367-374.
- Ihns, R., L. M. Diamante, P. Geoffrey and G.P. Savage. 2011. Effect of temperature on the drying characteristics, colour, antioxidant and beta-carotene contents of two apricot varieties. *International Journal of Food Science and Technology* 46(2): 275-283.
- Iglesias, H. A. and J. Chirife. 1976. Model for describing water sorption behavior of foods. *Journal of Food Science* 41(5): 984-992.
- Iglesias, H. A. and J. Chirife 1978. Empirical equation for fitting water sorption isotherms of fruits and related products. *Canadian Institute of Food Science and Technology Journal-* 11(1): 12-15.
- Iguaz, A. and P. Virseda. 2007. Moisture desorption isotherms of rough rice at high temperatures. *Journal of Food Engineering* 79(3):794-802.
- Jazini, M. H. and M. S. Hatamipour 2010. A new physical pretreatment of plum for drying. *Food and Bioproducts Processing* 88(C2-3): 133-137.
- Kingsly, R. P., R. K. Goyal, M. R. Manikantan, and S. M. Ilyas. 2007. Effects of pretreatments and drying air temperature on drying behavior of peach slice. *International Journal of Food Science and Technology* 42(1): 65-69.
- Kuhn, I. 1964. New theoretical analysis of adsorption phenomena - introductory part - Characteristic expression of main regular types of adsorption isotherms by single simple equation. *Journal of Colloid Science* 19(8): 685.
- Labuza, T. P. 1968. Sorption phenomena in foods. *Food Technology* 22(3): 15.
- Labuza, T. P. 1984. Application of chemical-kinetics to deterioration of foods. *Journal of Chemical Education* 61(4): 348-358.

Luh, B. S. and J. G. Woodroof. 1988. Commercial Vegetable Processing\_Second\_Edition. New York: Van Nostrand Reinhold, pp 387-473.

Di- Matteo, M., L. Cinquanta, Galiero, G. and Crescitelli, S. 2000. Effect of a novel physical pretreatment process on the drying kinetics of seedless grapes. *Journal of Food Engineering* 46(2): 83-89.

Di- Matteo, M., L. Cinquanta, Galiero, G. and Crescitelli, S. 2002. Physical pre-treatment of plums (*Prunus domestica*). Part 1. Modelling the kinetics of drying. *Food Chemistry* 79(2): 227-232.

Maskan, M. and F. Gogus 1998. Sorption isotherms and drying characteristics of Mulberry (*Morus alba*). *Journal of Food Engineering* 37(4): 437-449.

Maskan, M., S. Karatas and A.P.Vaschinin. 1998. An approach for estimation of critical points of water sorption isotherms of foods. *Drying Technology* 16(3-5): 863-876.

Moreira, R., F. Chenlo and M.D. Torris. 2009. "Simplified algorithm for the prediction of water sorption isotherms of fruits, vegetables and legumes based upon chemical composition." *Journal of Food Engineering* 94(3-4): 334-343.

NASS, 2009. Agricultural Statistics Board, United States Department of Agriculture, Noncitrus Fruits and Nuts 2009 Summary. Retrieved on November 25, 2010 from the World Wide Web  
[http://usda.mannlib.cornell.edu/usda/nass/NoncFruiNu//2010s/2010/NoncFruiNu-07-07-2010\\_new\\_format.pdf](http://usda.mannlib.cornell.edu/usda/nass/NoncFruiNu//2010s/2010/NoncFruiNu-07-07-2010_new_format.pdf)

Oswin, C. R. 1948. The kinetics of package life for diffusivity. *Journal of the Society of Chemical Industry-London* 67(7): 274-277.

Rockland, L. B., and Beuchat, L. R. 1986. Water activity: theory and Applications to Food. Marcel Dekker Inc., U.S.A.

Rockland, L. B. and S. K. Nishi 1980. Influence of water activity on food product quality and stability. *Food Technology* 34(4): 42.

Scott, D. B. 1957. Report on extraneous materials in dairy products. *Journal of the Association of Official Agricultural Chemists* 40(2): 392-396.

Shi, J., Z. Pan., T.H. McHugh, D. Wood, E. Hirschberg and D. Olson. 2008. Drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation heating. *LWT-Food Science and Technology* 41(10): 1962-1972.

Stojanovic, J. and J. L. Silva. 2007. Influence of osmotic concentration, continuous high frequency ultrasound and dehydration on antioxidants, colour and chemical properties of rabbiteye blueberries. *Food Chemistry* 101(3): 898-906.

Thakur, A. K., V. K. Saharan and R.K Gupta. 2010. Drying of 'Perlette' grape under different physical treatment for raisin making. *Journal of Food Science and Technology-Mysore* 47(6): 626-631.

Togrul, I. T. and D. Pehlivan 2003. Modeling of drying kinetics of single apricot. *Journal of Food Engineering* 58(1): 23-32.

USHBC, 2010. United States Highbush Blueberry Council, Folsom, California, U.S.A. Blueberry information. Retrieved December, 2010 from the World Wide Web <http://www.blueberry.org>.

Vega-Galvez, A., R. Lemus-Mondaca., C. Terlo-Ireland., M. Miranda and F. Yagnam. 2009. Kinetic Study of Convective Drying of Blueberry Variety O'neil (*Vaccinium corymbosum* L.). *Chilean Journal of Agricultural Research* 69(2): 171-178.

Zhang, X. W., X. Liu, D-X. Gu, W. Zhou, R-L. Wang and P. Liu. 1996. Desorption isotherms of some vegetables. *Journal of the Science of Food and Agriculture*, 70(3): 303-306.



Fig. 3.1- In-house fabricated mechanical scarifier in action with side view (left) and top view (right) 1. Conveyor belt 2. Serrated rollers 3. Handle to adjust clearance between 1 & 2.

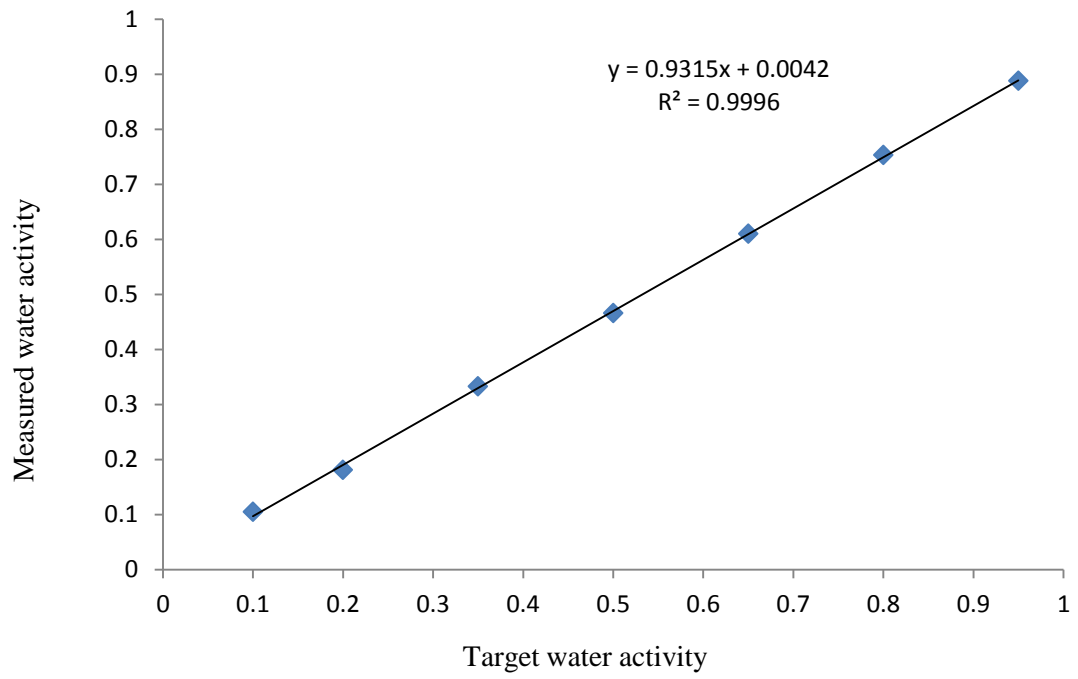


Fig 3.2: Calibration of water activity meter using different relative humidity standards

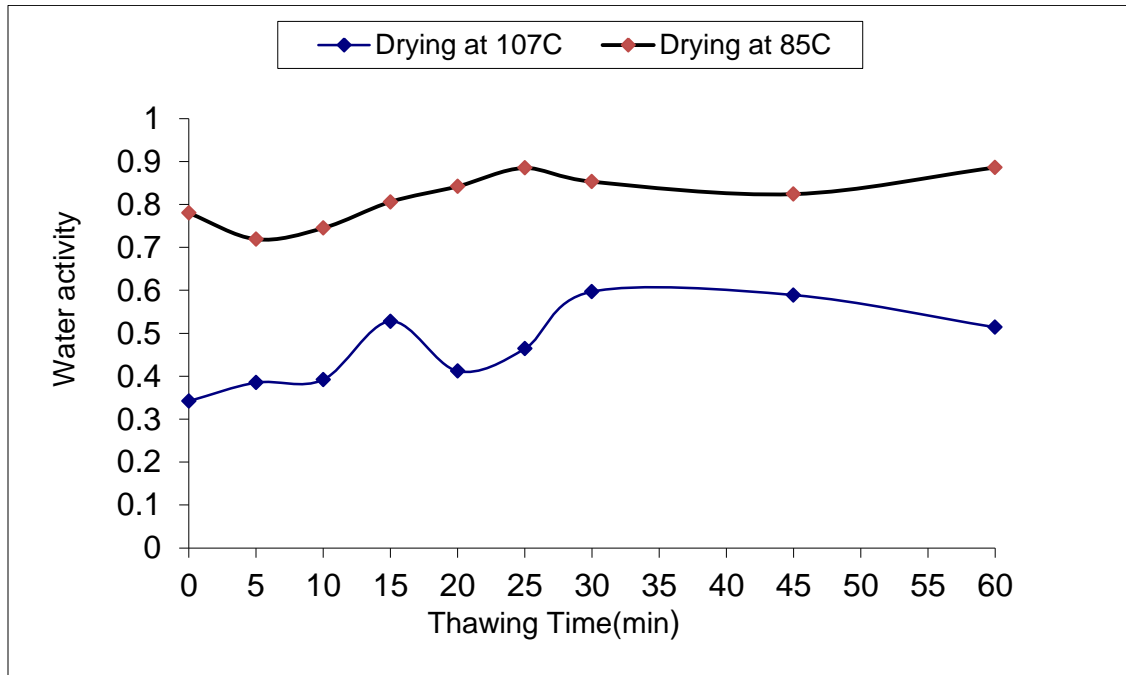


Fig. 3.3: Relation between thawing times and water activity of scarified partially thawed frozen blueberries when dried in an impingement oven for 60 min

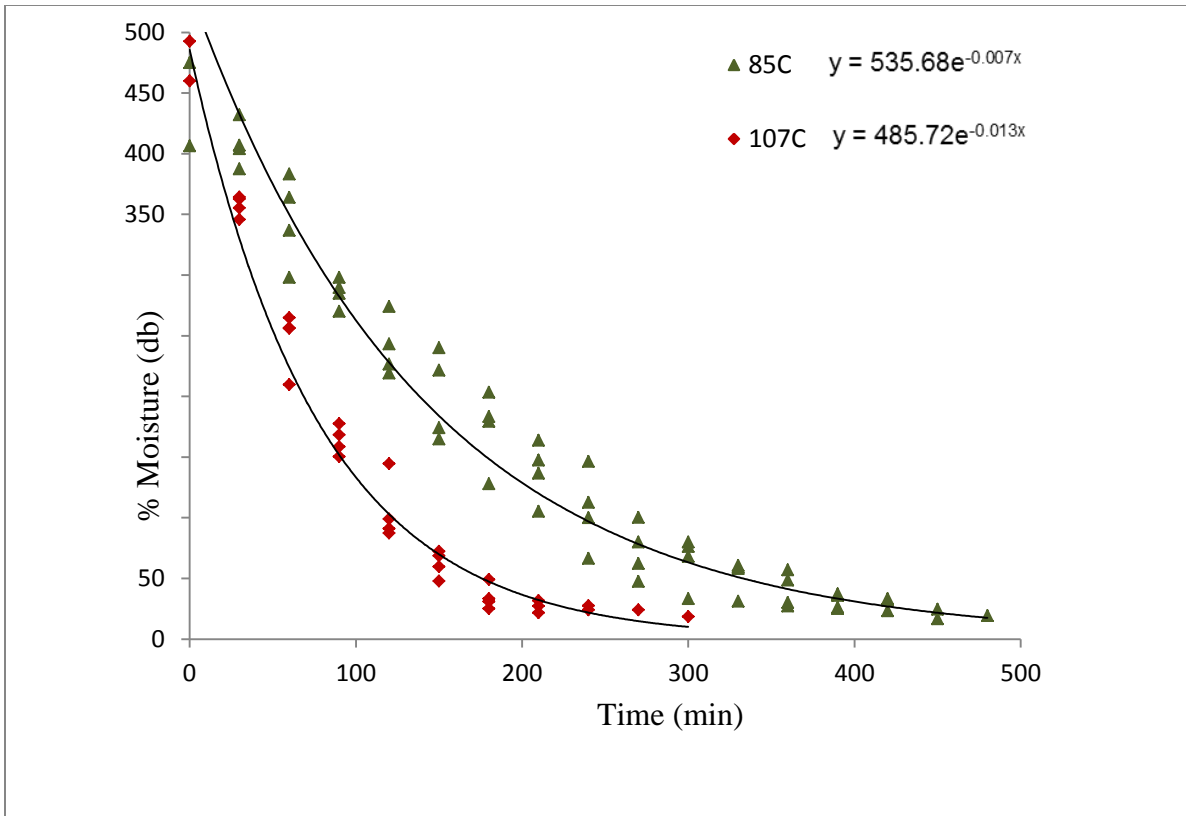


Fig 3.4: Drying curves of pretreated IQF rabbiteye blueberries

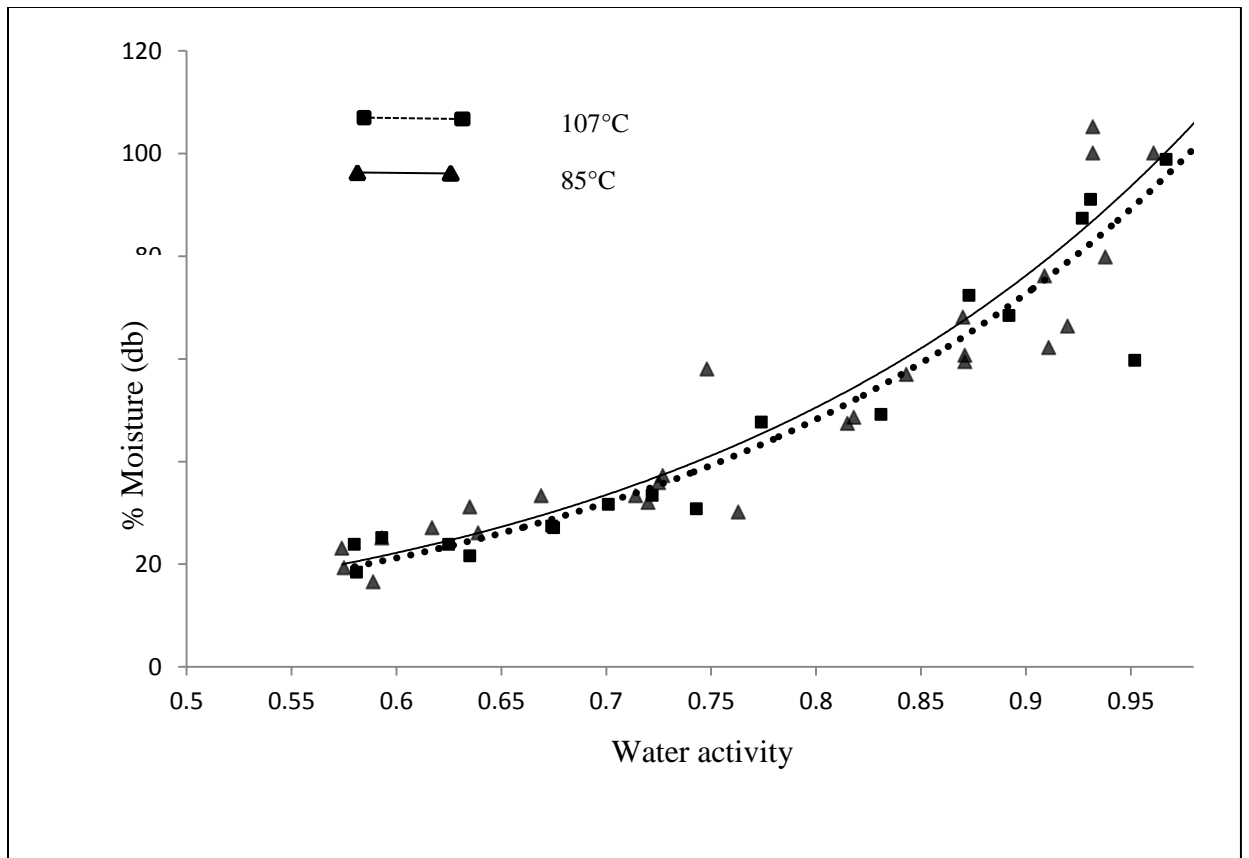


Fig.3.5. Comparison desorption isotherms of IQF rabbiteye blueberry at 85 and 107°C

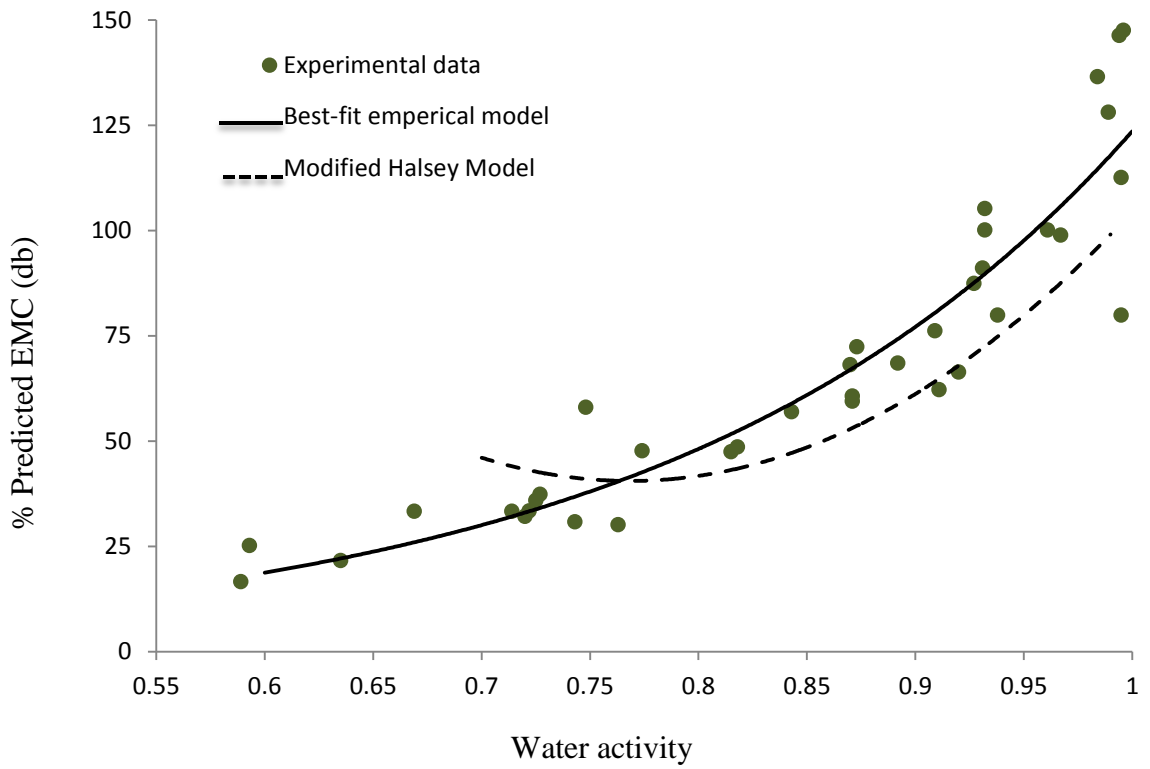


Fig 3.6: Comparison of goodness of fit of experimental data with modified Halsey model and empirical model

Table 3.1: Moisture content and water activity of blueberries dried in a forced air oven

Temp. (°C)	Cultivar	Grade	Parameter	Desorption data																
85	Brightwell	A	Time(min)	0	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	
			Water activity	0.999	0.998	0.998	0.997	0.997	0.996	0.996	0.984	0.961	0.911	0.870	0.748	0.818	0.727	0.720	0.589	
			Moisture (%db)	406.3	387.3	364.0	284.7	226.4	174.1	203.3	136.5	100.1	62.18	68.12	58.03	48.59	37.29	32.05	16.55	
		C	Time(min)	0	30	60	90	120	150	180	210	240	270	300	330	360	390	420	480	
			Water activity	0.999	0.999	0.998	0.998	0.997	0.997	0.996	0.996	0.994	0.932	0.909	0.871	0.843	0.725	0.714	0.575	
			Moisture (%db)	475.0	406.8	383.1	297.9	273.9	240.1	183.4	147.5	146.3	100.1	76.18	60.69	56.94	35.90	33.33	19.32	
	Powderblue	A	Time(min)	0	30	60	90	120	150	180	210	240	270	300	330	360	390			
			Water activity	0.999	0.999	0.998	0.998	0.997	0.996	0.989	0.932	0.920	0.815	0.669	0.635	0.617	0.593			
			Moisture (%db)	517.7	431.9	336.7	269.9	219.2	164.9	128.1	105.2	66.36	47.45	33.32	31.15	27.12	25.09			
		C	Time(min)	0	30	60	90	120	150	180	210	240	270	300	330	360	390	420		
			Water activity	0.999	0.999	0.998	0.998	0.997	0.997	0.996	0.996	0.995	0.995	0.938	0.871	0.763	0.639	0.574		
			Moisture (%db)	509.7	404.0	297.9	289.6	243.0	221.4	179.3	163.7	112.5	79.86	79.86	59.44	30.14	26.09	23.12		
107	Brightwell	A	Time(min)	0	30	60	90	120	150	180										
			Water activity	0.999	0.999	0.992	0.992	0.927	0.774	0.593										
			Moisture (%db)	492.8	345.8	209.8	150.4	87.37	47.69	25.17										
		C	Time(min)	0	30	60	90	120	150	180	210	240								
			Water activity	0.999	0.999	0.997	0.979	0.931	0.873	0.722	0.675	0.580								
			Moisture (%db)	505.3	355.4	256.0	158.5	91.06	72.38	33.38	27.13	23.89								
	Powderblue	A	Time(min)	0	30	60	90	120	150	180	210									
			Water activity	0.999	0.998	0.997	0.996	0.967	0.892	0.743	0.635									
			Moisture (%db)	522.3	364.2	264.8	177.6	98.88	68.46	30.79	21.61									
		C	Time(min)	0	30	60	90	120	150	180	210	240	270	300						
			Water activity	0.999	0.999	0.998	0.996	0.995	0.952	0.831	0.701	0.674	0.625	0.581						
			Moisture (%db)	459.9	362.7	256.2	168.2	144.5	59.69	49.16	31.65	27.43	23.89	18.46						

\*Reported values are mean of duplicate experiments.

Table 3.2: Parameter estimates of the regression equations for different drying experiments

<b>Cultivar</b>	<b>Temp (°C)</b>	<b>Grade</b>	<b>A</b>	<b>95% Confidence Interval of A</b>		<b>B</b>	<b>95% Confidence Interval of B</b>	
Brightwell	85	A	0.9794	-0.7160	2.6748	4.8843	3.0102	6.7584
		C	0.4270	0.0655	0.7884	5.8456	4.9576	6.7336
	107	A	2.5347	-1.1301	6.1996	3.8155	2.1704	5.4606
		C	1.4686	-0.1697	2.7675	4.4381	3.9176	5.9028
Powderblue	85	A	1.5362	-0.8245	3.8969	4.4092	2.7505	6.0680
		C	1.8671	-1.6853	5.4194	3.9656	1.9650	5.9663
	107	A	0.8558	-0.0701	1.6415	4.9102	3.9176	5.9028
		C	0.0118	-0.1404	0.1641	9.1690	-4.0135	22.3516

- \* The regression equation is of the form  $Y=Ae^{BX}$   
 Where Y is Equilibrium moisture content (%)  
 X is Water activity  
 A is intercept and B is slope

Table 3.3: Comparison of parameter estimates and  $R^2$  values among different isotherm models

<b>Model</b>	<b>A</b>	<b>B</b>	<b><math>R^2</math></b>
Predicted model	1.1078	4.7144	0.97
Modified Halsey	156943	3.4916	0.94
Kuhn	0.4501	46.3264	0.52
BET	0.7571	-3.73E36	0.51
Oswin	4.8E-42	17.2660	0.12

## **CHAPTER 4**

### **EFFECT OF DRYING METHOD ON DRYING TIME AND PHYSICO-CHEMICAL PROPERTIES OF DRIED RABBITEYE BLUEBERRIES**

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<sup>1</sup> Yemmireddy, V., Hung, Y. -C. and Chinnan, M.S. To be submitted to Journal of Food Science.

## **Abstract**

Partially thawed individually quick frozen (IQF) rabbiteye blueberry cultivars Brightwell and Powderblue were dried in an air-impingement oven at 85 and 107°C using two different configurations (Impingement of hot air from top and bottom of the product or method-1, impingement of hot air only from the top of the product or method-2). The effect of cultivar, pick time, grade, drying temperature and drying method on drying time and physico-chemical properties of dried blueberries were determined. Conventional forced air oven and a jet-zone fluidized bed dryer were used as control-1 and control-2 for comparison. Drying times were about 50% longer at 85°C when compared to 107°C for all drying methods. Among the drying methods; control-2 is fastest followed by method-2, method-1 and control-1 to achieve a final water activity of  $0.55 \pm 0.05$ . Cultivar, drying method and their interaction with drying temperature showed significant effect ( $P \leq 0.05$ ) on drying times. Interaction between pick time and cultivar showed significant effect on texture of the dried blueberries. Several of the tested variables and their specific interactions showed significant effect on color values. Pick time, grade, drying temperature, drying method and its interaction with cultivar showed significant effect ( $P \leq 0.05$ ) on bulk density. Pick time and drying temperature on fat, interaction between cultivar and grade on protein, cultivar and pick time on total carbohydrate content showed statistically significant ( $p \leq 0.05$ ) effect. Impingement drying method showed promise as an alternative drying method for IQF rabbiteye blueberries. The overall dried product quality is comparable to control methods.

**KEY WORDS:** Rabbiteye blueberry, cultivar, grade, impingement, physico-chemical properties

## **Introduction**

Blueberries (*Vaccinium Spp.*) are native to the North America and widely consumed due to their unique flavor and high nutritional value (Shi and others 2008). United States and Canada are the world leading producers of cultivated and wild blueberries, accounting for nearly 90% of the world production (US Highbush Blueberry Council, 2010). Recent trend showing continuous increase in production of blueberries in U.S. In 2009 United States produced 456 million pounds of blueberries with a value of 508 million dollars (National Agriculture and Statistical Services (NASS), US Department of Agriculture (USDA), 2009). As a result of continuous increase in production and reported health benefits, the per capita consumption of blueberries in the United States increased more than 70% over the last one decade and gaining popularity in other parts of the world as well (USHBC, 2010). Rabbiteye blueberry (*Vaccinium ashei*) is one of the three commercially grown varieties and highly productive in southeastern region of the USA. It is tolerant to high summer temperature, high draught resistance and requires only moderate chilling; making it ideally suitable for southeastern states particularly Georgia, Florida and Alabama (Basiouny, 1996).

In Georgia, Rabbiteye blueberry production gradually increased over a decade and reached around 43 million pounds with a value of ~56 million dollars in 2009 (NASS, USDA 2009). However, high perishability and short shelf life of fresh blueberries is a common problem for blueberry industry; which limits market availability and consumption (Shi and others 2008). Blueberries have a brief harvest season and under controlled atmospheric conditions can be stored only 6 wk after harvesting (Prange and Asiedu 1995). Increase in production as well as rapid machine harvesting quickly

saturates fresh market, as a result surplus produce needed to be frozen stored for later usage and value addition. High cost of frozen storage, packaging and distribution is a concern to many growers and processors.

Value addition in the form of drying is proven to be a good alternative to increase the market potential and availability of many fruits and vegetables. Several researchers in the past worked on various methods of drying blueberries. These methods include but not limited to forced air drying (Friar and Mark 1943), tunnel drying (Stafford and Guadagni 1977), continuous explosion puffing system (Sullivan and others 1982), micro-convection drying (Yang and Atallah 1985), freeze drying (Rahman, 1972), fluidized bed drying (Kim and Toledo, 1987), microwave- spouted bed drying (Feng and Tang 1999), Infrared drying (Shi and others 2008) and various combinations of these methods. All the above mentioned methods are unique in their operation and usage as per specific requirements.

Air-Impingement oven has been used successfully for baking and cooking products such as tortilla and potato chips, pizza crust, pretzels, crackers, cookies, bread and cakes (Rickard and others 1993) and drying coffee, cocoa beans, rice and nuts (Moreira, 2001). Also impingement oven is proved to be rapid, simple and efficient. Impingement oven adaptability for drying fruits especially blueberries is unknown. Also, there is a dearth of information on the effect of cultivar, pick time and different grades of blueberry on drying time and dried product quality. Understanding the effect of these variables on drying performance and dried fruit quality would help to identify significant variables in designing and optimizing a drying method as per the specific requirements. Therefore,

the objective of this study was to determine the effect of cultivar, pick time, grade and drying temperature and drying method on drying time as well as dried product quality.

## **Materials and Methods**

### ***Blueberries***

Individually quick frozen (IQF) rabbiteye blueberry (*Vaccinium ashei*) cultivars Brightwell and Powderblue from the first and second harvests of the year 2010; and machine graded as A and C were selected for this study. According to USDA-Agricultural Marketing Services (22 FR 3535 §52.613), on a 100 point scale based on color (20 points), absence of defects (40 points) and character (firm, fleshy and intact, 40 points); blueberries whose total score is above 90 are assigned as grade A. Grade C is assigned to blueberries with total score between 80 and 70. The frozen blueberries were obtained in 30 lb boxes from Alma Pak Industries (Alma, GA) and stored at below -18°C until used.

### ***Pretreatment***

To speed up the drying process, blueberry skin will need to be ruptured to facilitate the moisture removal during drying. A pretreatment developed by Yemmireddy and Hung (2011) was used. Frozen blueberries were thawed for 20 min at room temperature and subjected to surface scarification using a mechanical scarater described in Yemmireddy and Hung (2011) at a fixed distance of 5 mm between conveyor belt and serrated roller. This method of pretreatment allowed the formation of random pin holes on the surface of partially thawed IQF blueberries and hence speedup the drying process.

### ***Drying methods***

Four drying methods with 1 kg of scarified berries for each drying experiment were conducted. End point of drying was achieved when dried berries reached a final moisture content of 12 to 18% (wet basis) or a water activity of  $0.55 \pm 0.05$ .

1. ***Forced air oven***: Scarified blueberries were spread on a stainless steel screen ( $20 \times 8 \text{ cm}^2$ ) with same dimensions screen as top cover and dried in a conventional forced air oven (Lindberg/Blue M mechanical oven, Asheville, NC) at both  $85^\circ\text{C}$  and  $107^\circ\text{C}$  to a final water activity of  $0.55 \pm 0.05$ . The air velocity of the dryer was measured as 0.4 m/s using an anemometer (Taylor Briam's Type Anemometer, No.3132, Taylor Instrument Companies, Rochester 1, NY). This drying method was defined as control-1.
2. ***Fluidized bed dryer***: Drying experiments on a commercial scale fluidized bed dryer (The Jet Zone<sup>®</sup>, Model: SNB, Wolverine corporation, Merrimac, MA) was conducted at two temperatures ( $85^\circ\text{C}$  and  $107^\circ\text{C}$ ) to the same final water activity of  $0.55 \pm 0.05$ . Based on previous research experience on this dryer, the air velocity was set at about  $\sim 45 \text{ m/s}$ . This drying method was defined as control-2.
3. ***Air-impingement oven***: Drying experiments were conducted using an air impingement oven (Lincoln<sup>®</sup>, Model 1452, Food Service Products, Inc., Fort Wayne, IN) (Fig 4.1) at both  $85^\circ\text{C}$  and  $107^\circ\text{C}$  using the same screens to hold and cover blueberries as for control-1 method. Hot air impinges from top and bottom of the conveyor at an air velocity of  $\sim 1.4 \text{ m/s}$  from each side independently when measured using an anemometer.
4. ***Modified air-impingement oven***: Air-impingement oven was modified to only

allow air impinge from the top of the conveyor by completely blocking air flow from the bottom (B1-B4 in Fig 4.1 completely blocked). The purpose of this modification was to closely resemble the jet-zone fluidized bed dryer (Control-2). Air velocity was increased to ~1.6 m/s to achieve pseudo fluidization conditions while drying.

### ***Experimental design***

Drying experiments were conducted with combination of cultivar (Brightwell and Powderblue), pick time (pick-1, which is first harvest of a field in a season, and pick- 2, a subsequent harvest in the same field usually one week after the first harvest), grade (grade A and grade C) and temperature (85°C and 107°C). Factorial design based on cultivar\*pick\*grade\*temperature (2\*2\*2\*2) was implemented on each of the four drying methods with 1 kg sample size. Each combination of drying experiment was conducted in duplicate. Hence a total of 128 (2\*2\*2\*2\*4\*2=128) drying experiments were conducted and the dried products were stored in high barrier polyethylene bags for further quality analysis.

### ***Quality analysis***

#### **Water activity**

The water activity ( $a_w$ ) of thawed and scarified blueberries, as well as dried blueberries was determined using an Aqua Lab water activity meter (Decagon Devices, Inc., Series 3, Pullman, WA) at room temperature.

#### **Proximate composition**

Moisture, fat, protein and ash contents were determined on dried blueberries from the fluidized bed (Control-2) dried samples. The dried blueberries were grounded into

powder using a grinder (Black & Decker, Smart grind) for composition analysis. Moisture content was determined using the AACC method 44-40 (AACC 2000). Moisture free sample was used to determine crude fat using the AACC method 30-26 (AACC 1976) on Goldfish fat extraction apparatus. Moisture and fat free sample was used to determine protein content (Nx6.25) using the AOAC Official method 984.13 (AOAC 1995), Kjeldhal nitrogen analysis, performed by the Agricultural and Environmental Services Laboratories, University of Georgia, Athens, USA. Ash content was determined using the AOAC method 942.05 (AOAC 2006) by a muffle furnace. Carbohydrate content was calculated by difference. All measurements were made in duplicate for each drying experiment; hence final value is an average of four measurements.

**Bulk density**

The volume of dried blueberries was measured by a glass beads displacement method in a known volume of cylindrical container (Hwang and Hayakawa, 1980). Glass beads (30 to 40 Standard U.S. sieve size, Delong Equipment Co., Atlanta, GA) were used as displacement medium. Bulk density of dried blueberries were calculated as

$$\rho_{db} = W_{db} / [V_c - (W_{gb} - W_{db}) / \rho_{gb}]$$

Where  $\rho_{db}$  is bulk density of dried blueberries in g/cc

$W_{db}$  is weight of dried blueberries (g)

$V_c$  is volume of cylindrical container (ml)

$W_{gb}$  is weight of glass beads in cylindrical container with blueberry (g)

$\rho_{gb}$  is density of glass beads (g/ml)

The bulk density of each batch is measured and the reported values are an average of four measurements.

## **Color**

The CIE color coordinates ( $L^*$ ,  $a^*$ ,  $b^*$ ) of dried blueberry was measured using a Hunter Lab® Miniscan XE™ colorimeter, Model 45/0-L (Hunter Associates Laboratory, Reston, VA). The colorimeter was calibrated against a standard white tile and a black tile. Approximately 15 g of sample was placed in a 9 mm diameter and 10 mm deep plastic petridish and the surface was covered with dark background before color measurement to avoid diffraction errors. Three readings were taken on the same sample after rotating the dish to  $\sim 120^\circ$  angle and the values from three readings were averaged to have a representative  $L^*$ ,  $a^*$  and  $b^*$  values. The hue angle, defined as  $h^0 = \tan^{-1}(b^*/a^*)$ , was calculated and expressed in degrees. Hue angle of 0, 90, 180 and 270 degrees are of red, yellow, green and blue, respectively.

The total color difference ( $\Delta E$ ) represents the distance, in three-dimensional CIE color space, between the point representing the thawed blueberries and the point for the dried berries and was calculated as

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2}$$

$$\text{Chroma} = (a^{*2} + b^{*2})^{1/2}$$

Where the subscript '0' indicates color values of thawed IQF blueberry whose  $L_0^* = 16.04$ ,  $a_0^* = 3.78$  and  $b_0^* = -1.58$ .

## **Texture**

An Instron Universal Testing Machine Model 5544 (Instron Corporation, Canton, MA) was used to measure the force required to cut through individual berries using a Warner-Bratzler (WB) shear blade (triangular slot cutting edge, blade thickness 1.1 mm, height 50 mm and width 68 mm) at a cross head speed of 50 mm/min. A gap of 2 mm

was used between the two shear bars of the WB device. The maximum peak force (N) required to shear through the sample was recorded as shear force. Results were presented as a mean value of ten measurements.

### ***Statistical analysis***

The experimental data were arranged in a 5-way factorial design (FD) and analyzed by the analysis of variance (ANOVA) procedure at 5% level of significance using SAS version 9.1(SAS Inc., Cary, NC).

## **Results and Discussion**

### ***Composition***

Assuming method of drying will not show significant effect on composition, dried product from fluidized bed dryer was used for composition analysis. The effect of significant factors and their specific interaction on composition of dried blueberries is presented in Table 4.1. Statistical analysis of the composition data in dry basis revealed that the total ash content is not affected by any of the variables studied and is ranged from 1.27 to 1.34%. Pick time and drying temperature showed statistically significant effect ( $P \leq 0.05$ ) on fat content. However, the overall fat content only ranging between 0.47 and 0.84% and the difference may not have any practical significance.

The interaction between cultivar and grade showed statistically significant effect ( $P \leq 0.05$ ) on protein content. The overall protein content ranged from 2.22% (for Brightwell and grade-A combination) to 2.95% (for Powderblue and grade-C combination). The main composition of dried blueberry is carbohydrate/sugar. The interaction between cultivar and pick time has significant effect on total carbohydrate

content, and ranged from 94.86% for Powderblue from pick-1 to 95.65% for Brightwell from pick-2.

Changes in certain compositional parameters might be due to the different harvesting times and fruit grades. As the fat, protein, and ash contents are all very low it has no practical meaning for the differences due to variation among cultivars, pick times and grades. Rejman and Pliszka (1991) reported that 100 g of fresh blueberries will contain approximately 83.4 g water, 0.6 g protein, 0.6 g fat, 0.3 g ash, 15 g sugars and micro levels minerals and vitamins. Upon converting the composition information to dry basis, blueberries from Rejman and Pliszka (1991) studies had a composition of 3.6, 3.6, 1.8 and 91% for protein, fat, ash, and carbohydrates, respectively. For the current study the dry basis composition are 2.7, 0.6, 1.3 and 95.4% for protein, fat, ash, and carbohydrates, respectively. Based on the results from the current study when compared with Rajman and Pliszka (1991), drying may not have any significant effect on overall composition apart from removing water and concentrating total soluble solids. Luh and Woodroof (1988) reported that drying leaves the mineral content virtually unchanged and vitamin losses are no greater with drying than with other preservation methods.

### ***Drying time***

The statistical analysis of drying data indicated that cultivar, drying temperature and drying method all had significant effect ( $P \leq 0.05$ ) on drying time (Table 4.2). Also, the interaction effect between temperature and cultivar, temperature and drying method was found to be statistically significant. Whereas, pick time and grade had no statistically significant effect on drying time ( $P > 0.05$ ). Mean drying time(s) for the Brightwell (4.08hr) is higher than the Powderblue (3.95hr) (Table 4.2). When consider interaction

effect due to cultivar and temperature, Brightwell variety required longer drying time (5.20hr @ 85°C, 3.25hr @ 107°C) than Powderblue (4.87hr at 85°C, 2.98hr at 107°C). One reason for the variation in drying time between these two cultivars may be attributed to the differences in the basic cellular structure of the two varieties. Silva and others (2005) studied the physicochemical characteristics of highbush (Bluecrop, Jersey) and rabbiteye (Climax, Premier and Tifblue) blueberries and found differences in fruit textural characteristics were attributed to the differences in skin thickness and cell wall components among and/or within these varieties. However, using previously frozen blueberries for drying process may mitigate the structural differences at cellular level than using fresh blueberries. Secondly, Brightwell blueberry has medium to large in size while Powderblue blueberry has medium size (Krewer and NeSmith 2006). In a study conducted by McGregor (2005) on the effects of air velocity, air temperature and berry diameter on wild blueberry drying and found under similar drying conditions larger berries required longer drying time than smaller ones to reach a similar final moisture content.

The solubilization of sugars might hinder the moisture migration and evaporation in the later part of the falling rate drying period and thus extend the drying time. Dekazos (1978) reported a variation in percent soluble solids content among rabbiteye blueberry cultivars Brightblue (13.9%), T-19 (E.C. Lott) (14.1%), Woodard (16%) and Tifblue (16.8%). Bremer et al (2008) also observed a similar variation in the soluble solids content among six highbush cultivars harvested during different seasons. Miller and McDonald (1996) found difference in total soluble solids content among Brightwell (13.1%) and Tifblue (15.5%) cultivars of rabbiteye blueberries. For the current study,

Powderblue had lower carbohydrates (95.18%) than Powderblue (95.57%). The synergistic effect of all these factors discussed above might be the reason for contributing to a significant difference in drying time between Brightwell and Powderblue. However, in a previous study on drying characteristics of IQF rabbiteye blueberries (Yemmireddy and Hung 2011); cultivar (Brightwell vs Powderblue) had no significant effect on drying time. These contrasting results mainly attributed to the differences of sample size (500 g) and using only forced air oven for drying in the previous study.

Drying times were about 8.43, 2.80, 5.37 and 4.58 hrs at 85°C and 4.87, 1.47, 2.37 and 2.15 hrs at 107°C for forced air oven, fluidized bed dryer, impingement oven and modified impingement oven; respectively (Table 4.2). Drying times were approximately 50% longer at 85°C compared to 107°C for all drying methods. As expected, increase in drying temperature (from 85°C to 107°C) reduced the drying time significantly. At lower temperature it may take more time for the moisture to attain latent heat of vaporization and migrate through the inner capillary structure of the blueberry. Similar results were observed by Ihns and others (2011) for hot air drying of two apricot varieties at 60, 80, 100± 2°C with constant air velocity of 0.20 m/s. They concluded that constant rate period drying rate and first and second falling rate period drying coefficients increased with drying temperature for both varieties of apricot slices.

The mean drying times among four drying methods are found to be forced air oven (6.03hr), fluidized bed dryer (2.47hr), impingement oven (4.42hr) and modified impingement oven (3.58hr) (Table 4.2). Compared with forced air oven (control-1); drying times were 36 and 51% less for impingement oven and 46 and 44% less for modified impingement oven at 85°C and 107°C respectively. When compared with

fluidized bed dryer (control-2), the drying times were 92 and 61% more for impingement oven and 64 and 46% more for modified impingement oven at 85°C and 107°C respectively. The difference in the drying times among the four drying methods at a constant temperature may be attributed to the variation in the air velocities and configuration of the individual dryer. As noted by Sarkar and Singh (2003), in a jet impingement systems in spite of increasing air velocities, the boundary layer near the wall (the impingement surface) did not change significantly beyond a limiting velocity. Thus, beyond this limiting velocity there will be no significant increase in heat transfer. This might be the reason that the fluidized bed dryer (control-2) used in this study which resembles jet impingement system by creating zones of pseudo fluidization of product dried at high velocities (45 m/s) did not show the same proportion of reduction in drying times of impingement (1.4 m/s) and modified impingement oven (1.6 m/s). Drying times were lower for modified impingement oven in which entire hot air impinged on the top of the product when compared to impingement oven with air flow evenly impinged from top and bottom of the product. The interaction effects of impinging jets from both directions may reduced the turbulence created on the product surface and hence heat transfer coefficient in case of regular impingement oven. Although the drying times for impingement oven was longer than modified impingement oven (2.37 vs 2.15hr) at 107°C, the difference was not statistically significant. Modified impingement oven had a significantly shorter drying time than regular impingement oven (4.58 vs 5.37hr) at 85°C. This implies that modified impingement oven set up helped to increase the heat transfer coefficient (faster air velocity) and hence shorter drying time than the regular impingement oven arrangement. In general, limiting factor of drying at higher

temperature (e.g. 107°C) is moisture migration to the blueberry surface. Hence, higher heat transfer coefficient at blueberry surface (modified impingement oven vs regular impingement oven) will not help reduce the drying time.

As expected the laminar air flow conditions and slow air flow rate (0.4 m/s) in forced air oven required longer drying times when compared to other methods. McGregor (2005) reported that air velocity, air temperature and berry diameter showed significant effect on IQF frozen wild blueberries and the drying occurs solely in falling rate period. Herman-Lara (2010) reported that increase in air temperatures (from 50 to 90°C), air velocity (from 2 to 6 m/s) and periodical air flow reversal increased drying rate of carrots in packed bed dryer. Based on the findings from this current study, air impingement drying rate fits between forced air oven and high velocity jet-zone fluidized bed dryer. Modified impingement oven showed better performance than impingement oven in reducing drying time. Jet-zone fluidized bed dryer with about 30 times fast air flow rate only improved drying time around 70% than the impingement oven drying. Increasing impingement oven air speed to 4-6 m/s may further reduce the drying time to match jet-zone fluidized bed dryer.

### ***Bulk density***

Pick time, grade, drying temperature, drying method and interaction between drying method and cultivar showed statistically significant effect ( $P \leq 0.05$ ) on bulk density of dried blueberries (Table 4.3). Higher bulk density values were observed for berries dried at 85°C (0.845 g/ml) compared to drying at 107°C (0.800 g/ml). Karathanos and Anglea (1993) examined the structural changes in celery while hot air drying and reported that drying air temperature is a significant factor, which causes major changes in the

vegetable structure as the process progresses. Wang and Brennan (1995) studied structural changes of potato during drying with light microscopy. They observed that the degree of shrinkage of potato during low-temperature drying is greater than at high-temperature drying. This may explain the higher bulk density of blueberries dried at 85°C than 107°C for the current study.

Pick time and grade also had significant effect on bulk density. Berries which were picked in the second harvest (pick-2) have higher mean bulk density (0.866 g/ml) than first harvest (pick-1) (0.782 g/ml). In a research conducted by Swift (2010) on the effect of frozen storage and harvest time on the textural and sensory characteristics of various rabbiteye blueberry cultivars including Brightwell and Powderblue, found that the initial values of percent dry weight (soluble solids), skin toughness and fruit firmness were higher for the second harvest in general. These may help to explain dried blueberry from pick-2 had a higher bulk density than dried blueberry from pick-1. Among the grades A and C; grade A has higher mean bulk density (0.876 g/ml) than grade C (0.773 g/ml). As per the definition of grades of blueberries, grade C is more mature than grade A. Size of the berry will increase during maturation due to continuous uptake of water (Perkins-Veazie, 2004). Small berries will shrink more than large berries under the same drying conditions (McGregor, 2005). As a result, the combination effect of size and maturity might have influenced the bulk density of dried blueberries.

Lower bulk density values were observed for blueberries dried in modified impingement oven (0.767 g/ml) followed by fluidized bed dryer (0.815 g/ml), forced air oven (0.839 g/ml) and impingement oven (0.874 g/ml). However, the difference is not significant between forced air oven and fluidized bed dryer and between forced air oven

and impingement oven. Van-Arsdel (1973) reported the bulk density of food product dried to the same water content is dependent on the rate of shrinkage which in turn is strongly affected by the drying method and the drying conditions such as temperature and air flow within each method. Similarly, longer drying times at 85°C in all drying methods might be resulted in internal cell destruction and excessive shrinkage of blueberries and high bulk density. As noticed here, longer drying times leads to more shrinkage and higher bulk density values which is quite evident in forced air oven. At the same time high jet velocities in fluidized bed drier and impingement oven increased the drying rate which makes the berries to shrink more, even for shorter duration of drying. Nowak and Lewicki (2005) in a study conducted on quality of infrared dried apple slices reported that, the damage of tissue structure is much greater at high drying rate which leads to greater shrinkage when compared to that at lower drying rates. It should be noticed that two completely different drying methods forced air oven and jet-zone fluidized bed drier did not showed significant difference in their bulk density. Longer drying times in forced air oven may be resulted excessive shrinkage and high bulk density values; in the same way jet-zone fluidized bed drying of the berries may resulted in excessive shrinkage due to its highest drying rate and hence high bulk density. Hence bulk density resulted from prolonged drying times in forced air oven is synchronized with the shrinkage of berries at high jet velocities in fluidized bed dryer. Similar results were observed by Argyropoulos and Heindl (2011) while drying mushrooms at 60°C and at an air velocity of 0.9 m s<sup>-1</sup> using hot-air-convection drying. They believed that hot-air-drying caused considerable shrinkage and collapse of the cell walls.

Blueberries dried using modified impingement oven method had the lowest bulk density and this may be due to the synergistic effect of shorter drying times (about 3.6hr), medium air velocity (1.6 m/s) and pseudo fluidization during drying. The combination effects may help explain less shrinkage of blueberries when dried in the modified impingement oven which resulted in low bulk density when compared to dried blueberries from other drying methods.

As reported by Brown (1967) density characteristics may be perceived differently in different markets. High bulk density products were preferred in order to reduce shipping and storage costs in the re-manufacturing markets where as low bulk density products are preferred for psychological characteristics in the retail market. The dried product from the impingement oven and modified impingement oven in terms of bulk density might fit in between and can be used as per any market requirement.

### ***Color***

Mean color values of dried blueberries are reported in Table 4.4. Drying method, cultivar, grade and drying temperature showed significant effect ( $P \leq 0.05$ ) on color values. Pick time has no effect on most of the color values. However, pick time has significant effect on lightness ( $L^*$ ) values. Pick-2 has higher  $L^*$  value (15.59) value compared to pick-1 (15.21).

Drying method showed significant effect on color of dried blueberries. Color difference value ( $\Delta E$ ) account for the differences between the  $L^*$ ,  $a^*$  and  $b^*$  values of the sample and the standard (thawed blueberries). Statistical analysis of color difference values revealed that the drying method had no significant effect ( $P > 0.05$ ) on color difference. The lightness ( $L^*$ ) values of dried blueberries from forced air oven, fluidized bed dryer,

impingement oven and modified impingement were 16.29, 15.40, 13.42 and 16.24 respectively. Blueberries dried using impingement oven had the lowest  $L^*$  value (13.42) indicated it had the darkest color. However, the difference in the lightness  $\Delta L (L^*-L_0^*)$  between the standard and other methods is very low indicating that the dried blueberries retained typical dark color of blueberries after drying (Fig. 4.2).

Hue angle describes the visual sensation of the color perceived by the human eye. It represents the appearance of a color in comparison to one or proportions of two or more of the perceived standard colors of red, yellow, green and blue (Cheng-Jin Du and Da-Wen Sun 2004). The values of hue angle among four drying methods ranges from 300.96 to 339.78 in the color wheel between 270 (blue) and 360/0 (red) and representing reddish- blue tinge. Dried blueberries from fluidized bed drier had lowest hue angle (300.96) followed by impingement oven (321.52), modified impingement oven (335.85) and forced air oven (339.78). Lower hue angle value represents a more bluish appearance while higher value represents reddish tinge. The hue angles of forced air oven and modified impingement oven are not significantly different from each other. Van Teeling and Cansfield (1971), Ramaswamy and Nsonzi (1998) reported that with heat treatment, reddish anthocyanins are converted to a colorless carbinol base and remaining bluish brown co-pigments started to dominate the color of dried blueberries. This explains that the high jet air velocities in fluidized bed dryer and impinging jets from both directions in impingement oven might have resulted in greater loss of anthocyanins (red pigments) and hence dried blueberries appear more bluish when compared to forced air oven and modified impingement oven.

Drying temperature also showed significant effect on lightness, chroma and hue values (Table 4.4). Blueberries dried at 85°C has higher values of lightness (15.69), chroma (3.50) and hue angle (325.53) compared to 107°C ( $L^* = 15.07$ ,  $C=3.12$  and  $H =323.28$ ). It shows that the blueberries dried at 107°C are more bluish in appearance than blueberries dried at 85 °C. Nebesky and Esselen (1969) reported that oxygen and temperature were the most specific accelerating agents in the degradation of blueberry pigments. Hence the blueberries dried at higher temperature (e.g. 107°C) may resulted in greater loss of reddish anthocyanin pigments and appear darker (more bluish) compared to berries dried at lower temperature.

Cultivar and grade also had significant effect on the color values. Powderblue has higher  $L^*$  (15.94), chroma (3.88) and hue value (327.89) than Brightwell ( $L^* = 14.81$ ,  $C=2.74$  and  $H= 320.78$ ). Similarly grade- C has higher hue value (327.30) than grade- A ( $H=321.53$ ). Lohachoompol (2008) reported that the total anthocyanin content of Powderblue (expressed as g of cyanidin3-glucoside equivalent per kg of dry weight) ( $11.9\pm1.7$ ) was higher than Brightwell ( $10.1\pm0.1$ ). Since color values were highly dependent on anthocyanin/ pigments; the difference in the initial anthocyanin content may resulted in difference in the color values of dried blueberries from Brightwell and Powderblue cultivars in the present study. Overall, the tested variables in this study showed significant effect on color of the dried blueberries. However, these color changes were subtle to the human eye to perceive, indicating no major changes in the appearance of the dried blueberries.

### *Texture*

Texture of dried blueberries was expressed as shear force and is ranged from 16.38N to 33.15N. Here the shear force is defined as the maximum force required to shear through a dried blueberry using Instron equipped with Warner-Bratzler blade. The shear strength is an indication of the toughness of the product when consumed directly in the dry state (Kim and Toledo., 1987).

Statistical analysis of the texture data revealed that neither of the variables studied showed significant effect ( $P \leq 0.05$ ) on the texture. Among the four drying methods the mean shear force values were lower for fluidized bed dryer (19.91N) followed by forced air oven (21.97N), modified impingement oven (22.06N) and impingement oven (22.26N) respectively. However, the difference in the shear values are statistically not significant ( $P > 0.05$ ). These shear force values are lower than the shear strength values of explosion puffed (32.76N at 14% M.C) and high temperature fluidized bed (HTFB) (31.38N) dried rabbiteye blueberries as reported by Kim and Toledo (1987).

Venkatachalapathy and Raghavan (1998), observed similar behavior when blueberries osmotically dehydrated followed by microwave or freeze drying. They reported that there is no significant difference in toughness was observed among different drying methods. However, they reported a significant effect of drying temperature on toughness, which was not observed in our study.

The interaction between cultivar and pick time showed statistically significant effect ( $P \leq 0.05$ ) on shear force (Table 4.5). First harvest (pick-1) of Powderblue has higher shear values (24.03N) than Brightwell (20.89N); whereas second harvest (pick-2) of Brightwell has higher shear values (21.08N) than Powderblue (20.01N). Pick-1 of Powderblue

showed higher shear values (24.03) compared to pick-2 (20.01N). However, the difference between shear values of pick-1 (20.89N) and pick-2 (21.08N) for Brightwell are not significant ( $P>0.05$ ).

Swift (2010) reported that the first harvest of Powderblue is significantly firmer (3.71N) than second harvest (2.52N). Also, the mean skin toughness for both harvests of Powderblue (1.54N, 1.27N for first and second harvests respectively) was significantly higher than other rabbiteye blueberry cultivars in general. Texture of fruits and vegetables is strongly associated with composition and structure of the cell walls (Zivanovix and Buescher, 2004), variety, pH, maturity, and sample dimensions. In our present study we found that there is a significant influence of cultivar and pick time on the composition of dried blueberries (Table 4.1). Similar results were reported by Swift (2010) in the initial dry weight percent (soluble solids), pH and total acidity among different cultivars and harvest times of rabbiteye blueberries. These results indicate that the cultivar and pick time has an important role on the texture of the dried blueberries.

## **Conclusions**

Based on the results of this study a significant difference in the drying time was observed among different drying methods. Drying is faster at 107°C than 85°C for all drying methods. Impingement drying is faster than forced air oven and slower than Jet-zone fluidized bed dryer. Modified impingement increased heat transfer coefficients at lower drying temperatures (85°C) when compared to impingement drying. However, the difference in the drying time is not significant at higher temperature (107°C). Blueberry cultivar and its interaction with drying temperature showed influence on the drying time. Powderblue blueberry dried faster than Brightwell blueberry. Drying method, drying

temperature, cultivar, pick time, grade and their specific interactions showed significant influence on the overall quality of dried blueberries. However, the overall quality of impingement dried blueberries was comparable with the control methods. Air impingement drying showed promise to dry rabbiteye blueberries as an alternative to other commercial drying methods with similar dried blueberry quality and slightly longer drying time. Further improvements of air-velocities of impingement oven to a level of 4-6 m/s might help to match up with the drying time of Jet-zone fluidized bed dryer.

## **Acknowledgements**

This research was supported by a grant from the USDA Specialty Crop Block Grant Program to the state of Georgia and by the State and Hatch funds allocated to the University of Georgia Agricultural Experiment Station, Griffin Campus.

The authors would also like to thank Mr. Glenn Farrel for all the technical help, Mr. John Ed Smith for providing with IQF rabbiteye blueberries and help conduct experiments on jet-zone fluidized bed dryer, Mr. Phil Tyre of The Alma-Bacon County Economic Development Authority for providing materials and financial support, and Mr. Jerry Davis for assisting with statistical analysis of data.

## References

2000. AACC method 44-40. Approved Methods of the American Association of Cereal Chemists. 10<sup>th</sup> ed. St.Paul, MN: AACC International.
2009. SAS/STAT 9.1® User's Guide. Cary, NC: SAS Institute, Inc.
- Argyropoulos D, Heindl A and Muller J. 2011. Assessment of convection, hot-air combined with microwave-vacuum and freeze-drying methods for mushrooms with regard to product quality. *International Journal of Food Science and Technology* 46(2): 333-342.
- Basiouny FM. 1996. Blueberry fruit quality and storability influenced by post-harvest application of polyamines and heat treatments. *Proc.Fla.State Hort.Soc* 109: 269-272.
- Bremer V, Crisosto G, Molinar RH, Jimenez MJ, Dollahite S and Crisosto CH. 2008. San Joaquin Valley blueberries evaluated for quality attributes. *California Agriculture* 62(3): 91-96.
- Brown MS. 1967. Texture of frozen vegetables - effect of freezing rate on green beans. *Journal of the Science of Food and Agriculture* 18(2):77.
- Dekazos ED. 1978. Why blueberries turn tough. *Agricultural Research* 27(5): 17-17.
- Du CJ, Sun DW. 2004. Recent developments in the applications of image processing techniques for food quality evaluation. *Trends in Food Science & Technology* 15(5): 230-249.
- Feng H, Tang J. 1998. Microwave finish drying of diced apples in a spouted bed. *Journal of Food Science* 63(4): 679-683.
- Feng H, Tang J, Mattinson DS and Fellman JK. 1999. Microwave and spouted bed drying of frozen blueberries: The effect of drying and pretreatment methods on physical properties and retention of flavor volatiles. *Journal of Food Processing and Preservation* 23(6): 463-479.
- Friar H, Mark CM. 1943. Dehydration of blueberries. *Fruit Prod. J.* 22: 138.
- Herman-Lara E, Martinez-Sanchez CE, Amador-Mendoza and Ruiz-Lopez II. 2010. Effect of airflow reversal on packed-bed drying of carrots. *Journal of Food Process Engineering* 33(4): 684-700.
- Ihns R, Diamante LM, Geoffrey P and Savage GP. 2011. Effect of temperature on the drying characteristics, colour, antioxidant and beta-carotene contents of two apricot varieties. *International Journal of Food Science and Technology* 46(2): 275-283.

- Karathanos V, Anglea S and Karel M. 1993. Collapse of structure during drying of celery. *Drying Technology* 11(5):1005-1023.
- Kim MH, Toledo RT. 1987. Effect of osmotic dehydration and high-temperature fluidized-bed drying on properties of dehydrated rabbiteye blueberries. *Journal of Food Science* 52(4): 980-984.
- Krewer and NeSmith. 2006. Blueberry cultivars for Georgia (Accessed on December, 2010) from World Wide Web  
[http://www.smallfruits.org/Blueberries/production/06bbcproc\\_Nov0206.pdf](http://www.smallfruits.org/Blueberries/production/06bbcproc_Nov0206.pdf)
- Lohachoompol V, Mulholland M, Srzednicki G and Craske J. 2008. Determination of anthocyanins in various cultivars of highbush and rabbiteye blueberries. *Food Chemistry* 111(1): 249-254.
- Luh BS, Woodroof JG 1988. *Commercial Vegetable Processing\_Second\_Edition*. New York: Van Nostrand Reinhold, pp 387-473.
- MacGregor W. 2005. Effects of air velocity, air temperature, and berry diameter on wild blueberry drying. *Drying Technology* 23(1-2): 387-396.
- Mahmutoglu T, Pala M and Unal M. 1995. Mathematical modelling of moisture, volume and temperature changes during drying of pretreated apricots. *Journal of Food Processing and Preservation* 19(6): 467-490.
- Miller WR, McDonald RE 1996. Quality of 'Brightwell' and 'Tifblue' blueberries after gamma irradiation for quarantine treatment *Hortscience* 31(7): 1234-1234.
- Moreira RG. 2001. Impingement drying of foods using hot air and superheated steam. *Journal of Food Engineering* 49(4): 291-295.
- Mowry JK, Heldman DR. 1974. Analysis of moisture removal from surface of blueberry fruit using air-flow. *Transactions of the ASAE* 17(2): 360-363.
- NASS, 2009. Agricultural Statistics Board, United States Department of Agriculture, Noncitrus Fruits and Nuts 2009 Summary. Retrieved on November 25, 2010 from the World Wide Web  
[http://usda.mannlib.cornell.edu/usda/nass/NoncFruiNu//2010s/2010/NoncFruiNu-07-07-2010\\_new\\_format.pdf](http://usda.mannlib.cornell.edu/usda/nass/NoncFruiNu//2010s/2010/NoncFruiNu-07-07-2010_new_format.pdf).
- Nebesky EA, Esselen WB, Mcconnel JEW and Feller CR. 1949. Stability of color in fruit juices. *Food Research* 14(3): 261-274.
- Nijhuis HH, Toringa E. 1996. Research needs and opportunities in the dry conservation of fruits and vegetables. *Drying Technology* 14(6): 1429-1457.

- Nowak D, Lewicki PP. 2005. Quality of infrared dried apple slices. *Drying Technology* 23(4): 831-846.
- Perkins-Veazie P. 2004. Blueberry: The commercial storage of fruits, vegetables and florist and nursery stocks. USDA Agr. Handbook. Nr 66. Available from [www.ba.ars.usda.gov/hb66/039blueberry.pdf](http://www.ba.ars.usda.gov/hb66/039blueberry.pdf). (Accessed December 2010).
- Prange RK, Asiedu SK, DeEll JR and Westgarth AR. 1995. Quality of fundy and blomidon lowbush blueberries - effects of storage atmosphere, duration and fungal inoculation. *Canadian Journal of Plant Science* 75(2): 479-483.
- Ramaswamy HS, Nsonzi F 1998. Convective-air drying kinetics of osmotically pre-treated blueberries. *Drying Technology* 16(3-5): 743-759.
- Rahman AR. 1972. Increased density for military foods. Tech. Rpt. No. Ad-750-368. U.S. Army Natick Labs, Natick, MA.
- Rejman A, Pliszka K. 1991. Highbush blueberry, PWRIL Warszawa. 112.
- Rickard A, Wuerthner J, Barret G. 1993. Corn Snacks: Full speed ahead, *Snack World* (3): 278-300.
- Rohrbach RP. 1977. Air-jet drying and dewatering of blueberries. *Transactions of the ASAE* 20(5): 992-995.
- Sarkar A, Singh RP. 2003. Spatial variation of convective heat transfer coefficient in air impingement applications. *Journal of Food Science* 68(3): 910-916.
- Shi J, Pan Z, McHugh TH, Wood D, Hirschberg E and Olson D. 2008. Drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation heating. *Lwt-Food Science and Technology* 41(10): 1962-1972.
- Shi J, Pan Z, McHugh TH, Wood D, Hirschberg E and Olson D. 2008. Effect of berry size and sodium hydroxide pretreatment on the drying characteristics of blueberries under infrared radiation heating. *Journal of Food Science* 73(6): E259-E265.
- Silva JL, Marroquin E. 2005. Physicochemical, carbohydrate and sensory characteristics of highbush and rabbiteye blueberry cultivars. *Journal of the Science of Food and Agriculture* 85(11): 1815-1821.
- Stafford AE, Guadagni DG 1977. Storage stability of raisins dried by different procedures. *Journal of Food Science* 42(2): 547-548.
- Sullivan JF, Craig JC. et al. 1982. Dehydrated blueberries by the continuous explosion-puffing process. *Journal of Food Science* 47(2): 445-448.

Swift JE. 2010. Effects of Frozen Storage and Harvest Time on the Textural and Sensory Properties of Rabbiteye Blueberries (*Vaccinium virgatum* Aiton). [Masters]. Raleigh, NC: North Carolina State University.

Toribio JL, Lozano JE. 1986. Heat-induced browning of clarified apple juice at high-temperatures. *Journal of Food Science* 51(1): 172.

USHBC, 2010. United States Highbush Blueberry Council, Folsom, California, U.S.A. Blueberry information. Retrieved December, 2010 from the World Wide Web <http://www.blueberry.org>

VanArsdel WB. 1973. Drying phenomena. In "Food Dehydration", V. 1(Ed.) W.B. Van Arsdel, M.Copley, and A.Morgan, P.22 AVI Pub.Co., Westport, CT.

Van Teeling CG, Cansfield PE. et al. 1971. Anthocyanin complex isolated from syrup of canned blueberries. *Journal of Food Science* 36(7):1061.

Venkatachalapathy K, Raghavan GSV 1998. Microwave drying of osmotically dehydrated blueberries. *Journal of Microwave Power and Electromagnetic Energy* 33(2): 95-102.

Wang N, Brennan JG. 1995. Changes in structure, density and porosity of potato during dehydration. *Journal of Food Engineering* 24(1): 61-76.

Yang CST, Atallah WA 1985. Effect of four drying methods on the quality of intermediate moisture lowbush blueberries. *Journal of Food Science* 50(5): 1233-1237.

Yemmireddy, Hung. 2011. Drying characteristics of individually quick frozen (IQF) rabbiteye blueberries. (not yet published)

Zivanovic S, Buescher R. 2004. Changes in mushroom texture and cell wall composition affected by thermal processing. *Journal of Food Science* 69(1): S44-S49.

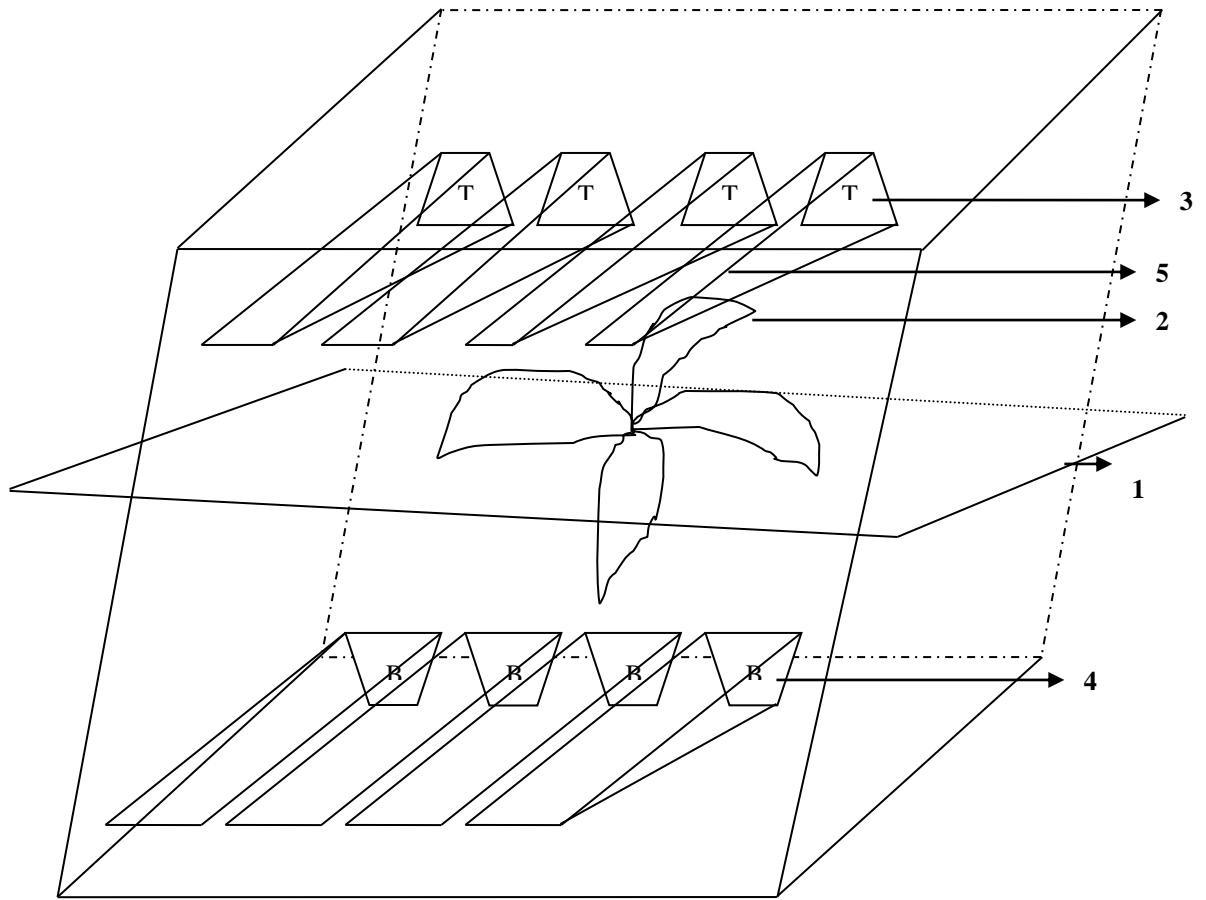


Fig. 4.1: Schematic diagram of hot-air impingent oven 1. Conveyor belt in drying chamber to move product trays. 2. Plenum chamber with centrifugal fan. 3. Top air vents (T1-T4) to blow hot air from plenum chamber downward. 4. Bottom air vents (B1-B4). 5. Air distribution chutes in the drying chamber



**Forced air oven**



**Fluidized bed drier**



**Impingement oven**



**Modified impingement oven**

Fig 4.2: Color comparison of dried blueberries (Brightwell, Grade-A, Pick-1) from forced air oven, fluidized bed drier, impingement oven and modified impingement oven

Table 4.1: Effect of various factors and their interaction on composition of dried blueberries

Variable 1		Variable 2	Fat (%)	Protein (%)	Ash (%)	Carbohydrate (%)
Cultivar	Brightwell	Pick-1	0.67 <sup>a</sup>	2.55 <sup>a</sup>	1.28 <sup>a</sup>	95.49 <sup>a</sup>
		Pick-2	0.47 <sup>a</sup>	2.58 <sup>a</sup>	1.30 <sup>a</sup>	95.65 <sup>a</sup>
	Powderblue	Pick-1	0.84 <sup>a</sup>	2.99 <sup>a</sup>	1.31 <sup>a</sup>	94.86 <sup>b</sup>
		Pick-2	0.48 <sup>a</sup>	2.73 <sup>a</sup>	1.31 <sup>a</sup>	95.49 <sup>a</sup>
Cultivar	Brightwell	Grade-A	0.56 <sup>a</sup>	2.22 <sup>b</sup>	1.31 <sup>a</sup>	95.92 <sup>a</sup>
		Grade-C	0.59 <sup>a</sup>	2.92 <sup>a</sup>	1.27 <sup>a</sup>	95.23 <sup>a</sup>
	Powderblue	Grade-A	0.65 <sup>a</sup>	2.78 <sup>ab</sup>	1.31 <sup>a</sup>	95.27 <sup>a</sup>
		Grade-C	0.67 <sup>a</sup>	2.95 <sup>a</sup>	1.31 <sup>a</sup>	95.08 <sup>a</sup>
Pick	1		0.75 <sup>a</sup>	2.77 <sup>a</sup>	1.30 <sup>a</sup>	95.18 <sup>a</sup>
	2		0.47 <sup>b</sup>	2.66 <sup>a</sup>	1.30 <sup>a</sup>	95.57 <sup>a</sup>
Temperature	85		0.70 <sup>a</sup>	2.67 <sup>a</sup>	1.26 <sup>a</sup>	95.38 <sup>a</sup>
	107		0.53 <sup>b</sup>	2.76 <sup>a</sup>	1.34 <sup>a</sup>	95.37 <sup>a</sup>

\*All composition data are expressed in dry basis

\*Mean values with the same superscript in the same column within the same variable combination are not significantly different ( $p > 0.05$ ).

Table 4.2: Effect of various factors on drying time to achieve a final water activity of  $0.55 \pm 0.05$

Variable	Level	Drying time (hr)		Mean drying time (hr)
		Temperature ( $^{\circ}\text{C}$ )		
		85	107	
Cultivar	Brightwell	5.20 <sup>a</sup>	3.25 <sup>a</sup>	4.08 <sup>a</sup>
	Powderblue	4.87 <sup>b</sup>	2.98 <sup>b</sup>	3.95 <sup>b</sup>
Drying method	Forced air oven	8.43 <sup>a</sup>	4.87 <sup>a</sup>	6.03 <sup>a</sup>
	Fluidized bed dryer	2.80 <sup>d</sup>	1.47 <sup>c</sup>	2.47 <sup>d</sup>
	Impingement oven	5.37 <sup>b</sup>	2.37 <sup>b</sup>	4.42 <sup>b</sup>
	Modified impingement oven	4.58 <sup>c</sup>	2.15 <sup>b</sup>	3.58 <sup>c</sup>
Drying temperature		5.37	3.1	

\*Mean values with the same superscript in the same column within the same variable are not significantly different ( $P > 0.05$ ).

Table 4.3: Effect of various factors on bulk density of the dried blueberries

Variable	Level	Bulk density (g/ml)		Average
		Brightwell	Powderblue	
Pick	1	0.783 <sup>A</sup>	0.782 <sup>A</sup>	0.782 <sup>b</sup>
	2	0.854 <sup>A</sup>	0.877 <sup>A</sup>	0.866 <sup>a</sup>
Grade	A	0.862 <sup>A</sup>	0.888 <sup>A</sup>	0.876 <sup>a</sup>
	C	0.775 <sup>A</sup>	0.771 <sup>A</sup>	0.773 <sup>b</sup>
Drying temperature (°C)	85	0.836 <sup>A</sup>	0.854 <sup>A</sup>	0.845 <sup>a</sup>
	107	0.796 <sup>A</sup>	0.803 <sup>A</sup>	0.800 <sup>b</sup>
Drying method	Forced air oven	0.840 <sup>A</sup>	0.838 <sup>A</sup>	0.839 <sup>ab</sup>
	Fluidized bed dryer	0.835 <sup>A</sup>	0.795 <sup>B</sup>	0.815 <sup>b</sup>
	Impingement	0.871 <sup>A</sup>	0.877 <sup>A</sup>	0.874 <sup>a</sup>
	Modified impingement	0.695 <sup>B</sup>	0.815 <sup>A</sup>	0.767 <sup>c</sup>

\*Mean values with same low case superscript in the same column within the same variable are not significantly different (P>0.05).

\*Mean values with same capital case superscript in the same row are not significantly different (P>0.05).

Table 4.4: Color values of dried blueberries as affected by drying method, cultivar, pick time, grade and drying temperature

<b>Variable</b>	<b>L</b>	<b>Chroma</b>	<b>Hue angle</b>
<b>Drying method</b>			
Forced air oven	16.29 <sup>a</sup>	4.59 <sup>a</sup>	339.78 <sup>a</sup>
Fluidized bed dryer	15.40 <sup>b</sup>	2.10 <sup>c</sup>	300.96 <sup>c</sup>
Impingement oven	13.42 <sup>c</sup>	2.49 <sup>b</sup>	321.52 <sup>b</sup>
Modified impingement oven	16.24 <sup>a</sup>	4.43 <sup>a</sup>	335.85 <sup>a</sup>
Brightwell	14.81 <sup>b</sup>	2.74 <sup>b</sup>	320.78 <sup>b</sup>
Powderblue	15.94 <sup>a</sup>	3.88 <sup>a</sup>	327.89 <sup>a</sup>
1	15.21 <sup>b</sup>	3.22 <sup>b</sup>	323.57 <sup>a</sup>
2	15.59 <sup>a</sup>	3.42 <sup>a</sup>	325.40 <sup>a</sup>
A	15.38 <sup>a</sup>	3.06 <sup>b</sup>	321.53 <sup>b</sup>
C	15.41 <sup>a</sup>	3.57 <sup>a</sup>	327.30 <sup>a</sup>
85°C	15.69 <sup>a</sup>	3.50 <sup>a</sup>	325.53 <sup>a</sup>
107°C	15.07 <sup>b</sup>	3.12 <sup>b</sup>	323.28 <sup>b</sup>
Standard (Thawed blueberry)	16.04	4.10	

\* Mean color values with same superscript in the column within the same variable are not significantly different (P>0.05).

Table 4.5: Effect of cultivar and pick time on shear force values of dried blueberries

<b>Cultivar</b>	<b>Shear force (N)</b>	
	<b>Pick-1</b>	<b>Pick-2</b>
Brightwell	20.89 <sup>aA</sup>	21.08 <sup>aA</sup>
Powderblue	24.03 <sup>bA</sup>	20.01 <sup>bB</sup>

\*Mean values with same low case superscript in the same column are not significantly different ( $P>0.05$ ).

\*Mean values with same capital case superscript in the same row are not significantly different ( $P>0.05$ ).

**CHAPTER-5**  
**SUMMARY AND CONCLUSION**

Pretreatment step is an important factor to speed up the drying process. Partial thawing (20 min) followed by surface scarification using a mechanical scarater increased the drying rate. Drying is faster at 107°C compared to 85°C to achieve a shelf-stable final water activity of < 0.60. Effect of blueberry cultivar and grade was not significant on drying curve with a forced-air oven method. The desorption behavior of IQF rabbiteye blueberries was successfully described using an empirical equation as  $Y=Ae^{BX}$  (A=1.1078 and B= 4.7144) where Y is the dry basis moisture content and X is the water activity. The effect of blueberry cultivar, grade and drying temperature (85°C vs 107°C) does not have significant effect on the desorption isotherm. Several well-known predictive isotherm equations were tested and only modified Halsey model closely fitted the experimental data to predict the desorption behavior of rabbiteye blueberries.

Impingement oven method of drying proven to be a viable option to produce dried blueberries following a mechanical pretreatment. Impingement drying reduced the drying time when compared to forced air oven and is more efficient even at lower air velocities when compared to jet-zone fluidized bed dryer. Modified impingement oven with an air flow only from the top significantly reduced the drying time at 85°C when compared to impingement oven. However, the overall drying time is lowest for jet-zone fluidized bed dryer followed by modified impingement oven, impingement oven and forced air oven at both temperatures (85 or 107°C). Drying times were approximately 50% lower at 107°C than at 85°C for all drying methods. The main difference in drying time among these methods is attributed to the difference in the configuration and air velocities of individual drier. Blueberry cultivar and drying method with an interaction with drying temperature showed significant effect on drying time. The mean drying times of Brightwell blueberry

(4.08 hr) was higher than Powderblue blueberry (3.95 hr). The main reason for the difference is attributed to the difference in basic cellular structure, size of blueberries on the whole and difference in the total soluble solids content. However, the difference due to cultivar is noticeable only when the batch size is bigger ( $\geq 1$  kg).

Assuming method of drying will not show any effect on composition; the dried blueberries from jet-zone fluidized bed dryer were used for proximate analysis. Cultivar, pick time, grade, drying temperature and several interactions among these variables showed significant effect on the composition of dried blueberries. However, the fat, protein and ash contents are all very low in blueberries; it has no practical meaning for the difference due to variation among cultivars, pick times and grades. Similarly, different tested variables and their specific interactions showed significant effect on bulk density, color and texture of the dried blueberries. Mainly, the variation in physical properties correlated with differences among the drying methods and biological characteristics of the blueberries. Overall, modified impingement oven drying resulted in lowest bulk density (0.767 g/ml) dried blueberries. Only, the interaction between cultivar and pick time showed significant effect on the texture of the dried blueberries.

Powderblue and pick-1 combination had the highest shear force value (24.03N) and Powderblue and pick-2 combination has lower shear force value (20.01N). The color values (Lightness, Chroma and Hue) are comparable with the other drying methods.

This research findings suggest impingement oven can be an alternative drying method to produce high quality dried products from rabbiteye blueberries. Future work should focus on the further improvements to the modified impingement oven to match up with

the jet-zone fluidized bed drier drying times as well as analyzing nutritional, microbiological quality and consumer acceptability of the dried blueberries.

## **APPENDICES**

**APPENDIX A:** Comparison of drying time(s) among different drying methods affected by different variables to achieve a water activity of  $0.55 \pm 0.05$

Cultivar	Grade	Temp (°C)	Pick time	Drying time (hrs.)			
				Forced air oven	Fluidized bed dryer	Impingement oven	Modified impingement oven
Brightwell	A	85	1	7.80	2.75	5.50	4.50
			2	8.20	2.75	4.75	5.00
	C	85	1	8.25	2.92	5.50	4.50
			2	8.30	2.75	4.75	4.75
	A	107	1	4.58	1.58	2.50	2.33
			2	4.75	1.50	2.33	2.00
	C	107	1	4.33	1.50	2.50	2.33
			2	5.17	1.33	2.33	2.50
Powderblue	A	85	1	8.00	2.92	4.50	4.50
			2	7.83	2.75	5.00	4.25
	C	85	1	7.25	2.75	4.50	4.50
			2	7.83	2.58	5.25	4.50
	A	107	1	5.00	1.50	2.33	2.17
			2	4.50	1.50	2.33	2.17
	C	107	1	5.00	1.50	2.17	2.00
			2	4.50	1.50	2.50	2.00

**APPENDIX B:** Comparison of bulk density of dried blueberries among different drying methods affected by different variables

Cultivar	Grade	Temp (°C)	Pick time	Bulk density (g/cc)				
				Forced air oven	Fluidized bed dryer	Impingement oven	Modified impingement oven	
Brightwell	A	85	1	0.956	0.765	0.934	0.720	
			2	0.889	0.884	0.969	0.799	
	C	85	1	0.806	0.736	0.828	0.617	
			2	0.862	0.846	0.987	0.696	
	A	107	1	0.835	0.943	0.667	0.687	
			2	0.881	0.840	0.842	0.710	
	C	107	1	0.670	0.800	0.747	0.639	
			2	0.827	0.831	0.765	0.704	
	Powderblue	A	85	1	0.861	0.750	0.887	0.908
				2	0.912	0.991	1.016	0.905
C		85	1	0.810	0.588	0.770	0.740	
			2	0.838	0.924	0.928	0.854	
A		107	1	0.806	0.832	0.871	0.802	
			2	0.853	0.856	0.946	0.945	
C		107	1	0.785	0.776	0.727	0.682	
			2	0.855	0.705	0.827	0.674	

**APPENDIX C:** Comparison of color values of dried blueberries among different drying methods as affected by different variables

Cultivar	Grade	Tem P (°C)	Pick	Color Readings on Hunter Lab Colorimeter															
				Forced air oven (Control-1)				Fluidized bed dryer (Control-2)				Impingement oven (Method-1)				Modified Impingement oven (Method-2)			
				L*	a*	b*	ΔE	L*	a*	b*	ΔE	L*	a*	b*	ΔE	L*	a*	b*	ΔE
BW	A	85	1	17.06	3.69	-1.45	4.49	15.31	1.24	-1.84	2.90	12.38	0.42	-1.22	2.34	15.46	2.31	-1.38	2.80
			2	15.43	4.23	-1.37	3.48	16.28	1.23	-1.95	4.50	14.35	1.43	-1.24	2.89	15.74	3.04	-1.50	3.56
	C	85	1	16.28	4.46	-1.57	2.19	15.62	1.42	-2.09	2.46	12.45	2	-1.51	5.23	15.36	2.71	-1.72	2.28
			2	15.80	4.42	-1.32	1.79	16.08	1.11	-1.74	1.93	13.30	0.60	-1.01	3.88	15.63	3.31	-1.48	1.11
	A	107	1	15.95	3.53	-1.50	3.40	13.99	0.96	-2.15	2.00	11.74	1.1	-1.27	1.98	14.26	1.41	-1.60	1.92
			2	14.74	3.22	-1.31	2.55	14.95	1.23	-1.98	3.34	13.03	1.40	-1.39	1.78	14.59	2.01	-1.28	2.58
	C	107	1	16.26	3.71	-1.53	1.78	14.37	0.99	-2.04	3.74	12.63	0.87	-1.11	5.58	14.74	1.77	-1.40	3.01
			2	14.66	2.91	-1.21	1.77	14.18	1.33	-1.90	2.86	12.86	1.67	-1.22	3.75	15.15	1.82	-1.39	1.67
PB	A	85	1	17.29	5.68	-1.73	4.31	15.77	1.00	-1.65	2.06	14.52	2.39	-1.55	0.22	16.87	5.41	-1.92	3.84
			2	17.57	5.71	-1.58	4.52	17.40	1.24	-1.85	3.27	14.28	2.78	-1.41	0.37	17.49	5.68	-1.81	4.44
	C	85	1	17.37	6.03	-1.75	2.94	16.14	1.56	-1.72	3.62	14.00	3.20	-1.39	4.99	17.08	5.80	-1.69	2.89
			2	17.55	6.41	-1.76	3.14	17.55	0.83	-1.67	3.30	13.53	2.83	-1.99	5.58	17.70	5.97	-1.79	2.72
	A	107	1	15.40	2.56	-1.71	2.48	14.17	0.69	-1.55	1.84	13.37	2.07	-1.51	1.33	16.28	3.93	-1.74	2.37
			2	16.48	4.65	-1.51	3.01	15.70	0.86	-1.74	2.11	13.34	1.12	-1.10	1.82	16.70	4.68	-1.67	3.17
	C	107	1	16.39	4.68	-1.40	2.76	14.51	1.17	-1.45	5.12	13.57	3.36	-1.65	5.42	16.70	5.09	-1.19	2.63
			2	17.70	5.84	-1.58	2.77	15.31	0.73	-1.63	4.75	13.77	1.75	-0.94	5.53	16.87	5.44	-1.63	2.80

**APPENDIX D:** Comparison of shear force values among different drying methods as affected by different variables

Cultivar	Grade	Temp (°C)	Pick time	Shear force (N)			
				Forced air oven (Control-1)	Fluidized bed dryer (Control-2)	Impingement oven (Method-1)	Modified impingement oven (Method-2)
Brightwell	A	85	1	23.73	22.26	22.56	21.77
			2	25.60	20.99	19.02	20.40
	C	85	1	22.95	22.75	20.89	18.53
			2	20.30	17.85	17.75	19.22
	A	107	1	20.59	19.71	24.91	21.87
			2	18.73	16.38	26.87	21.87
	C	107	1	21.57	18.83	20.59	23.54
			2	21.18	20.59	27.07	22.26
Powderblue	A	85	1	28.24	26.87	20.79	22.65
			2	25.01	20.69	20.40	21.18
	C	85	1	31.97	30.50	24.82	29.32
			2	22.46	17.95	21.18	22.36
	A	107	1	29.52	22.56	21.48	22.16
			2	17.75	17.26	19.02	20.40
	C	107	1	33.15	26.18	25.89	25.20
			2	20.20	18.34	19.71	19.32

**APPENDIX E:** Composition analysis data of dried blueberries

Variety	Grade	Pick	Temp(°C)	% M.C	% Crude Fat (wb)	% Protein (wb)	% Ash (wb)
Brightwell	A	1	85	19.93	0.62	1.52	0.96
Brightwell	A	2	85	17.62	0.46	2.02	1.11
Brightwell	C	1	85	17.79	0.68	2.82	1.07
Brightwell	C	2	85	17.64	0.43	2.08	0.92
Brightwell	A	1	107	18.39	0.31	1.47	1.03
Brightwell	A	2	107	21.37	0.40	2.15	1.12
Brightwell	C	1	107	18.54	0.58	2.51	1.12
Brightwell	C	2	107	16.87	0.23	2.18	1.08
Powderblue	A	1	85	16.98	0.62	2.43	1.08
Powderblue	A	2	85	17.12	0.58	2.14	1.04
Powderblue	C	1	85	14.60	0.83	2.29	1.09
Powderblue	C	2	85	18.67	0.38	2.29	1.05
Powderblue	A	1	107	15.23	0.67	2.55	1.11
Powderblue	A	2	107	19.66	0.28	2.07	1.11
Powderblue	C	1	107	15.32	0.70	2.84	1.15
Powderblue	C	2	107	17.36	0.32	2.42	1.09

**APPENDIX F: Water activity data of dried blueberry**

<b>Sl.No</b>	<b>Sample ID</b>	<b>Drying Method</b>	<b>Temp(°C)</b>	<b>Water activity</b>	<b>Time(hr)</b>	<b>Dried Sample Wt(gm)</b>
B-Bright well/P-Powder blue, GA-Grade A/ GC-Grade C, Rep -1/ Rep-2 (Temp, pick)						
1	BGA1(185,1)	Forced air oven	85	0.599	8.15	179
2	BGA2(185,1)			0.506	7.45	164
3	BGC1(185,1)			0.537	8.15	172
4	BGC2(185,1)			0.559	8.15	173
5	PGA1(185,1)			*0.485	8	168
6	PGA2(185,1)			0.557	8.10	188
7	PGC1(185,1)			*0.449	7.15	188
8	PGC2(185,1)			0.562	7.15	198
9	BGA1(225,1)		107	0.573	4.30	147
10	BGA2(225,1)			0.582	4.40	167
11	BGC1(225,1)			0.495	4.30	137
12	BGC2(225,1)			0.584	4.15	148
13	PGA1(225,1)			0.510	5	149
14	PGA2(225,1)			0.598	5	
15	PGC1(225,1)			0.582	4.55	176
16	PGC2(225,1)			0.511	5	179
17	BGA1(185,2)		85	0.500	8.25	158
18	BGA2(185,2)			0.553	8	163
19	BGC1(185,2)			0.502	8.20	153
20	BGC2(185,2)			0.516	8.20	169
21	PGA1(185,2)			*0.465	7.30	164
22	PGA2(185,2)			0.509	7.55	170
23	PGC1(185,2)			0.539	7.45	166
24	PGC2(185,2)			0.550	7.55	150
25	BGA1(225,2)		107	0.518	4.45	167
26	BGA2(225,2)			0.509	4.45	170
27	BGC1(225,2)			0.505	5.10	166
28	BGC2(225,2)			0.560	4.30	148
29	PGA1(225,2)			0.524	4.30	166
30	PGA2(225,2)			0.518	4.35	171
31	PGC1(225,2)			0.565	4.30	168
32	PGC2(225,2)			0.539	4.30	162
33	BGA1(185,1)	Impingement oven	85	0.518	5.30	178
34	BGA2(185,1)			0.510	5.30	171
35	BGC1(185,1)			0.582	5.25	189
36	BGC2(185,1)			0.587	5.40	189
37	PGA1(185,1)			0.590	4.35	183
38	PGA2(185,1)			0.527	4.30	184
39	PGC1(185,1)			0.520	4.30	186
40	PGC2(185,1)			0.601	4.35	199

41	BGA1(225,1)		107	*0.469	2.30	175
42	BGA2(225,1)			*0.490	2.35	179
43	BGC1(225,1)			0.499	2.40	174
44	BGC2(225,1)			*0.480	2.30	169
45	PGA1(225,1)			0.585	2.15	189
46	PGA2(225,1)			0.541	2.30	
47	PGC1(225,1)			0.528	2.10	192
48	PGC2(225,1)			0.554	2.15	195
49	BGA1(185,2)		85	0.586	4.50	183
50	BGA2(185,2)			0.520	4.45	195
51	BGC1(185,2)			*0.470	4.50	169
52	BGC2(185,2)			0.532	4.45	176
53	PGA1(185,2)			0.575	5	192
54	PGA2(185,2)			0.593	5	175
55	PGC1(185,2)			0.583	5.15	184
56	PGC2(185,2)			0.578	5.20	175
57	BGA1(225,2)		107	0.524	2.20	184
58	BGA2(225,2)			0.498	2.25	177
59	BGC1(225,2)			0.540	2.20	162
60	BGC2(225,2)			0.554	2.25	164
61	PGA1(225,2)			*0.492	2.25	179
62	PGA2(225,2)			*0.476	2.30	175
63	PGC1(225,2)			*0.472	2.30	169
64	PGC2(225,2)			*0.458	2.30	171
65	BGA1(185,1)	Modified	85	0.552	4.30	179
		Impingement oven				
66	BGA2(185,1)			0.585	4.30	178
67	BGC1(185,1)			0.532	4.40	168
68	BGC2(185,1)			0.587	4.30	178
69	PGA1(185,1)			0.530	4.45	180
70	PGA2(185,1)			0.553	4.15	182
71	PGC1(185,1)			0.508	4.45	192
72	PGC2(185,1)			0.598	4.15	206
73	BGA1(225,1)		107	0.551	2.30	185
74	BGA2(225,1)			*0.480	2.15	161
75	BGC1(225,1)			0.574	2.10	185
76	BGC2(225,1)			0.572	2.25	199
77	PGA1(225,1)			0.521	2.05	173
78	PGA2(225,1)			*0.486	2.15	173
79	PGC1(225,1)			0.584	2	190
80	PGC2(225,1)			0.582	2	201
81	BGA1(185,2)		85	0.496	5	161
82	BGA2(185,2)			*0.480	5	172
83	BGC1(185,2)			0.499	4.45	151
84	BGC2(185,2)			*0.475	4.45	151
85	PGA1(185,2)			0.520	4.25	178
86	PGA2(185,2)			0.555	4.05	183

87	PGC1(185,2)			0.532	4.40	174
88	PGC2(185,2)			0.547	4.25	163
89	BGA1(225,2)		107	*0.468	2.15	167
90	BGA2(225,2)			0.520	2.05	173
91	BGC1(225,2)			*0.457	2.35	146
92	BGC2(225,2)			*0.472	2.25	165
93	PGA1(225,2)			0.507	2.05	168
94	PGA2(225,2)			0.493	2.05	167
95	PGC1(225,2)			0.522	2.05	164
96	PGC2(225,2)			0.530	2.05	165
97	BGA1(185,1)	Fluidized bed dryer	85	0.585	2.55	175
98	BGA2(185,1)			*0.620	2.55	192
99	BGC1(185,1)			0.590	2.55	189
100	BGC2(185,1)			0.548	2.55	177
101	PGA1(185,1)			0.540	2.55	163
102	PGA2(185,1)			0.504	2.50	173
103	PGC1(185,1)			0.535	2.45	192
104	PGC2(185,1)			0.510	2.45	179
105	BGA1(225,1)		107	0.545	1.40	175
106	BGA2(225,1)			0.558	1.30	179
107	BGC1(225,1)			*0.635	1.30	182
108	BGC2(225,1)			0.570	1.30	157
109	PGA1(225,1)			0.541	1.30	174
110	PGA2(225,1)			0.532	1.30	175
111	PGC1(225,1)			0.509	1.30	192
112	PGC2(225,1)			0.527	1.20	188
113	BGA1(185,2)		85	0.541	2.50	171
114	BGA2(185,2)			0.548	2.45	168
115	BGC1(185,2)			0.561	2.45	167
116	BGC2(185,2)			0.573	2.45	168
117	PGA1(185,2)			0.550	2.50	157
118	PGA2(185,2)			0.528	2.45	174
119	PGC1(185,2)			*0.474	2.35	174
120	PGC2(185,2)			0.532	2.35	155
121	BGA1(225,2)		107	*0.658	1.30	168
122	BGA2(225,2)			0.577	1.30	169
123	BGC1(225,2)			0.560	1.20	148
124	BGC2(225,2)			0.516	1.30	152
125	PGA1(225,2)			0.547	1.25	160
126	PGA2(225,2)			0.587	1.25	167
127	PGC1(225,2)			0.575	1.25	162
128	PGC2(225,2)			0.516	1.30	153

Note: Values marked with asterisk (\*) were fall out of the range of  $0.55 \pm 0.05$  and hence excluded from statistical analysis.