Drying Characteristics of Saskatoon Berries under Microwave and Combined Microwave-Convection Heating

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Thesis Submitted By

Lakshminarayana Reddy

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DEDICATION

Dedicated to my Amma (mother)

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ABSTRACT

The study on dehydration of frozen saskatoon berries and the need for dried fruits have been strategically identified in the Canadian Prairies. The motivation for this research was to find a suitable method for dehydration and extend saskatoon berry shelf life for long term preservation. Microwave, convection and microwave-convection combination drying processes were identified to finish-dry saskatoon berries after osmotic dehydration, using sucrose and high fructose corn syrup (HFCS) sugar solutions. Osmotic dehydration removes moisture in small quantities introducing solutes into the fruit that acts as a preservative and also reduces the total drying time.

Due to the very short harvesting season of saskatoon berries, an accelerated process such as the microwave combination drying can reduce the moisture to safe storage levels immediately after harvest. Untreated and osmotically dehydrated berries were subjected to convection (control), microwave and microwave-convection combination drying conditions at different product drying temperatures (60, 70 and 80^{o}C) until final moisture content was 25% dry basis. A laboratory-scale microwave combination dryer was developed with integrated temperature and moisture loss data acquisition systems using LabView 6i software. A thin-layer cross flow dryer was used for convection-only drying and for comparison.

Drying kinetics of the process were studied and curve fitting with five empirical equations, including the Page equation, was carried out to determine drying constant, R^2 and standard error values. The microwave-combination drying method proved to be the best for drying saskatoon berries. Dehydrated product quality analyses were accomplished by measuring the color changes, rehydration ratio and any structural changes, using a scanning electron microscope technique.

This research was instrumental in the modification and development of a novel drying system for high-moisture agricultural materials (fruits). Microwave-convection combination drying at 70^{o}C, yielded good results with higher drying rates and better end-product quality.

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LIST OF SYMBOLS AND GLOSSARY

MC	Moisture Content (%)
RH	Relative Humidity (%)
m/s	Airflow Rate Unit
brix	Total Soluble Solids Unit
MR	Moisture Ratio
k	Drying Constant (h^{-1})
W	Unit of Power (Watts)
V	Unit of Voltage (Volts)
P1, P2 and P3	Microwave Power Levels (In-built)
MC/min	Drying Rate Unit
Saskatoons	saskatoon berries
OD	Osmotic Dehydration
COR	Coefficient of Rehydration
SEM	Scanning Electron Microscope
TSS	Total Soluble Solids
MW	Microwave
RF	Radio Frequency
DAQ	Data Acquisition
HP	Hewlett-Packard
I/O	Input / output
HFCS	High Fructose Corn Syrup
ε'	Dielectric Constant
ε”	Dielectric Loss Factor
L	Lightness Indicator
a and b	Chromacity Coordinates
ΔE_{ab}	Total Color Difference
TSS	Total Soluble Solids (brix)
MHz	Unit of Frequency (Mega Hertz)

δ	Loss angle of dielectric (dissipation factor)
FSA	Food Standard Agency
EU	European Union
SSR	Solid State Relay

GLOSSARY OF TERMS

Equilibrium MC (EMC)	Moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time.
Relative Humidity (RH)	Defined as ratio of vapor pressure of water in the air to the vapor pressure of water in saturated air at the same temperature and atmospheric pressure.
Osmotic - Dehydration (OD)	Two-way counter flow of fluids from food material into an osmotic solution through a semi-permeable membrane.
U-Pick	Harvesting operation for fruits where consumer picks fruits of desired quality and quantity on the farm.

I. INTRODUCTION

The technique of dehydration is probably the oldest method of food preservation practiced by humankind. The removal of moisture prevents the growth and reproduction of microorganisms causing decay and minimizes many of the moisture-mediated deteriorative reactions. It brings about substantial reduction in weight and volume, minimizing packaging, storage and transportation costs and improves storability of the product under ambient temperatures. These features are especially important for both developed and developing countries in military feeding and new product formulations.

Saskatoon berries (*Amelanchier alnifolia*), also known as saskatoons are grown primarily in the Prairie Provinces of Canada and the plains of the United States. Up to nine varieties of saskatoons are reported according to their habitat, flowering and ripening time, growth form and size, color, seediness and flavor for production (Turner, 1997). Certain varieties are more likely to be dried fresh like raisins for winter use, while others are cooked to the consistency of jam before being dried. The berries are an excellent source of vitamin C, manganese, magnesium, iron and a good source of calcium, potassium, copper and carotene. The berries are also higher in protein, fat and fibre content, than most other fruits (Turner et al., 1990).

The length of saskatoon berry harvest season ranges from 1 to 4 weeks. Many producers are not able to harvest and sell their entire crop during the short harvest season. Freezing on the farm has increased market flexibility for consumers, producers and processors by extending the length of time saskatoons are available. Frozen saskatoon berries are marketed for direct consumption and for processed product manufacture.

A sharp rise in energy costs has promoted a dramatic upsurge in interest in drying Worldwide over the last decade. Advances in techniques and development of novel drying /processing methods have made available a wide range of dehydrated products, especially instantly reconstitutable ingredients, from fruits and vegetables with properties that could not have been foreseen some years ago (Ratti and Mujumdar, 1995). Longer shelf-life, product diversity and substantial volume reduction are the reasons for popularity of dried berries, and this could be expanded further with improvements in product quality and process applications. These improvements could increase the current degree of acceptance of dehydrated berries (saskatoons, blueberries etc.) in the market. Microwave and microwave-combination drying could be a possible alternative to freezing of fresh berries. Freezing and storage of frozen berries are not only quite expensive operations but also energy-intensive processes involving cold storage logistics and economics, for the bulk of material.

1.1 Objectives

A very scant supply of data currently exists on processing (drying, processing, packaging etc.) of fresh saskatoons to extend their shelf life. Even though drying of horticultural crops (fruits, vegetables and spices) has been reported, there is not much literature reported on drying/dehydration of saskatoon berries. Therefore, the overall objective of this study was to develop an integrated drying system suitable for berries (saskatoons, raspberries etc.) and in particular, to study the drying behavior of saskatoons and to compare the drying characteristics under microwave, convection and microwave-convection drying methods with respect to drying, shrinkage and rehydration characteristics obtained by these drying schemes.

The specific objectives of this research were:

1. to modify a domestic microwave oven and eventually develop the microwave-convection combination drying system for real-time weight-loss and temperature monitoring along with data acquisition,
2. to evaluate osmotic dehydration as a pre-treatment for drying and study its effect on dielectric properties, drying rate, and final berry quality and
3. to conduct drying studies under microwave and microwave-convection combination and convective (thin-layer) conditions using the newly developed dryer and study the quality and sensory evaluation (rehydration and color) characteristics.

1.2 Organization of the Thesis

This thesis is complete with six chapters, references and appendix sections. Each chapter ends with a 'Summary' of that chapter.

Chapter II outlines the background research and review of literature;

Chapter III is the materials and methods section;

Chapter IV explains development of a microwave dryer system;

Chapter V is the results and discussion section;

Chapter VI is the conclusions section of the thesis.

II. LITERATURE REVIEW

According to Statistics Canada, in 2001 the food processing industry sector contributed 6.3% to the Canadian Gross Domestic Product (GDP). This sector was mainly comprised of meat processing, bakery, fruit and vegetable processing (specialty products) industries (Statistics Canada, 2001).

The major fruit crops of Canada are apples, oranges, prairie berry and cherry crops. Prairie fruits include blueberries, cranberries, saskatoon berries and chokecherries. Many of these prairie fruits are gaining importance as a commercial fruit crop and more and more producers are planting for diversified commercial production /processing. This poses a need for research studies to preserve and process for extended shelf-life of these crops (Statistics Saskatchewan, 2001).

2.1 Saskatoon Berries

Amelanchiar alnifolia is the botanical name and this Prairie fruit belongs to the rose family (Rosaceae). Saskatoon berry is also identified as juneberry, western service berry and most commonly as saskatoons. Most common cultivars of saskatoons are:

- *arborea* (Downy serviceberry),
- *asiatica* (Asian serviceberry),
- *canadensis* (shadblow serviceberry) and
- *laevis* (Allegheny serviceberry).

In the past two decades, saskatoons have gained importance as a commercial fruit crop from being a wild fruit of the Prairies. Saskatchewan has a total of 376 hectares and Alberta the largest producer of saskatoons, lists 617 hectares of saskatoon berry production, according to a 2001 census. Currently saskatoons are being exported to United Kingdom (U.K.) after a 2004 European Union agreement. There is an increasing demand for fresh and processed saskatoon berries in the international market (Canada's International Market Access Priorities, 2005).

Researchers have started exploring the post harvest applications of saskatoon berries from the past decade or so. After the research studies by Green and Mazza (1986) on saskatoon berries (saskatoons) confirming that saskatoons are rich in anthocyanins and antioxidants which prevent heart diseases and cancer, more importance has been given to large-scale production of saskatoons. Green and Mazza (1986) also confirmed that dried saskatoons can be used in nutraceuticals, functional foods and extraction of bioactives.

The current post-harvest operation for fresh saskatoons is primarily to freeze the berries within 2 h of harvest to make them available for year-round consumption. Frozen berries are used to prepare processed products such as jams, jellies, fruit extracts, and other products. It is noted that only 15% of the total saskatoon berry production is sold as fresh fruit in the super markets due to the short shelf life of the berries and loss of fruit integrity, flavor and quality only a few days after harvest (Research and Discover, 2005). The harvest season also lasts for about three weeks which leaves freezing as the only post-harvest process method to preserve the produce. Very recently, processed saskatoons products have been sold at retail outlets (e.g., Zellers, Co-op stores) in Western Canada.

Currently, little or no research studies are reported to explore the possibility of drying (dehydration) saskatoon berries. Blueberries and grapes were successfully dried to raisins (from grapes) by Kostaropoulus and Saravacos (1995), Venkatachalapathy (1998) and Grabowski et al. (1994). Osmotic dehydration pretreatment in grapes to infuse sugars and remove small quantities of moisture was investigated by Venkatachalapathy (1998).

Saskatoon berries like other raisin crops such as grapes, cranberries, cherries and blueberries have a protective waxy layer on the surface protecting the fruit from weather changes, insect and parasite attack and controlling the rate of transpiration (Mazliak 1970; Somogyi and Luh 1986; Somogyi et al., 1984). This protective layer obstructs the removal of moisture during dehydration or drying. Different chemical pretreatments using alkali or ethyl oleate with NaOH solutions have yielded positive results in drying of blueberries, grapes and strawberries (Kostaropoulus and Saravacos (1995), Venkatachalapathy (1998) and Tulasidas et al., (1994)).

In this research, effort was made to investigate the application of advanced drying techniques (microwave and microwave combination) to extend the shelf life of saskatoon berries. An osmotic dehydration step was explored as a pre-treatment operation in order to target the reduction of total drying time.

2.2 Saskatoon Berry Composition

Table 2.1 Nutrient values of berries grown in Western Canada

Per 100g	Saskatoons	Blueberries	Strawberries	Raspberries
Energy (Ca)	84.84	51	37	49
Protein (g)	1.33	0.42	0.7	0.91
Carbohydrate (g)	18.49	12.17	8.4	11.57
Total Lipid (g)	0.49	0.64	0.5	0.55
Total Fiber (g)	5.93	2.7	1.3	4.9
Vitamin C (mg)	3.55	2.5	59	25
Iron (mg)	0.96	0.18	1	0.75
Potassium (mg)	162.12	54	21	152
Vitamin A (IU)	35.68	100	27	130

Source of Data: Mazza and Davidson, 1993

The pH value of saskatoon berries varies between 4.2 and 4.4 due to the presence of malic acid. Total soluble solids (TSS) range from 20 to 29.4%. Sucrose levels are between 15.9 and 23.4%, and reducing sugars range from 8 to 12% of fresh fruit weight (Mazza 1979, Green and Mazza 1986). Chemical composition of different prairie berries are listed in Table 2.1 and physico-chemical characteristics of different saskatoon berry cultivars are listed in Table 2.2.

Table 2.2 Physico-chemical characteristics of five saskatoon cultivars

Cultivar	**10 Berry wt.**	**pH**	**Titrable acidity**	**Total Solids**	**Soluble Solids**	**SS/Ac**	**Anthocyanins**
	(g)		(% malic acid)	(% dry wt)	(% sucrose)		mg/100g
Honeywood	12.7	3.8	0.54	25.6	18.7	34.7	114
Northline	8	3.9	0.45	25.1	16.1	35.5	111
Porter	7.8	3.8	0.56	22.7	16.3	29.5	108
Regent	6.8	4.4	0.29	20.8	14.8	52.8	72
Smoky	10.1	4.5	0.25	27	16.3	66.2	68

Source: Mazza and Davidson, 1993

2.3 Saskatchewan Fruit Sector

Table 2.3 lists the total number of farms in Saskatchewan between 1985 and 2001. The number of hectares of berries and grapes has increased considerably over this 20-year period. This shows that more farmers are planting berry crops for their commercial value. Production statistics for the province of Saskatchewan and Canada are listed in Table 2.3 and Table 2.4.

Table 2.3 Saskatchewan statistics for Horticulture products (2001 Census of Agriculture)

(Saskatchewan)	1981	1986	1991	1996	2001
Total number of farms	67,318	63,431	60,840	56,995	50,598
Total berries and grapes (Ha)	8	120	225	443	542
Total vegetables (Ha)	595	491	422	477	397

1. Conversion factor: 1 hectare equals 2.471 acres.
2. Conversion factor: 1 square meter equals 10.76391 square feet.
Source: Statistics Canada, Census of Agriculture.

Table 2.4 Canadian Statistics for Horticulture products (2001 Census of Agriculture)

(Canada)	1981	1986	1991	1996	2001
Total number of farms	318,361	293,089	280,043	276,548	246,923
Total berries and grapes (Ha)	31,458	40,470	45,759	57,523	69,165
Total vegetables (Ha)	117,216	116,573	122,594	127,697	133,851

1. Conversion factor: 1 hectare equals 2.471 acres.
2. Conversion factor: 1 square meter equals 10.76391 square feet.
Source: Statistics Canada, Census of Agriculture

In 2004, there were approximately 550 fruit growers in the province and an estimated 728 hectares planted to fruit crops (Table 2.5). Producers and processors originally focused on four major crops: saskatoon berry, strawberry, chokecherry and sea buckthorn. The industry is now rapidly expanding production to include a number of new crops (sour cherries and haskaps). With recent developments in the domestic fruit program at the Department of Plant Sciences, University of Saskatchewan, the industry is now also focusing on dwarf sour cherries, blue honeysuckle (haskaps), dwarf apples and black currant. There are 10 major processors marketing frozen and processed fruit and fruit products in Saskatchewan (Table 2.6) and approximately 70 people employed in the fruit processing industry.

Table 2.5 Number of acres of fruit crops planted in the Province of Saskatchewan in the year 2004

No.	Fruits Planted	Hectares
1	Saskatoon berry	505
2	Strawberry	100
3	Dwarf Sour Cherry	60
4	Apple	40
5	Raspberry	40
6	Chokecherry	40
7	Blue Honeysuckle	8
8	Black Currant	6

Source: Canada's Fruit Industry, Government of Canada, http://ats.agr.ca

Table 2.6 Major fruit processing and research centers in the Province of Saskatchewan

No.	Food Processing / Research Centre	City
1	Berryview Farms	Lloydminster
2	C and V Orchards	Weyburn
3	Dawn Food Products (Canada) Ltd.	Saskatoon
4	Gramma Beps	Swift Current
5	Harvest Pie	Pangam
6	Heavenly Hills Orchard	Blaine Lake
7	Last Mountain Berry Farms	Southey
8	Nature Berry	Air Ronge
9	Parenteau's Saskatoon Berry	Langham
10	Prairie Berries Inc.	Keeler
11	Riverbend Plantation	Saskatoon
12	Saskatchewan Food Development Centre	Saskatoon
13	Saskatchewan Food Centre	Saskatoon
14	University of Saskatchewan (Ag Eng. College)	Saskatoon

Source: Canada's Fruit Industry, Government of Canada, http://ats.agr.ca

2.4 Fruit Pretreatment

Fruit pretreatments including chemical pretreatment, freezing, thawing and osmotic dehydration can influence the dehydration and/or drying rate as well as maintain the overall quality of the final product.

2.4.1 Chemical Pretreatment

As stated in an earlier section, the waxy layer on the skin of saskatoon berries obstructs diffusion of solutes during dehydration and also slows down the drying process. Alkaline dipping by Salunkhe et al, (1991) has shown improvement in drying by forming fine cracks on the fruit surface. Ethyl esters dipping as a pretreatment to drying produced a significant reduction in the drying time (Tulasidas et al., 1993; Ponting and McBean, 1970)

2.4.2 Osmotic Dehydration

Osmotic dehydration is a complex process of counter-current mass transfer between the plant tissue and a hypertonic solution. This leads to dehydration of the material and changes in its chemical composition as well (Ratti and Mujumdar, 1995). Hence, it must be expected that the properties of the material dehydrated by osmosis will differ substantially from those dried by convection methods.

The two-step combination of thermal drying after osmotic dehydration is noted as an energy-efficient drying technology (Lewicki and Lenart, 1992; Grabowski and Mujumdar, 1992; Grabowski et al. 1994). Osmotic dehydration removes considerable amounts of moisture without any application of thermal energy and also infuses sugars into the fruit (mainly aimed at raisin fruits such as saskatoon berries, blueberries, cranberries, etc.) which also is a good self-preservative.

Osmotic dehydration followed by thermal drying (accelerated drying methods) in combination with convection air or vacuum help reduce the moisture content to safe storage levels with minimal loss of natural colorant and chemical compositions (Tulasidas et al 1994). Saskatoons are rich in natural colorant and also in anthocyanins which are antioxidants. Dried saskatoons can be used in the manufacture of other processed bakery products such as cookies, icecreams, cakes and snacks. It also has applications in the pharmaceutical industry for extraction of nutraceuticals /functional foods and micro-encapsulation of bioactive compounds and natural health ingredients.

Traditional drying methods such as flat bed, thin-layer cross-flow and cabinet dryers have high demands in energy and time and compromise the nutritional quality of the end-product because of over-exposure to high temperatures for long durations. Anthocyanins are heat sensitive and therefore, adapting conventional drying techniques may lead to loss of valuable antioxidants in saskatoons (Green and Mazza, 1986). Mantius and Peterson (1995) have successfully infused sugar into cranberries but minimal work is done on successful thermal drying of berries after sugar infusion (Ramaswamy and Nsonzi, 1998; Karathanos et al., 1995).

Mazza et al. (1993) were successful in getting a chewy texture by osmotic-hot air combination drying of blueberries. Few data currently exist on processing (drying, processing, packaging etc.) of fresh saskatoons to extend shelf life and improve stability for packaging and distribution. Only 10-12% of fresh saskatoon berries are sold fresh and the remaining are either frozen or canned. Dark pigmentation (color) of the fruit with its high nutritional content and significant anthocyanin content will make it an attractive fruit to consumers.

2.5 Freezing vs. Drying

The frozen fruit and vegetable industry uses large amounts of energy in order to freeze the large quantity of water present in fresh products. Huxsoll (1982) proved that a reduction in moisture content of the material directly has a direct implication on reducing the refrigeration load during freezing. Other advantages of partially concentrating fruits and vegetables by osmotic dehydration (OD) or sugar infusion prior to freezing includes savings in packaging and distribution costs and higher end-product quality Further drying of the product can be performed for preservation or utilization for product preparations. This will also allow better handling and transporting operations.

The advantages of drying of fruits and vegetables compared with freezing are listed as follows (Ratti and Mujumdar, 1995):

• large energy consumption for freezing and also to maintain the fruit in frozen condition until it is either consumed or processed,

• as the bulk volume is not reduced due to freezing, more storage space is required that again adds to the storage costs,

• drying reduces the moisture content of the produce that has an impact of lowering the microbiological activity in the fruit, and

• drying without freezing the product itself will avoid the energy consumption for freezing and in new product /process development.

2.6 Dehydration/Drying

The term drying refers generally to the removal of moisture from a substance. It is the most common and most energy-consuming food preservation process. With literally hundreds of variants actually used in drying of particulate solids, pastes, continuous sheets, slurries or solutions, it provides the most diversity among food engineering unit operations (Ratti and Mujumdar 1995).

Dehydration is a means of preserving the safety and quality of foods at the forefront of technological advancements in the food industry. It has greatly extended the consumer acceptable shelf life of appropriate commodities from a few days and weeks to months and years. The lower storage and transportation costs associated with the reduction of weight and volume due to water removal have provided additional economic incentives for widespread use of dehydration processes (Ratti and Mujumdar 1995). The expanding variety of commercial dehydrated foods available today has stimulated competition to maximize their quality attributes, to improve the mechanization, automation, packaging, and distribution techniques and to conserve energy at maintained quality.

2.7 Electrical Properties of Foods

Microwave frequency is between 300 MHz and 300 GHz and located in the high frequency range on the electromagnetic spectrum, and heating of a material by electromagnetic waves in the above mentioned frequency is defined as microwave heating (Risman, 1991). Measurement of dielectric properties gives insight into material temperature profiles, heating homogeneity and heat dissipation patterns.

Measurement of dielectric properties of agricultural material helps us understand the electrical behavior, level of mechanical damage and also predict moisture content and bulk density of the material based on the indirect nondestructive method of determining the physical characteristics. Venkatesh et al. (1998) found that size reduction or chopping of corn at comparable bulk densities and moisture contents had different dielectric properties. Nelson (1973) reported that agricultural material dielectric properties are dependent on moisture content, bulk density and size of the material.

2.7.1 General Principles – Microwave Parameters (Dielectric Properties)

The dielectric properties of usual interest are the dielectric constant (∈’), dielectric loss factor (∈”) and penetration depth (*Dp*). ∈’ and ∈” are the real and imaginary parts, respectively, of relative complex permittivity ($\in_r$).

The dielectric properties are often defined by the complex permittivity equation (Nelson, 1973):

$$\in_r = \in' - j\ \in'' \quad \textbf{(2.1)}$$

Where,

$\in_r$= Complex permittivity,
∈’= Dielectric constant (real part), and
∈”= Dielectric loss factor (imaginary part).

Values that can be presented are those of the dielectric constant, *ε’*, and the dielectric loss factor, ∈”, respectively, the real and imaginary parts of the complex
relative permittivity, ∈=∈’ - j∈” (Nelson, 1973). Values for the loss tangent*, tan δ* =∈”/∈’ (where δ is loss angle of the material) can be calculated from the ∈’ and ∈” values. The dielectric constant, loss factor, and loss tangent (sometimes called the dissipation factor) are dimensionless quantities.

2.8 Microwave Drying

Microwave heating increases interior product temperature that is dependent on the dielectric properties of the material (as discussed above) and this is enhanced by an internal pressure gradient.

Microwave heating has three main advantages (Van Arsdel et al., 1973):

- A penetrating quality of electromagnetic waves and distribution leading to uniform heating (unlike conventional drying where the surface gets over-heated or even damaged due to high temperatures);
- Selective absorption by water (liquid), which leads to a uniform moisture profile within the material; and
- Ease of control due to rapid, volumetric heating response.

2.8.1 Microwave-Hot-Air Combination Drying

Microwave and convection heating may be applied simultaneously or at different times. It has been proven that combination drying is an effective way particularly when microwaves are introduced in the final stages of drying to reduce the product moisture below 20% (Mudgett, 1989). Microwave application can be effectively utilized in the falling rate period where hot-air drying is too slow affecting the quality of the dried product with over exposure to hot-air conditions. Application of microwave or combination drying technique for potato (Bouraout et al. 1994), apple and mushroom (Funebo and Ohlsson 1998), carrots (Litvin et al. 1998, Prabhanjan et al. 1995, Lin et al. 1998), raisins (Kostaropoulos and Saravacos 1995, Tulasidas and Raghavan 1993), herbs (Giese 1992), blueberries (Ramaswamy and Nsonzi 1998) and banana (Maskan 2000) has been successfully experimented. These researchers also noted the improvement in the end product quality along with the reduction of total drying time compared to hot-air only drying. This technique combines the capability of microwaves to heat the product internally (depending on the dielectric properties and interaction of the material with electromagnetic energy) and enables faster removal of the surface moisture due to conventional heating of the surroundings.

2.9 End-product Quality Analysis

Color and rehydration ratio are very important quality attributes of dehydrated products. Processing steps such as slicing, cutting and drying always promote the color changes, which may lead to reduction in visual, sensory and organoleptic quality of the dried product.

Rehydration ratio of the dehydrated product, i.e., the ratio of weight of processed food after rehydration to the weight of dehydrated processed food without water (g dehydrated product/g dehydrated product), can be determined as described by Ranganna (1986). The moisture content of both dehydrated and fresh berries can be determined by oven drying (AOAC 930.04 1990).

2.10 Berry Drying Studies

The drying time of chemically pretreated grapes (ethyl oleate, alkalies, etc.,) was cut down by half (Kostaropoulus and Saravacos 1995 and Gragowski et al. 1992). Venkatachalapathy (1998) observed significant difference in drying rates using 3% ethyl oleate and 0.5% NaOH dipping for microwave drying of grapes, but only a 10% improvement in convective drying rate. The most effective treatment for surface waxy layer fruits was proved as ethyl esters of fatty acids, especially oleic acid (Ponting and Mcbean, 2001).

Beaudry (2001) found osmotic dehydration as an advantage before thermal drying considering that no heat is applied in this stage and also higher retention of food characteristics like color, aroma, nutritional constituents and flavor compounds. They studied drying of cranberries with microwave and convection mode combination.

Tulasidas et al. (1993) and Yang and Atallah (1985) showed that microwave convective drying of grapes and lowbush blueberries maintained the quality even at higher drying rates. Reddy and Meda (2005) reported that drying of saskatoon berries in microwave-combination condition could be an effective preservation method for the short harvest seasoned fruit crop. Dielectric properties of saskatoon berries were measured to observe the effects of osmotic dehydration (Reddy et al., 2005) and reported that solute uptake due to osmotic dehydration increased dielectric loss factor values. Yang et al. (1987) have studied the combined process of osmotic dehydration and freeze drying to produce a raisin type blueberry product and reported that the product exhibited good flavor, texture and overall quality and long shelf stability.

2.11 Summary

This chapter essentially summarized various topics and aspects related to:

- Production, physico-chemical characteristics study of saskatoon berries,
- Dielectric properties measurement principles and techniques,
- Chemical pretreatment for berries / fruits,
- Osmotic dehydration technique and effect on drying methods,
- Drying techniques for agri-food / high moisture plant materials, and
- Development of microwave-convection drying system.

Saskatoon berry is now being recognized as a commercial fruit crop with its nutraceutical & medicinal value. Processors have identified the potential of this prairie fruit in the manufacture of various processed products. The main drawback is the use of frozen berries in the manufacturing process compromising the end product quality.

This research was aimed at developing a dried saskatoon berry product using conventional, advanced and combination drying techniques.

III. MATERIALS AND METHODS

In this section, experimental plan, sample preparation, different analytical techniques used, modeling studies on drying data and end-product quality analysis methodologies will be discussed.

3.1. Experimental Plan and Procedure

To meet the proposed research objectives, research outlines stated in Figure 3.1 were followed in our experimental drying process. This involved procurement of Northline saskatoon berries of 2005 harvest, from a producer in Saskatoon region and storing them in the freezer (-15^{o}C).

Frozen Saskatoon Berries

↓

Chemical Pretreatment

↓

Osmotic Dehydration

↓

Microwave / Convection / Combination Drying

↓

End Product Quality Analysis

↓

Statistical Data Analysis

Figure 3.1 Stages of saskatoon berry drying / dehydration process.

Fresh berries were U-picked during the harvesting season. The next step was to chemically pre-treat the berries prior to osmotic dehydration to verify the effect of chemical pretreatment. Chemically pretreated berries were subjected to osmotic dehydration using two solutes of three different concentrations. As a standard practice for control treatment untreated berries were also used in the drying process. The important and final step of our experiments was drying of untreated and osmotic dehydration berries under microwave, convection and combination drying methods. A quality change due to drying was analyzed by measuring the color changes and rehydration-ratio after drying. All experiments were conducted during summer and winter of 2005. The drying steps are detailed in the following sections of this chapter.

3.1.1 Berry Sample Preparation

Frozen berries (Northline variety) of 2005-harvest season were procured from Riverbend Plantations, Saskatoon. Prior to all experiments, frozen berries were taken out of cold storage and thawed at room temperature for 2 h, until the produce temperature was equilibrated. Initial moisture content and total soluble solids (TSS) content were 76% and 15.8^{o} brix, respectively. Prior to individual drying experiments, the whole fruit samples were taken out of cold storage and thawed for 2 h. The moisture content of each sample was measured individually.

3.1.2 Chemical Pretreatment

To study the effect of chemical pretreatment on osmotic dehydration an ethyl oleate mixture was used. Chemical pretreatment tests were performed using a solution of 2% ethyl oleate and 0.5% NaOH (mass basis) in distilled water. Liquid ethyl oleate was previously kept in a freezer at –20^{o}C, and granular NaOH at ambient temperature. After thawing, the berries were wiped with soft tissue and dipped into the prepared solution for different time periods of 60,120 and 180 s separately. All experiments were done at room temperature (23^{o}C). The chemically pre-treated berries were then kept ready for osmotic dehydration experiments.

3.1.3 Osmotic Dehydration

Osmotic dehydration was carried out with two osmotic agents: sucrose (solution), commercially available fine granulated sugar with 99° brix, and high fructose corn syrup (HFCS) of 70° brix. The effect of these two osmotic agents with respect to dipping time was compared. Three concentration levels of sugar solution were used in this study to compare the effect of the concentration of the osmotic agents on osmotic dehydration. The sugar solution with 40, 50, and 60° brix concentration were prepared and the chemically treated and untreated (thawed but without treated with chemicals) saskatoon berries were immersed in the osmotic reagents for a duration 6, 12, 18, 24 and 36 h, respectively.

Optimal chemical and mechanical pretreatments were determined, different factors of osmotic dehydration were tested. These factors and their levels were studied as below:

- Type of sugar agent (Crystal sucrose and liquid high fructose corn syrup);
- Concentration of sugar agent (40, 50 and 60° brix); and
- Time of osmotic dehydration (6,12, 18, 24 and 36 h).

Varied concentration of sugar solutions were prepared and equivalent weight of berries were added. The solution was mixed and known weights of berries were collected after every 6 h and washed with tap water to remove the solute on the berry surface during each sampling.

For simplification, only two counter-diffusions are usually assumed to take place in osmotic dehydration process, with one being the water diffusing out from the inner cell to the surrounding solution and the other being the solute diffusing from the surrounding solution into the cell. Water loss (WL, kg/kg fresh material) and solute gain (SG, kg/kg fresh material) are two main parameters to consider in this process. Both diffusion processes are interdependent.

3.1.4 Saskatoon Berry Drying

Drying is an important operation in the preservation of saskatoon berries, to reduce the moisture content from 75% (60% after osmotic dehydration) to 25% (or lower) in a very short time after harvest. The experiments conducted under different drying conditions are listed in Table 3.1.

The following parameters were measured and maintained in the experiments:

- Product temperature: 60, 70, and 80^{o}C (Microwave power levels: P1, P2 and P3),
- Airflow rate: 1 to 1.4 m/s,
- Relative humidity: 14-18%, and
- Final moisture content: 25%

Table 3.1 Experimental design indicating treatments, drying modes and power levels (Numbers indicate the replicates).

Pre-treatment Condition	**Microwave**			**Combination (MW + Convection)**			**Convection**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
60% Sucrose (24 h)	3	3	3	3	3	3	3	3	3
60% HFCS (24 h)	3	3	3	3	3	3	3	3	3
Untreated	3	3	3	3	3	3	3	3	3

Note: Convection air temperatures were higher (15^{o}C) to maintain product temperatures at 3 power levels of P1 (60), P2 (70), and P3 (80^o)C.
HFCS stands for high fructose corn syrup.

3.1.5 Microwave and Microwave-Convection Drying

For all the microwave and microwave combination drying studies, a Panasonic Microwave-Convection oven NNC980W (Panasonic Canada Ltd, Mississauga, ON) that was developed into a stand-alone drying system was used. The dryer system features and modifications are detailed in Chapter IV (Development of dryer).

3.1.6 Convection Drying

For convection-only drying, a cross flow dryer in the bioprocessing laboratory (ABE Dept., U of S) that was developed for thin layer drying of both high and low moisture agricultural materials (Adapa et al. 2002), was successfully used. This dryer had the following features and capabilities:

- Convection air temperature from 25 to 150^{o}C;
- Relative humidity adjustment from 5 to 75%;
- Airflow rate from 0 to 2 m/s;
- Measurement of air (T-type thermocouples) and product temperatures (Infrared sensor);
- Online moisture loss measurement; and
- Ability to record moisture loss, air temperature, product temperature, air flow rate, and relative humidity during drying using a computer with LabView 6i (National Instruments, Austin,TX) data acquisition software.

3.2 Analytical Procedures

Different analytical methods to determine the physical and electro-magnetic properties of saskatoon berries are explained in this section.

3.2.1 Moisture Content Determination

Saskatoon berry samples of 5 g were dried in a vacuum oven at 70°C and 25 psi for 7 h to assess their initial moisture contents. This experiment was carried out in three replicates. The initial moisture content (MC) of the saskatoon berries was determined as 76% dry basis (d.b.) according to AOAC 930.04 Standard (1990).

3.2.2 Total Soluble Solids (TSS) Measurement

Saskatoon berries were manually crushed and the fruit syrup was extracted using cheesecloth. A digital hand held pocket Refractometer (PAL-1, 0-53° brix, and PAL-2, 50-93° brix, ATAGO Co. Ltd, Japan) was used to determine the brix level of the fruit syrup. The PAL-1 had a measuring range of 0 to 53° brix and PAL-2 from 53 to 95° brix. For all measurements, 0.3 ml of the fruit extract sample was used.

3.2.3 Dielectric Properties Measurement and Sample Preparation

In order to better understand the interaction of microwave and fruit samples, the dielectric properties measurement was undertaken. Also, from modeling point of view this information may be useful. Measurement of the dielectric properties was performed with an open-ended coaxial probe connected to HP 8510B Network Analyzer (Agilent Technologies, Santa Clara, CA) setup in bioprocessing laboratory at the University of Saskatchewan. The analyzer generates a microwave signal through the coaxial probes. The material is tested by bringing in contact the flat surface of the probe with the material under test. The fields at the end of the probe “fringe” into the material and change as they come in contact with the material. The network analyzer detects the magnitude and phase shift of the reflected signal and calculates the reflection coefficient. Then graphically computer controlled software calculates the dielectric properties from these data and display them as a function of frequency.

The coaxial probe (Figure 3.2) is a convenient and broadband technique for lossy (materials with high dielectric loss factor values) liquids and solids. It is non-destructive and little or no sample preparation is required for liquids or semi-solids. In the case of a solid material under test, the material face must be machined at least as flat as a probe face, as any air gap can be a significant source of error. It operates at frequencies between 0.045 and 26.5 GHz. The technique assumes the material under test to be non-magnetic and uniform throughout.

The HP 8510 is a high performance microwave Vector Network Analyzer (VNA) system. It consists of a HP 8510B, a Test Set (e.g. HP8515A S-Parameter Test Set), and a microwave signal source (HP 8341B). This Agilent VEE (Vector network analyzer driver) controls the HP 8510 "system" as a whole. That is, commands issued through the HP 8510 driver also control the test set and the signal source.

An HP software program provided the permittivity based on the measured reflection coefficient (Engelder and Buffler 1991). For coaxial probe measurements, the HP dielectric probe kit (HP 8510B) is utilized, which consists of the probe, related software, and calibration standards. The calibration consists of measuring three known standards with the probe (usually open air, short block, and distilled water at room temperature). The calibration process removes systematic errors from the measurement. The operating frequency range of the system was set to 0.5 MHz to 5 GHz. All the measurements were taken at room temperature (23^{o}C) and constant bulk density. The menu driven software was installed on the personal computer and the control algorithm based software computes the complex permittivity of the material under test from the S-parameter information, which was relayed from the vector network analyzer (VNA).

To reduce cable flexure and probe motion errors during measurements, a fixture was developed which securely clamps the probe (as shown in Figure 3.2) and its cable in a vertical position. The fixture is equipped with a small table on which the calibration standard or material under test is placed. This table is mounted to a manually operated vertical position translator, which allows the operator to raise the material under test up to the probe tip with high positional precision and with the proper contact pressure.

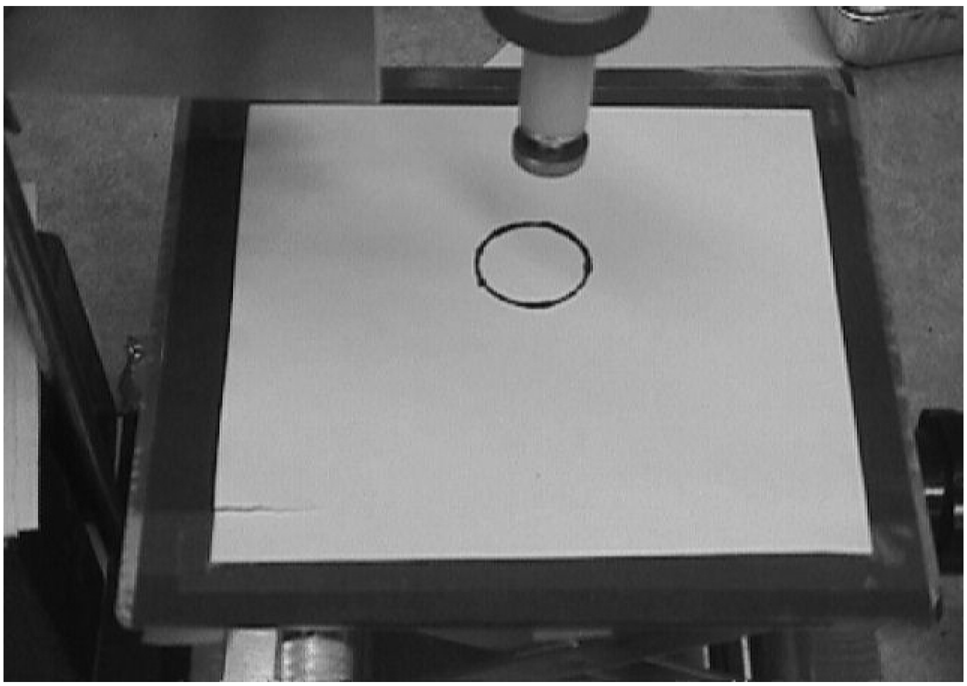

Figure 3.2 Open-ended coaxial probe and adjustable platform.

All dielectric measurements were performed at room temperature (23^{o}C). Measurements for dielectric properties were performed using the HP Network analyzer system on fresh and frozen saskatoon berries for the following different fruit components:

- Whole berry,
- Cut berry,
- Berry paste, and
- Berry juice / syrup

Osmotic dehydration process that involves loss of moisture and solid gain can affect the dielectric properties of the fruit. As the drying experiments involved drying of untreated and osmotically dehydrated saskatoon berries under microwave conditions, measurement of dielectric properties before and after osmotic dehydration revealed the effect of osmotic dehydration on drying characteristics and microwave absorption characteristics of the material.

3.3 Dehydrated Product Quality Analysis

Quality analysis by measuring color changes and rehydration ratio were carried out to explain the effect of the drying process and conditions on final dried product.

3.3.1 Color Measurements

The color measurements were done using Hunterlab Color Analyzer (Hunter Associates Laboratory Inc., Reston, VA, U.S.A.). The Hunter L, a and b coordinates of convection, microwave and microwave combination dried berries was determined by measuring their respective L, a and b coordinates. After initial calibration against standard white and black surface plates, three replicated measurements for each sample were taken. The coordinate L being the lightness indicator, a the greenness to redness indicator and b indicates blueness to yellowness of an object. Color difference values ΔL, Δa and Δb were calculated according to the following equations:

$$\Delta L = L - L_t \tag{3.2}$$

$$\Delta a = a - a_t \tag{3.3}$$

$$\Delta b = b - b_t \tag{3.4}$$

Where L, a and b are the measured values of the specimen and L_t, a_t, b_t are values of the target color. The target colors in this experiment are L, a and b of the fresh saskatoon berry fruit. The total color difference ΔE_{ab} is measured using the L, a, b color coordinates and as defined by the Equation 3.5 (Minolta, 1991):

$$\Delta E_{ab} = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{0.5} \qquad (3.5)$$

3.3.2 Rehydration Test

Rehydration tests of dried samples were performed using a recommended method (Annon., 1991). A 500 ml beaker containing 150 ml of distilled water was placed on a hot plate and covered with a watch glass. The water was brought to the boiling point and a known quantity of the sample was added to the boiling water and boiled for an additional 5 min. The mixture was transferred to a 7.5 cm Buchner funnel covered with Whatman No. 4 filter paper. Water was drained out until there were no more drops from the funnel. The sample was then removed and weighed. Rehydration ratio was calculated as the ratio of mass of rehydrated sample to that of the dehydrated sample. The coefficient of rehydration (COR) is calculated by equation 3.6.

$$COR = \frac{M_{rh}\,(100 - M_{in})}{M_{dh}(100 - M_{fn})} \qquad (3.6)$$

Where,

COR = Coefficient of rehydration,

M_{rh} = Mass of rehydrated sample (g),

M_{dh} = Mass of dehydrated sample (g),

M_{in} = Initial moisture content of the sample before drying (%), and

M_{fn} = Moisture content of the dry sample (%).

3.3.3 Micro-structural Analysis

The Phillips Scanning Electron Microscope (SEM 505, Phillips, Holland Electrons Optics, Eindhoven, and Netherland) was used to examine the microstructure of the samples and study specimens that require higher magnifications and greater depths of field that can be attained optically. Saskatoon berries were observed for physical changes that occurred after osmotic dehydration treatment and drying experiments. The photograph and functional components of the scanning electron microscope is shown in Figure 3.3 and figure 3.4 respectively.

Samples were prepared in the following manner. The samples were kept free from moisture and other contaminants as possible and then they were pinned down to a sample holder using a conductive carbon tape that contained adhesive on both the sides. The samples were first dried in a vacuum dryer at a pressure of 1080 Pa and temperature of 31.5^{o}C.

Figure 3.3 Photograph of SEM system with computer.

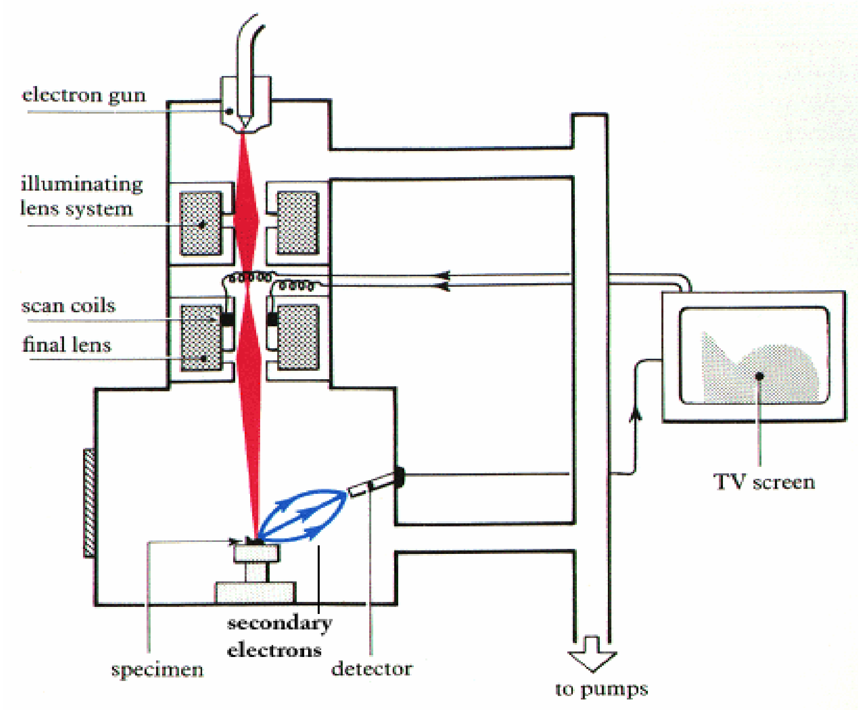

Figure 3.4 Functional components and operating principle of Scanning Electron Microscope (SEM).

3.4 Modeling of Drying Process

Many researchers have adopted empirical drying models for simplicity and accuracy. The simple type of drying model assumes that rate of exchange in moisture content is proportional to the difference between moisture content and equilibrium moisture content (EMC) of the material. This section deals with five identified drying models reported in the literature and adapted to this work.

3.4.1 Moisture Ratio Determination

Moisture ratio was determined in order to compare each set of data, e.g., berries at 60^{o}C and different drying treatments (microwave, convection and combination). Moisture ratio was calculated using following equation:

$$MR = \frac{M - M_e}{M_i - M_e} \tag{3.7}$$

Where,

MR = Moisture ratio,

M = Average moisture content, % (d.b.),

M_i = Initial moisture content, % (d.b.), and

M_e = EMC, % (d.b.).

Based on extensive review of the literature, the drying models listed in Table 3.2 were adapted in this research. The moisture content data at different microwave, combination and convection temperature (power levels) were fitted against drying time, using the various models given in Table 3.2.

Table 3.2 Drying models fitted for the drying data

Model No.	**Name**	**Drying Models**	**References**
1	Page Eqn.	$MR=\exp(-k\,t^{n})$	Liu and Bakker-Arkema (1997)
2	Modified Drying Eqn.	$MR=a+\exp(-k\,t^{n})$	Agrawal and Singh (1977)
3	Wang and Singh	$MR=1+at+bt^{2}$	Wang and Singh (1978)
4	Sharma et al.	$MR=a*\exp(-bt)+c*\exp(-dt)$	Sharma et al. (2005)
5	Midilli Equation	$MR=a*\exp(-k(tn))+b*t$	Midilli et al. (2002)

Where,

MR = Moisture Ratio (Equation 3.7),

k = Drying constant, min^{-1}

t = Drying time, min

a, b, c, and d = constants.

3.5 Statistical Analysis

Statistical methods adapted for different experiments are explained below.

3.5.1 Chemical Pretreatment

One-way analysis of variance (ANOVA) was performed to verify if there was any significant difference in solute uptake between the control treatment and 3 chemical pre-treatment levels.

The factors for analysis considered include:

- 1 control treatment – Untreated berries,
- 3 treatments – 60, 120 and 180 s chemical pretreatment duration, and
- 3 replications.

3.5.2 Osmotic Dehydration

The three-factor randomized complete block design (RCBD) was used to verify the effect of solutes, solute concentrations and time effect on solute uptake and mass loss.

RCBD: After the experimental units are blocked, treatments are assigned at random within each block such that each treatment occurs once in every block (Albert et al., 1972). During the conduct of the experiment where the order of processing the material may make a difference, units are processed by block and in a completely random order within each block.

Model for RCBD is shown below:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \tag{3.8}$$

Where:

Y_{ij} = Observed value for the j^{th} replicate of the i^{th} treatment (where i=1 to t and j=1 to b),

μ = Grand mean,

τ_i = Treatment effect for the i^{th} treatment; the treatment effects may be either fixed or random,

β_j = Block effect for the j^{th} block, and

ε_{ij} = Random error associated with the Y_{ij} experimental unit.

For osmotic dehydration, there were 3 treatments (i=3) and 3 replications (j=3).

The treatments were:

- Solutes – sucrose and high fructose corn syrup,
- Solute concentrations - 40, 50, and 60%, and
- Time - 6, 12, 18, 24, and 36 h.

3.5.3 Drying Experiments

Two-factor RCBD was used to verify the effect of 2 treatments and 3 replications on drying time.

The treatments were:

- Drying modes – microwave, microwave-convection, and convection drying, and
- Power level – 3 levels (60, 70 and 80°C product temperatures).

IV. DEVELOPMENT OF A MICROWAVE DRYER SYSTEM

In this research study, dryer development was a major contribution and majority of the research time and effort was dedicated towards equipment modification. Modification including installation of sensors, tools, data acquisition system and other accessories were integrated into a domestic microwave-convection oven to ‘develop’ a laboratory scale microwave-convection combination dryer system. This section explains the above mentioned points in detail. Modification of the oven by installing necessary instrumentation for measurement systems (temperature, weight-loss, etc) along with data acquisition system capabilities were carried out.

4.1. Configuration of Microwave-Convection Oven

A commercially available Microwave-convection oven Panasonic (NNC980W) (Panasonic Canada Ltd, Mississauga, ON) was used to develop a stand-alone drying system. The system controls the microwave power output in continuous mode rather than as a duty cycle. The dimensions of the cavity were 0.24 x 0.41 x 0.42 m. From the ceiling of the oven cavity, a blower fan forced the preheated air through a meshed inlet into the cavity. A variable transformer controlled a pair of electrical heaters of 1400 W capacity to supply heated air at varied temperature levels.

The following design and operating features were built-in the commercial oven:

- 10 different modes of microwave power (220 – 1000 W);
- Inverter technology for variation of microwave power;
- The dimensions of the cavity are 0.24 x 0.41 x 0.42 m;
- Convection / Hot-air (1400 W) stream which operated independently and also in combination with microwave at two set-point convection temperatures;

- Convection fan running with a 12 V input voltage and a maximum air flow rate of 1.5 m/s; and
- Humidity sensor at the outlet of convective air from the dryer system.

The following system modifications were identified to be developed into an integrated combination dryer system:

- Separate controls for microwave and convection air;
- Temperature controller installation for convection air and fan control;
- Inserting fibre optic probes into the oven and making arrangements for online temperature measurement using fibre optic sensors and record the data using LabView 6i software;
- Sample holder design to dry approximately 100 g of berries; and
- Weighing the sample during drying to measure the real-time moisture loss and record the data using LabView software.

4.2. Microwave and Convection System Instrumentation

There was an option to toggle between preset system conditions and modified settings. The following were the preset settings:

- Microwave control was from the front panel (set different power levels and time) both in manual and automatic manner;
- A second panel; convection panel in Figure 4.1, was integrated to the system having two stopwatches, one for convection and the other one for microwave. One digital counter with display was added to this circuitry to count the number of times toggling between microwave and convection; and
- Convection fan operation during convection / combination / manual mode was continuous.

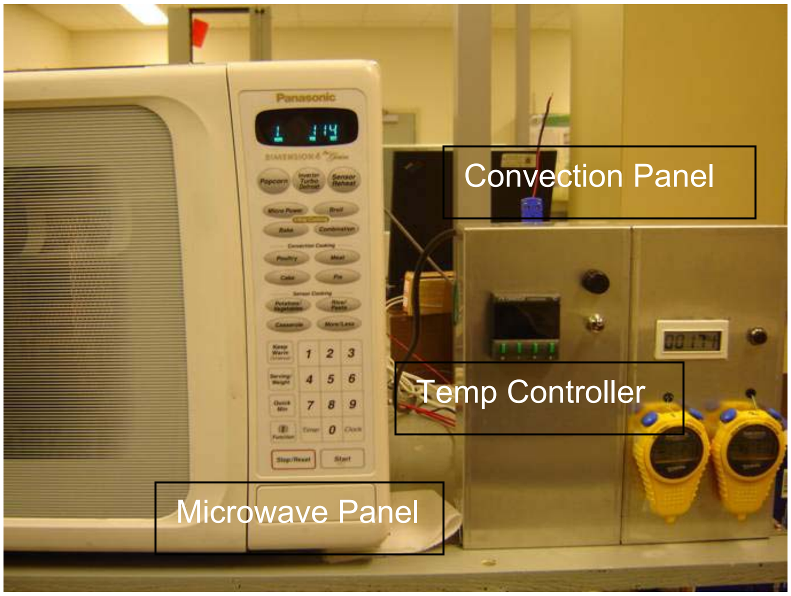

Figure 4.1 Front panels of the microwave drying system (left panel to set microwave power and run-time and right panel to set and monitor convection temperatures).

4.3. Convection Air Temperature Controller Installation

In manual control setting for convection air temperature adjustment, a OMEGA CN9000A temperature controller (Omega Inc., Stamford, CT) was installed (Figure 4.1). The temperature controller had a set point for temperature setting ranging from room temperature to 150^{o}C. Once the set point temperature was reached, a solid-state relay (SSR) circuit switched off the connection stream, which was in series with the temperature controller and heater filament system.

To acquire online temperature data, fibre optic probes were passed into the oven cavity through a teflon block (Figure 4.2) attached on the side of the oven cavity (as shown in Figure 4.3).

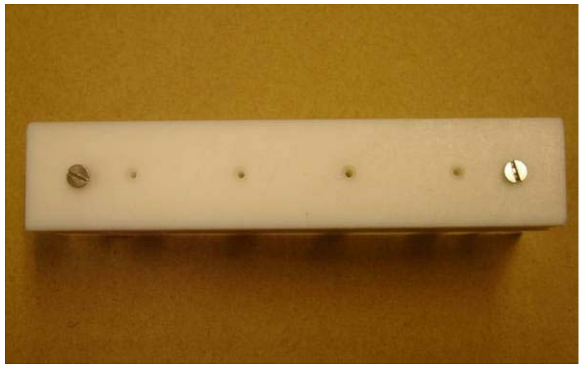

Figure 4.2 Teflon block fabricated to insert fibre optic temperature probes in to the microwave cavity.

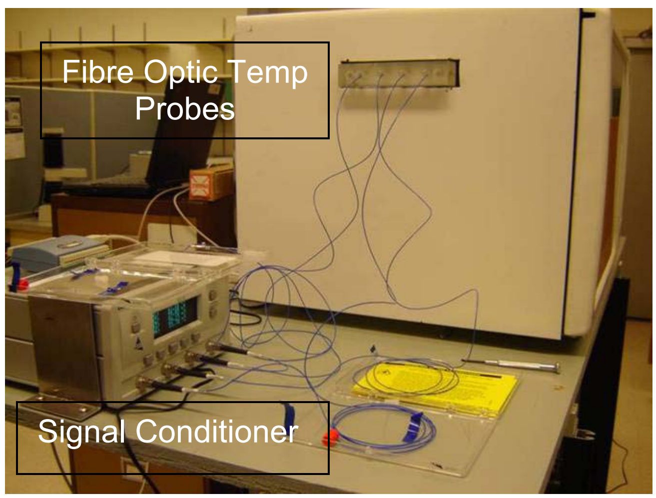

Figure 4.3 An assembly of fibre optic temperature sensors and signal conditioner for temperature measurement.

Based on the set of preliminary experiments, it was observed that the power supply to the heater was 1400 W (maximum) all the time. The fan and heater units turned off automatically when the set point temperature was reached. This was not a favorable condition in a continuous drying system where the fan must be running all the time to maintain constant airflow. An aerial view of the convection fan, connected to the oven cavity fan is shown in Figure 4.4. To have the convection fan running continuously, a rheostat was connected in series with the temperature controller set-up and voltmeter was used to read the voltage through the circuit. By varying the rheostat the resistance varied in the circuit causing a change in voltage supply to the heater that was displayed on the voltmeter. This circuit helped to supply a known voltage to the heater to attain the set point temperature and maintain the same throughout. The Convection fan supplied has a constant voltage of 12V to run continuously even when the heater went off, maintaining a constant airflow rate (flowchart shown in Figure 4.5).

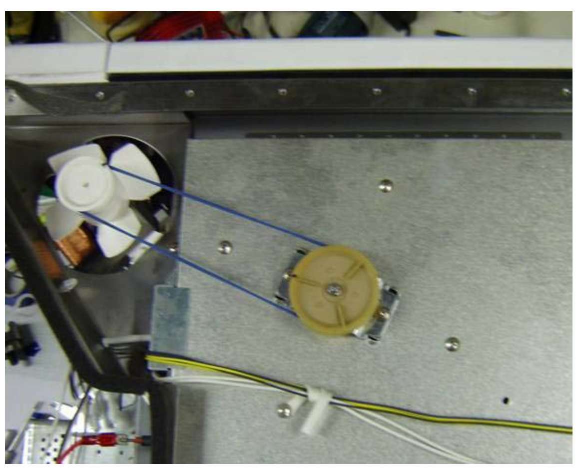

Figure 4.4 Aerial view of the convection fan and the belt pulley arrangement.

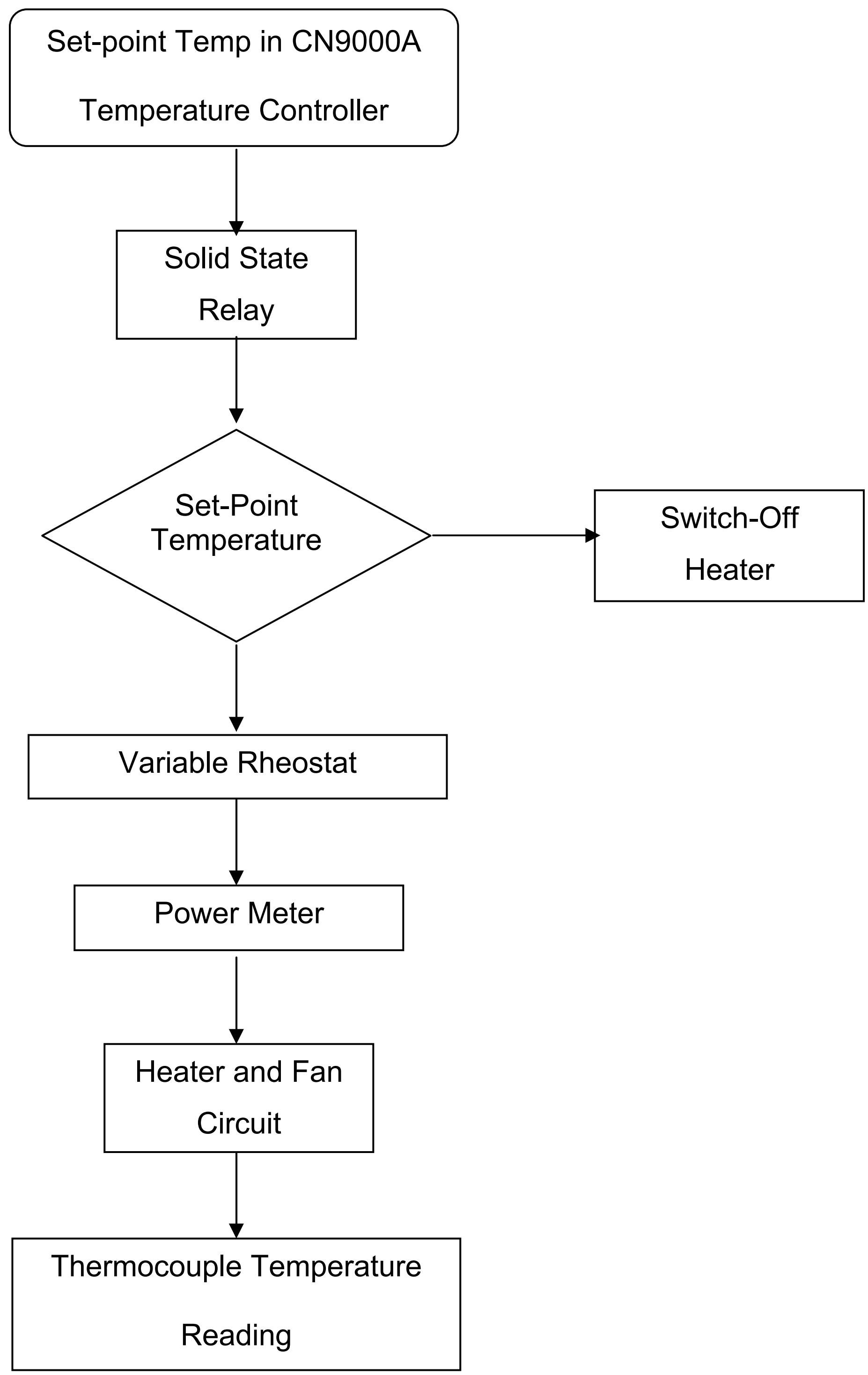

Figure 4.5 Flowchart of the convection heating system explaining the working operation of the convection heating circuit.

4.3.1 Airflow Rate Measurement

Airflow rate measurement was carried out using a hot-wire anemometer at different spots in the microwave chamber. Airflow variation at the sample holder position was 1 ± 0.1 m/s around the sample holder location.

4.4 Data Acquisition Module Integration

Data acquisitions for temperature and weight loss were performed simultaneously during drying using an IBM laptop (Pentium II) with programs written in LabView 6i.

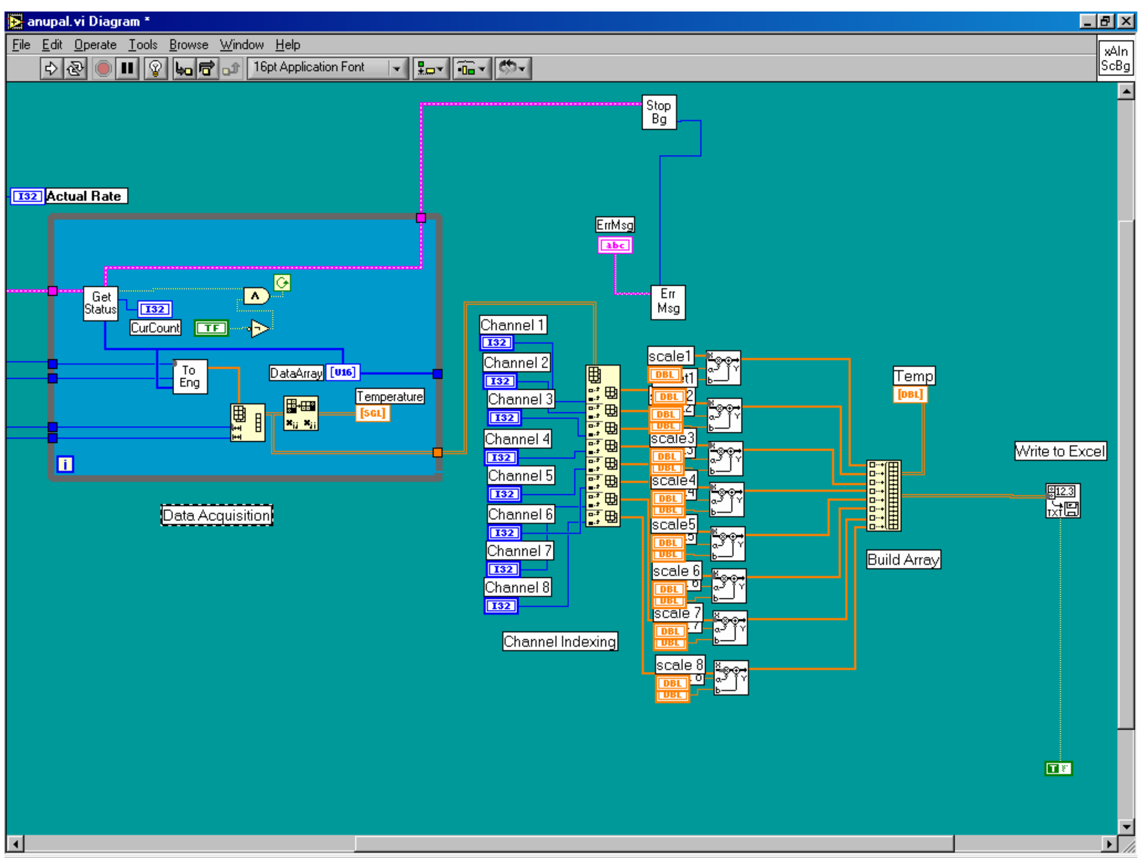

Figure 4.6 Temperature data acquisition flowchart explaining the step-by-step procedure adapted in temperature data acquisition.

4.4.1. Temperature Data Acquisition

The Fiso four channel sensor and signal conditioner ((UMI 250, Fiso Canada, Quebec, QC), -50 to 250°C, 0.01°C accuracy) computer modules are a family of complete solutions designed for data acquisition systems based on personal computers and other process based equipment's with standards I/O ports.

The module converts four analog input signals to engineering units (shown in Figure 4.6 and Figure 4.7) and transmits in ASCII format to any host with standard RS-485 or 232C ports. The maximum number of channels for temperature measurement was limited to four. The unit was interfaced to a personal computer via an RS 232 serial port or USB post from the DAQ card.

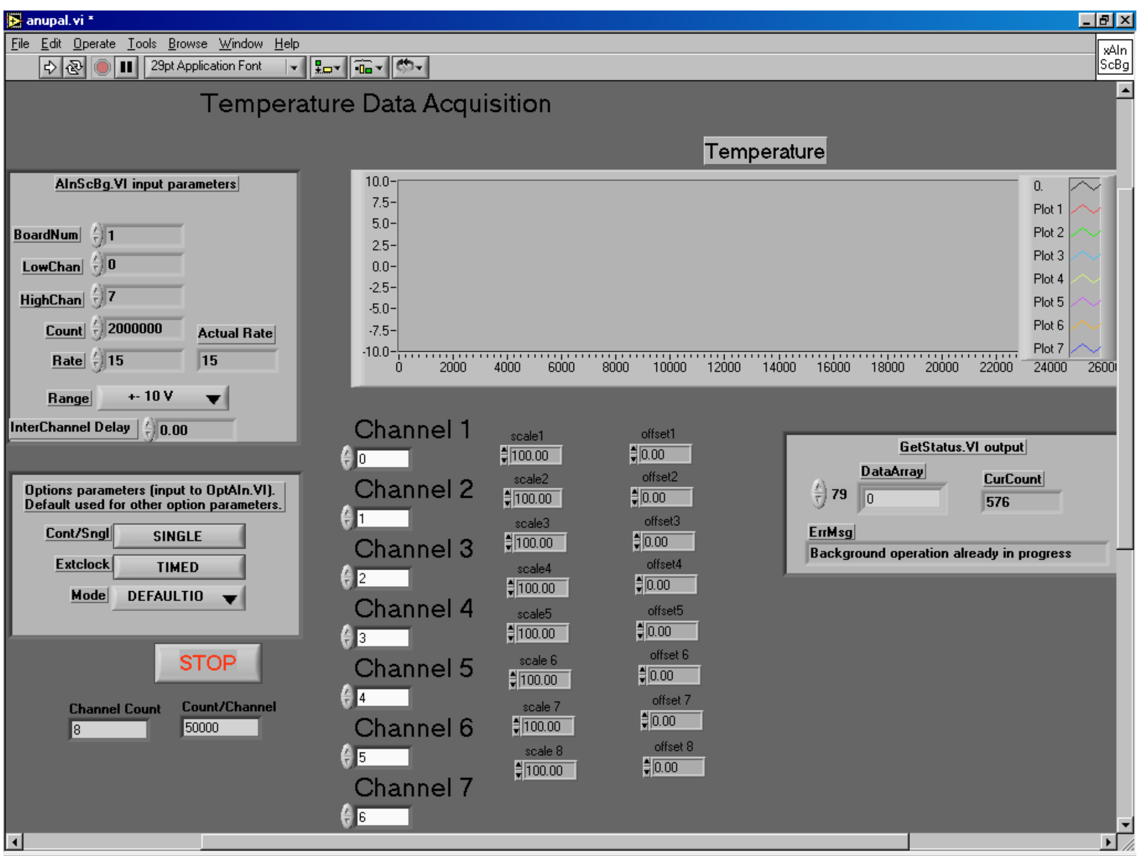

Figure 4.7 Temperature data acquisition main screen of LabView 6i program.

4.4.2. Data Acquisition Software

In order to get continuous temperature and time data, the LabView 6i module software was used for data acquisition. Data acquisition hardware was connected to LabView through the Fiso UMI Signal conditioner module for temperature data and through serial I/O port for weight loss data.

4.4.3. Online Weight-Loss Measurement

Ohaus Adventurer (Ohaus Corp., Mississauga, Ontario, Canada, 2004, 0.1g accuracy) 800 g balance was mounted on top of the microwave oven (shown in Figure 4.8). A sample holder specifically designed for drying of 100 g of sample, made of polycarbonate, was hooked on to the below-balance hook (shown in Figure 4.10 & Figure 4.11).

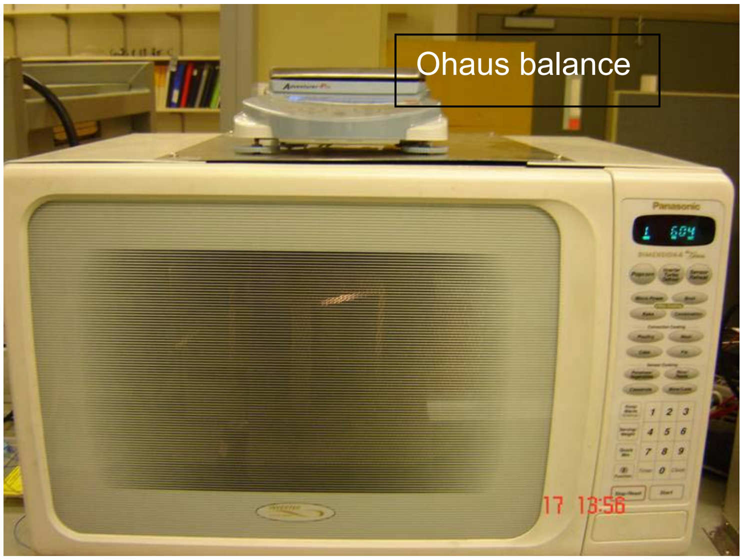

Figure 4.8 Ohaus balance mounted on top of the microwave system to record online weight loss data.

This balance was connected to the laptop computer via Serial I/O post to record the data at specific intervals using serial communication VI (LabView software program shown in Figure 4.9 & Figure 4.11) and finally written onto a Microsoft Excel (2003) spreadsheet. There was slight variation in the data acquisition pattern due to convective air movement.

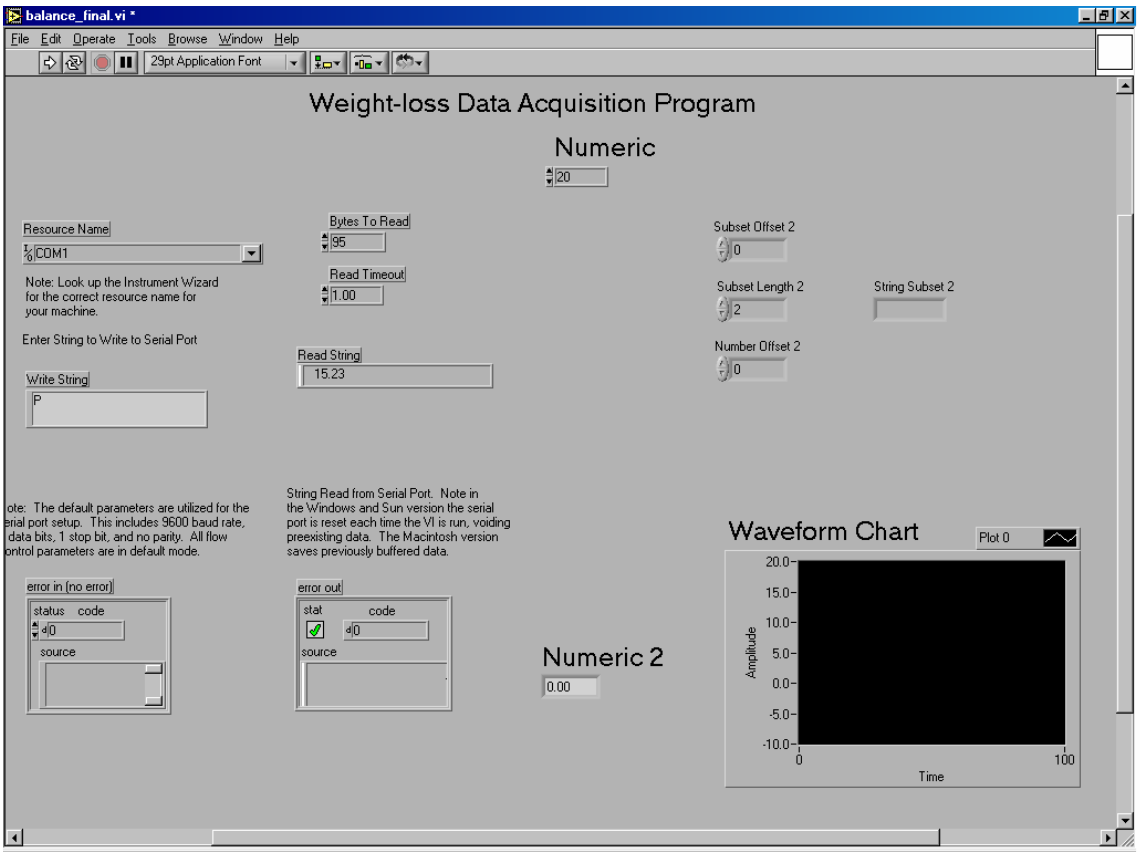

Figure 4.9 Weight-loss data acquisition flowchart indicating the step-by-step procedure adapted in temperature data acquisition.

Figure 4.10 Sample holder connected to a weighing scale by nylon string.

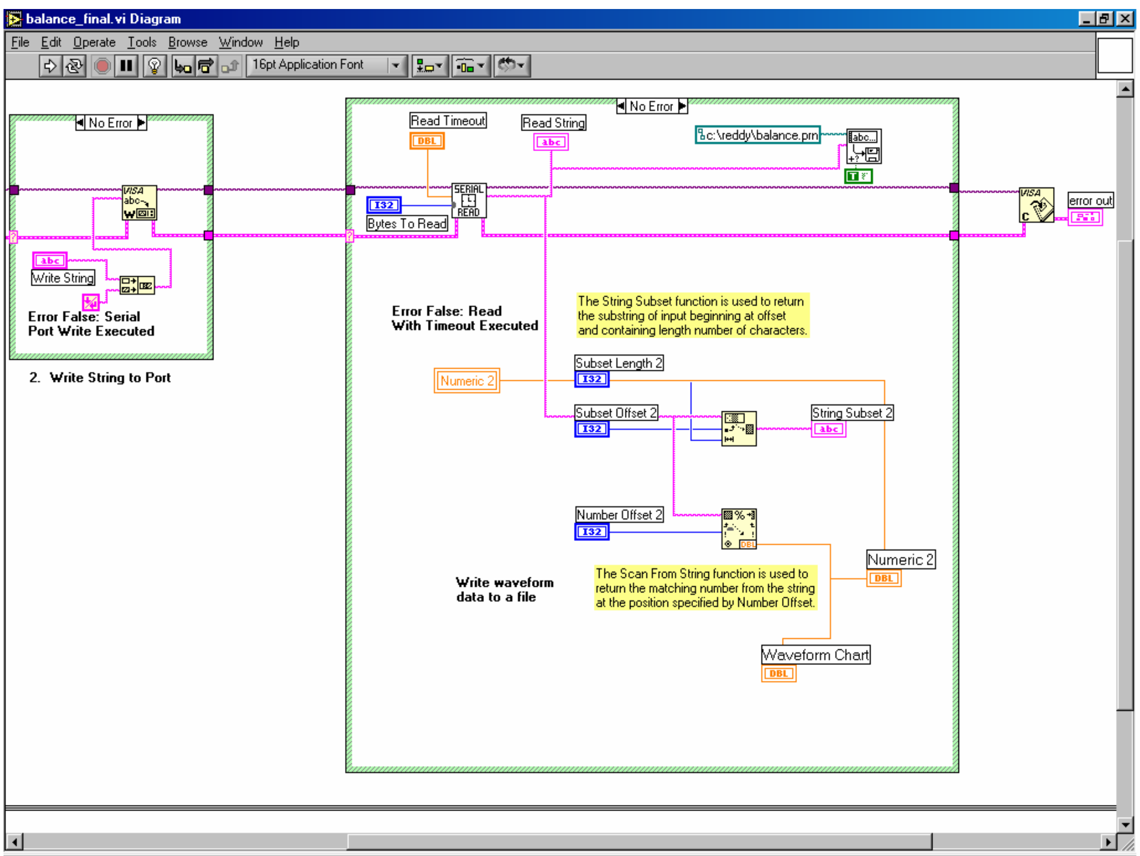

Figure 4.11 Weight-loss data acquisition snap-shot of LabView program.

4.4.3.1. Weight-loss Calibration

Airflow movement surrounding the sample holder would cause change in weight measurement. To overcome this problem, the Ohaus balance was calibrated to acquire data after the sample holder stabilized with the air movement. Berries of known mass (100 g) were placed in the sample holder (as shown in Figure 4.12) with three fibre optic probes inserted into the berries. The data acquisition software acquired data on the laptop and this weight was berry weight with error factor due to air movement. Target final weight of the berries was predetermined and it was possible to calculate actual berry weight by deducting the error factor value.

Figure 4.12 Sample holder with saskatoon berry dried samples with temperature sensors.

4.5. Standard Reference Material (Water) Testing

The measurement of power output of the microwave oven was determined calorimetrically (Khraisheh et al., 1997), i.e., the change of temperature of a known mass of water for a known period of time. The basic equation is:

$$\mathrm{MW}_{\mathrm{abs}} = \frac{(4.187 m C p \Delta T)}{\Delta t} \qquad (4.1)$$

Where,

MW_{abs} = Absorbed microwave power (W),

m = Mass of sample (g),

C_p = Specific heat of the material (kJ/kg-C),

ΔT = Temperature rise in the water load (^{o}C), and

Δt = Heating time (s).

Water into two one-liter beakers weighing 2,000 ± 5 g were placed in the center of the oven, side-by-side in the width dimension of the cavity, and touching each other. The beakers initially should be at ambient room temperature and the initial water temperature should be 20°C ± 2°C (Buffler, 1993). The oven was run at all inbuilt microwave power levels for 2 min and 2 s, the beakers were removed and the final temperatures recorded. Absorbed microwave power is calculated from a simplified formula of Equation (4.1):

$$P = 35 \times (\Delta T_1 + \Delta T_2) \qquad (4.2)$$

Where,

P is the microwave power output (Watts)

$\Delta T1$ and $\Delta T2$ are the temperature increases of the water in the two beakers (^{o}C).

Power measurement was repeated three times, with the final oven power being the average of the three readings (Table 4.1). If any individual measurement was more than 5% away from the average, the complete test was repeated.

NOTE: The water in each vessel should be well stirred before measuring both the starting and final temperature. A small object, such as a plastic spoon or the handle of a wooden spoon works well.

Table 4.1 Measured output power of the microwave system

POWER LEVEL (Settings in Microwave)	MEASURED POWER (Watts)
P10	1000
P9	751
P8	682
P7	689
P6	628
P5	500
P4	392
P3	295
P2 (Pulsating)	295 (7 sec off and 14 sec on)
P1 (Pulsating)	295 (14 sec off and 7 sec on)

4.6 Summary

An existing domestic microwave oven was developed into an integrated laboratory-scale drying system with the following capabilities:

- System Feasibility – The developed drying system can be used for drying of varied agricultural / food materials under microwave, convection and microwave-convection combination drying conditions,

- Microwave Power Control – Different output power levels of the microwave can be selected depending on the power requirement to dry a product,
- Convection Power Control – Output temperatures in the oven can be set in the temperature controller (room temperature to 200^{o}C) that is maintained by the variable rheostat and the solid-state relay circuit,
- Temperature Measurement – Installed fibre optic temperature probes with signal conditioner will measure online product and the drying environment temperature that is recorded on the laptop with a LabView program, and
- Weight Measurement – Weighing scale mounted on top of the oven was connected to the sample holder that acquired product weight loss data online and these data were transferred to the laptop (connected through serial port) with LabView program.

V. RESULTS AND DISCUSSION

In this chapter, drying experiments results obtained using the developed laboratory-scale microwave drying system (discussed in detail in Chapter IV) will be explained. Data obtained from chemical pre-treatment, dielectric properties measurement, osmotic dehydration and final-drying experiments will be presented with statistical analysis.

5.1. Chemical Pre-treatment Experiments

To assess the effect of ethyl esters (ethyl oleate) and NaOH on osmotic dehydration (OD), untreated sample brix (TSS) measurement was used as a control, as explained in Chapter 2.2.3.

Another factor to assess the effect of chemical pre-treatment was by observing the berry surface under a scanning electron microscope (before and after treatment) for any physical changes that might occur on the fruit surface (waxy layer / epithelial tissues) of fresh and chemically pre-treated osmotically dehydrated berries. Figure 5.1 shows the effect of different sugar concentration (40, 50 and 60 ^{o}brix) on untreated and chemically pre-treated berries after 60, 120 and 180 s after 6 h of osmotic dehydration. The solute gain increased with the increase of sugar concentration of the solution; fruit brix of untreated berries was higher than pre-treated samples. Pre-treatment after 180 s showed higher brix values for all three-sugar concentrations. One-way ANOVA on the results shows chemical pre-treatment had no significant ($P=0.753$) effect on osmotic dehydration process on saskatoon berries. Data for both high fructose corn syrup and sucrose osmotic dehydration results is presented in Table 5.1.

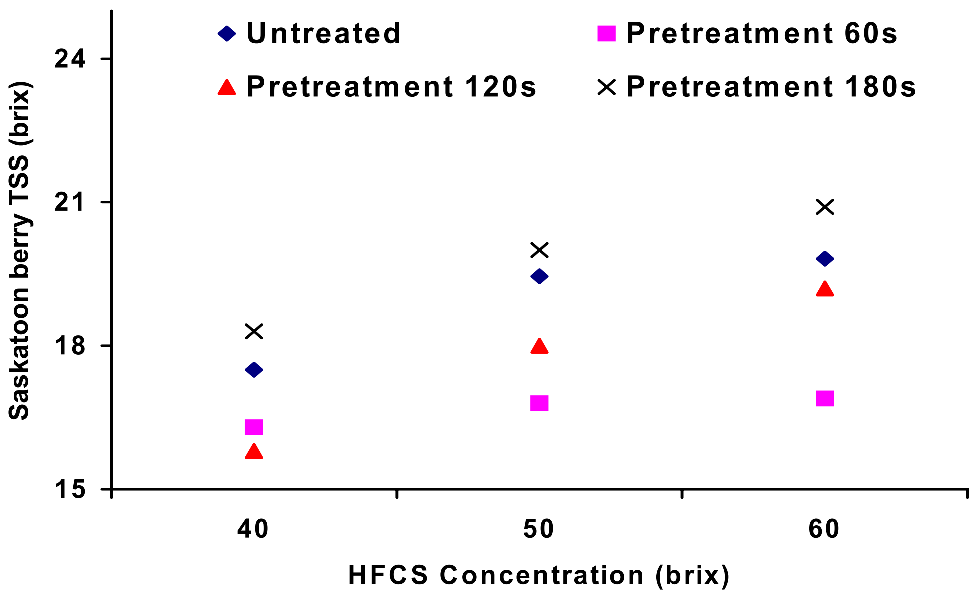

Figure 5.1 Saskatoon berries brix levels (TSS) after Chemical Pre-treatment and 6 h Osmotic Dehydration with high fructose corn syrup.

Table 5.1 Moisture content and total soluble solids of osmotic dehydrated berries after chemical pre-treatment

Osmotic Agent	Chemical pre-treatment (sec)	Sugar Content (Brix)		Moisture Content (% wb)	
	Treatment	Final	Initial	Initial	Final
Sucrose	(P1)60	19.1	15.8	76	73.1
	(P2)120	18.6	15.8	76	74
	(P3)180	20.2	15.8	76	73
HFCS	(P1) 60	16.9	15.8	76	72.7
	(P2) 120	19.8	15.8	76	73.8
	(P3)180	20.1	15.8	76	73.15
	Untreated	19.5	15.8	76	73.8

Frozen berry surface layer sections were observed under SEM before and after osmotic dehydration. Figure 5.2 shows a section of the fruit with waxy skin layer and a spot on the fruit where the surface layer is peeled off exposing the epithelial cell. The black color observed in the cell was mainly water and other cellular constituents. These spots were more than at least five on a single whole berry. The damage of the fruit might have occurred during the freezing process or after freezing during storage. Frozen berries when packed in polythene bags attach to each other that might have left scars on the berry surface while thawing. From observation under SEM after osmotic dehydration, Figure 5.3 and Figure 5.4 showed white spots within the cell and were assumed to be sugar crystals / molecules.

Preliminary Experiment with Blueberries: In the summer of 2005, a series of microwave drying experiments were conducted with fresh blueberries available in the market as a comparative study for saskatoon berries. It is reported that blueberries have similar physical and chemical properties to that of saskatoon berries. Even at low power microwave heating, the berries tend to rupture due to the enormous heating capability of the microwaves. Results from the study are presented in Appendix B1. This study suggests that frozen berries physical state favors osmotic dehydration and drying but fresh berries should have a pre-treatment step before dehydration.

5.1.1. Effect on Osmotic Dehydration

Solute uptake was assessed by measuring the TSS content of the fruit after each stage of osmotic dehydration. Table 5.1, shows that pre-treatment had very minimal or no significant effect in increasing the osmotic reaction for both sucrose and high fructose corn syrup. One of the reasons for this could be the immediate freezing of the fruit after harvest, which can disturb the integrity of berry structure. This can be seen in Figure 5.2, when a whole berry is observed under Scanning Electron Microscope (SEM), the wax coated epithelial layer is disturbed and the epithelial cells are being exposed. These spots were more than one region on a single fruit, which might as well help during osmotic dehydration process for the two-way diffusion process.

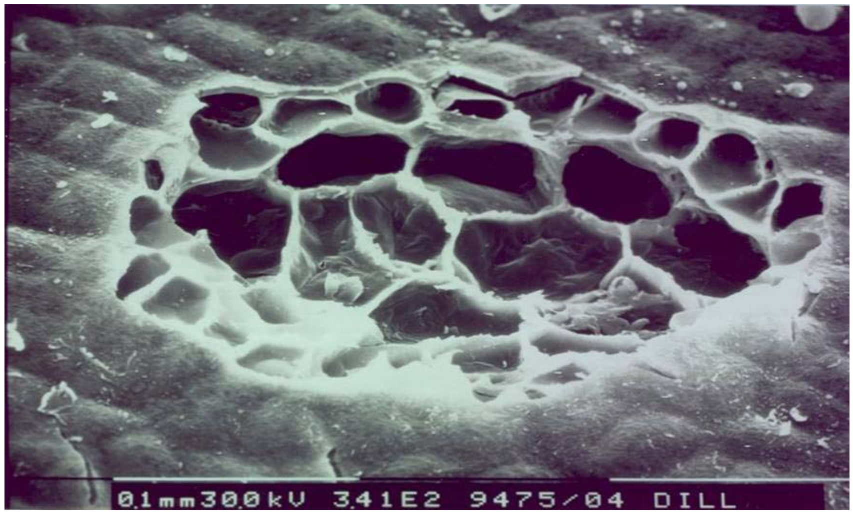

Figure 5.2 Frozen berry cut section of the berry skin under SEM.

Figure 5.3 SEM of saskatoon berry osmotically dehydrated with 50% high fructose corn syrup (HFCS) solution for 24 h without chemical pre-treatment.

Figure 5.4 SEM of saskatoon berry osmotically dehydrated with 50% sucrose solution for 24 h without chemical pre-treatment.

5.2. Osmotic Dehydration (OD) Experiments

The effect of osmosis as a pre-treatment, mainly related to the improvement of nutritional, sensory and functional properties of the products are analyzed. The distinctive aspect of this process when compared to other dehydration methods is the 'direct formulation' achievable through the selective incorporation of solutes without modifying the food integrity. By balancing the two main osmotic effects, water loss and soluble solids uptake, the functional properties of saskatoon berries could be adapted to many different food systems, functional foods and new product development. For simplification, only two counter-diffusions are usually assumed to take place in the osmotic dehydration process, with one being the water diffusing out from the inner cell to the surrounding solution and the other being the solute diffusing from the surrounding solution into the cell. Moisture loss (ML, %) and solute gain (SG, brix or TSS) are the main parameters considered in this process.

5.2.1. Effect on Moisture Loss and Solid Gain

Table 5.2 TSS and moisture content values during osmotic dehydration from 6 to 36 h duration

	TSS (brix)				Moisture Content (%)			
Sucrose	**6h**	**12h**	**18h**	**24h**	**6h**	**12h**	**18h**	**24h**
40	19.5	21.1	22.1	23.0	75.3	73.7	73.3	71.4
50	21.0	23.1	26.0	26.7	75.0	71.6	70.3	68.0
60	23.7	28.4	27.6	30.5	74.4	69.0	67.1	63.1
HFCS	**6h**	**12h**	**18h**	**24h**	**6h**	**12h**	**18h**	**24h**
40	22.3	24.8	25.0	27.2	74.1	72.1	71.1	68.5
50	23.8	28.4	28.9	32.1	71.4	69.8	66.7	64.9
60	24.7	30.4	31.9	34.8	70.6	66.8	63.7	60.6

Figures 5.5 and 5.6 reveal the removal of water from saskatoon berries during osmotic dehydration process using different concentrations of sucrose and high fructose corn syrup solutions. It can be seen that solute gain increased with the increasing osmotic solution concentration in the range of 40-60% (Figures 5.7 and 5.8). Rate of moisture loss and solute gain in sucrose solution during the initial phase (6 h period) was very slow for all concentrations and a higher rate of two-way diffusion was observed in the second phase (12 h period) of the osmotic dehydration process. After the second phase osmotic dehydration process follows a straight-line trend until the end of a 24 h period (1-day). The diffusion rate after 24 h reduces very much and there is very less solute uptake during the next 12 h period. Table 5.2 shows the mean values of moisture loss and solute gain for the 36 h osmotic dehydration process and both the factors had significant difference ($P<0.05$) with time, sugar solution concentration and interaction effect of time and solution concentration.

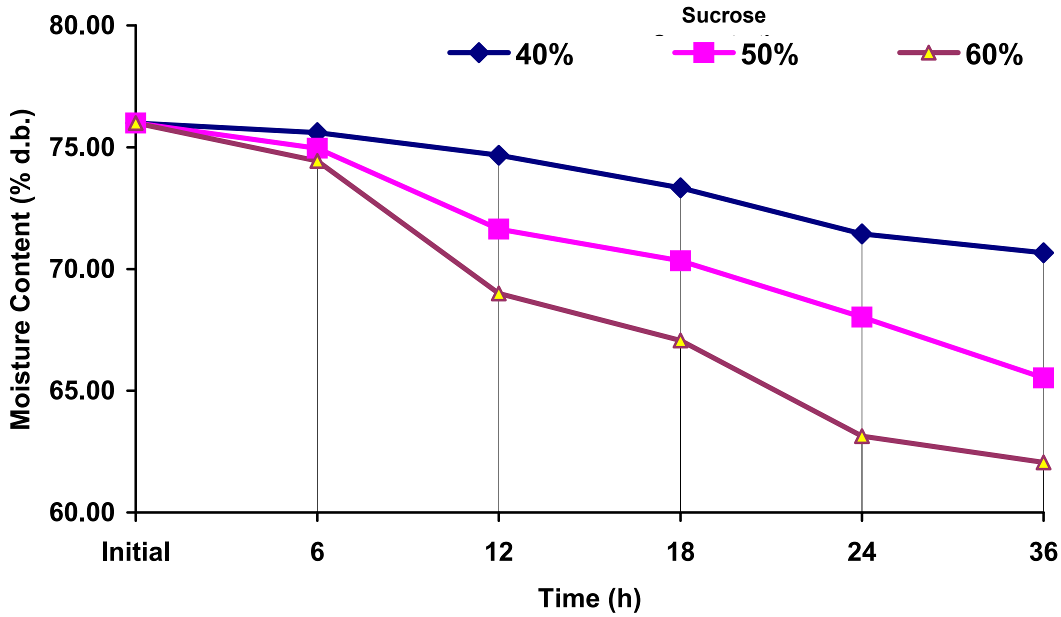

Figure 5.5 Moisture content during the 36 h osmotic dehydration in sucrose solution at 40, 50 and 60% concentrations.

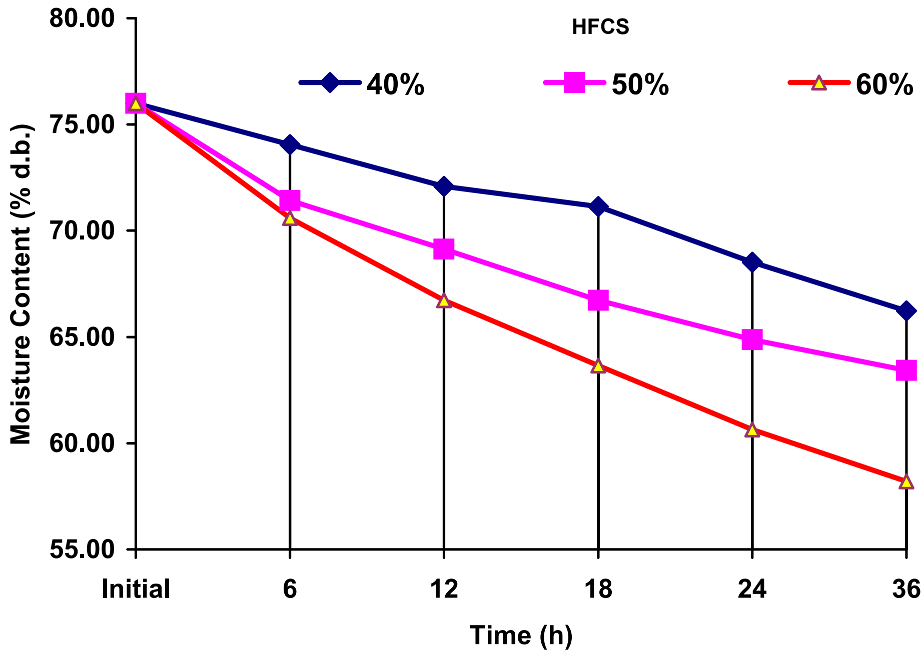

Figure 5.6 Moisture content during 36 h osmotic dehydration in high fructose corn syrup (HFCS) solution at 40, 50 and 60% concentrations.

5.2.2. Effect on Solute Gain

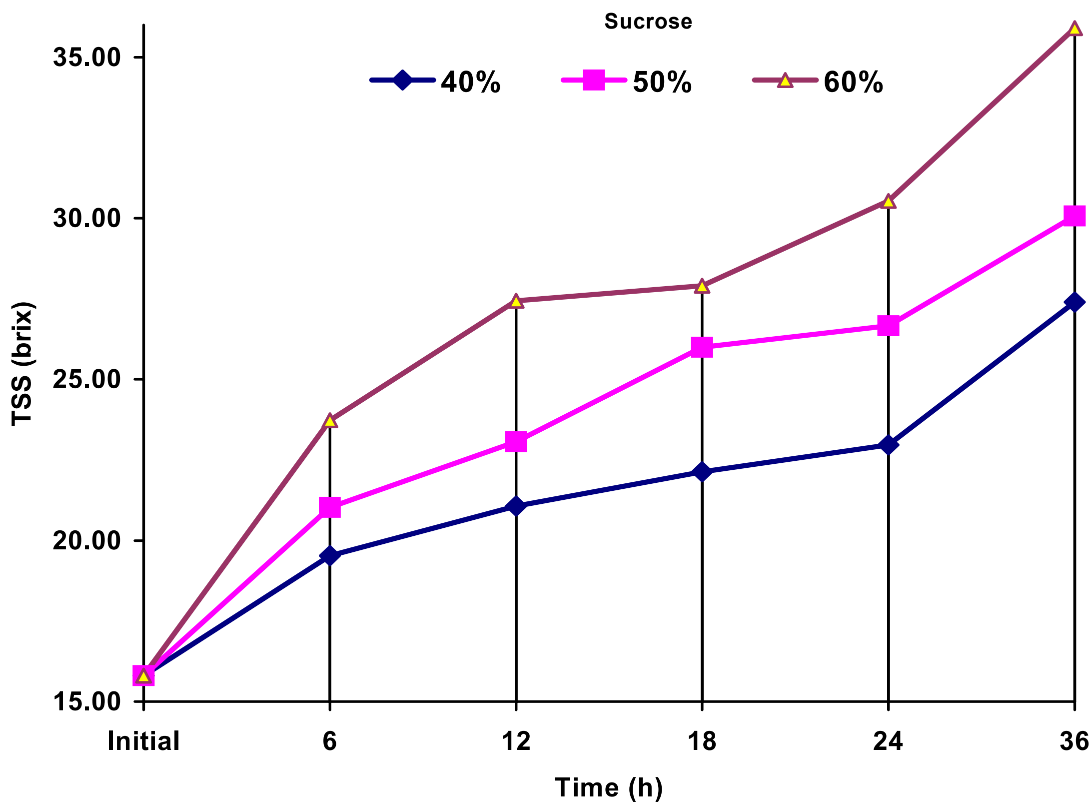

Figure 5.7 TSS (in brix) during 36 h osmotic dehydration in sucrose solution at 40, 50 and 60% concentrations.

The kind of sugar utilized as osmotic substance strongly affects the kinetics of water removal and the solid gain. By increasing the molar mass of solutes (HFCS), a decrease of solute gain and an increase of moisture loss were obtained, thus favoring weight loss and the dehydration aspect of the entire process. Glucose that has low molecular weight has a more profound effect on water activity depression than polysaccharides like sucrose (Argaiz et al., 1994). Therefore, when compared to sucrose, high fructose corn syrup contributed to an effective water removal rate.

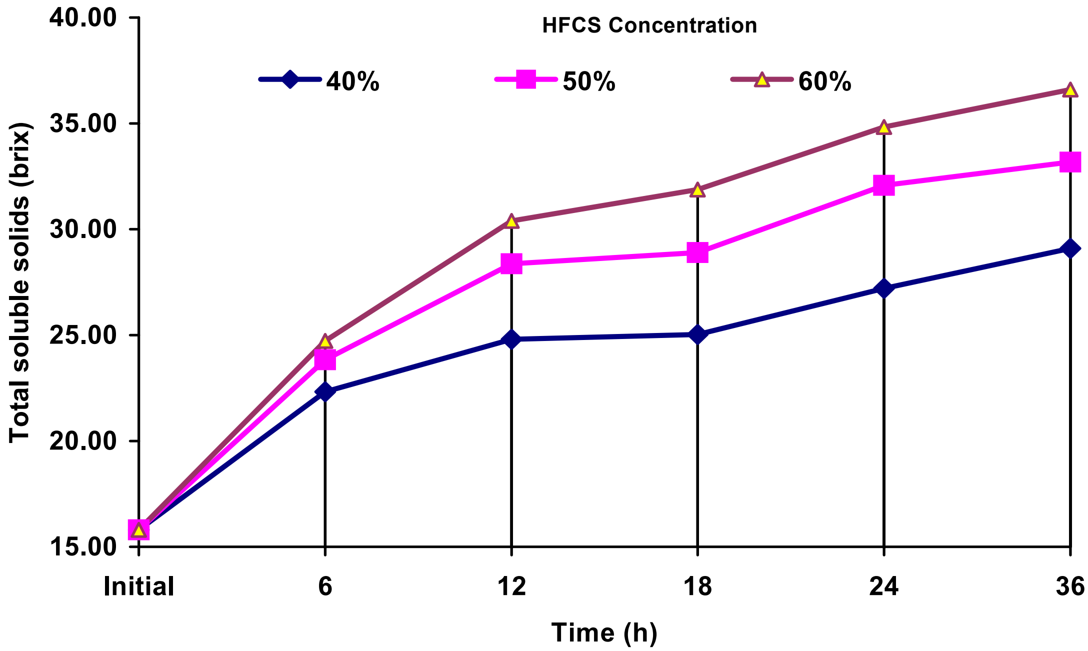

Figure 5.8 TSS (in brix) during 36 h osmotic dehydration in high fructose corn syrup solution at 40, 50 and 60% concentrations.

As osmotic dehydration is effective at ambient temperature, heat damage to color and flavor is minimized and the high concentration of the sugar surrounding fruit material prevents discoloration. In fruits, the cell wall membranes are considered as living biological units, which stretch and expand under the influence of growth and turgor pressure generated inside the cells. In natural food systems, there is also some leakage of solute (sugars, organic acids, minerals, salts, etc.) across membrane layers. Though quantitatively negligible, it may be essential as far as organo-leptic (sensory) or nutritional qualities are concerned. Therefore, compared to single drying process, osmotic dehydration achieves a twofold transformation of the food item, by both a decrease in water content and a solute incorporation, which may result in a subsequent weight reduction.

5.2.3. Effect on Dielectric Properties

Loss of moisture can reduce the dielectric constant value and also solute gain with increase in dielectric loss factor values that affect the microwave absorption in microwave environments. Therefore, measurement of dielectric properties prior to microwave drying yielded useful information on energy absorption and dissipation levels for berries.

5.2.3.1. Effect on Dielectric Constant

The dielectric constant decreased with increasing solute concentration in the berry. The lower the moisture content, the lower the dielectric constant (Figure 5.9 and Figure 5.10).

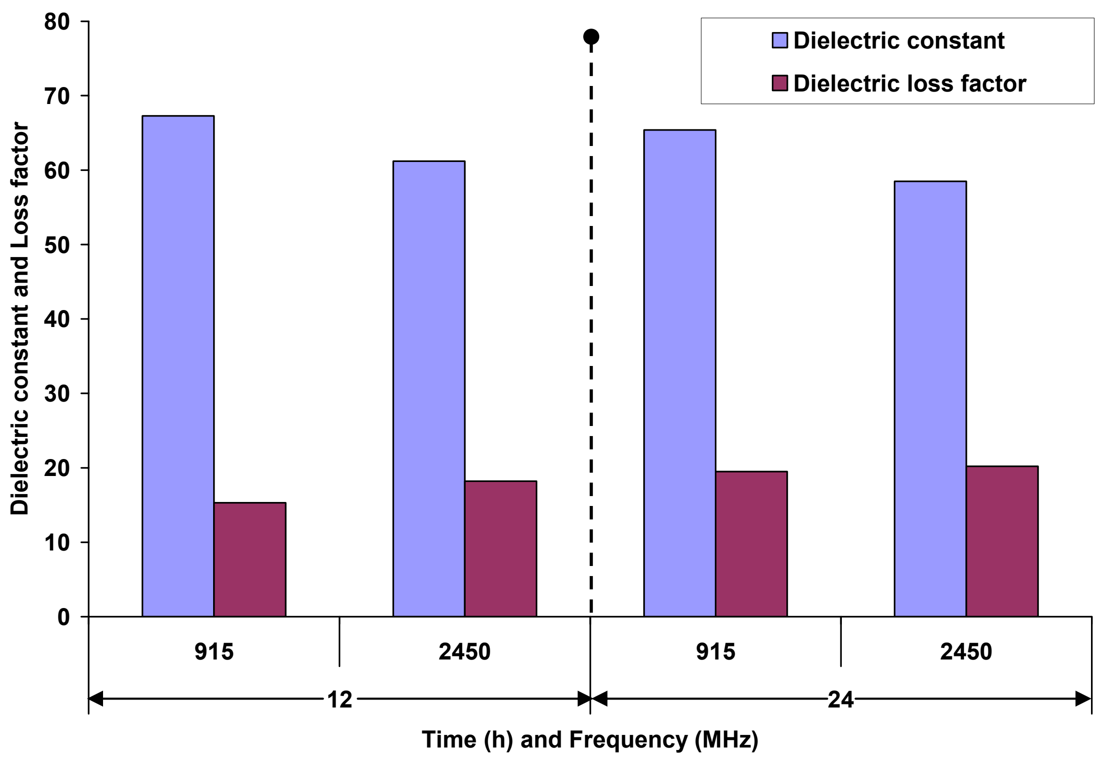

Figure 5.9 Osmotic dehydration effects on dielectric properties after 12 and 24 h durations at 50% high fructose corn syrup concentration.

This was expected, since water being a strong polar solvent in most foods, the molecules reoriented in response to changes in field polarity. Therefore, water as a component of food contributed to the dielectric constant response. As discussed in Chapter III (section 3.2.3), the higher the ash content (mostly composed of solutes), and the lower was the dielectric constant. Solutes bind with water molecules and decrease their ability to reorient themselves in response to the changing electromagnetic field direction and this lowers the dielectric constant ((Engelder and Buffler, 1991).

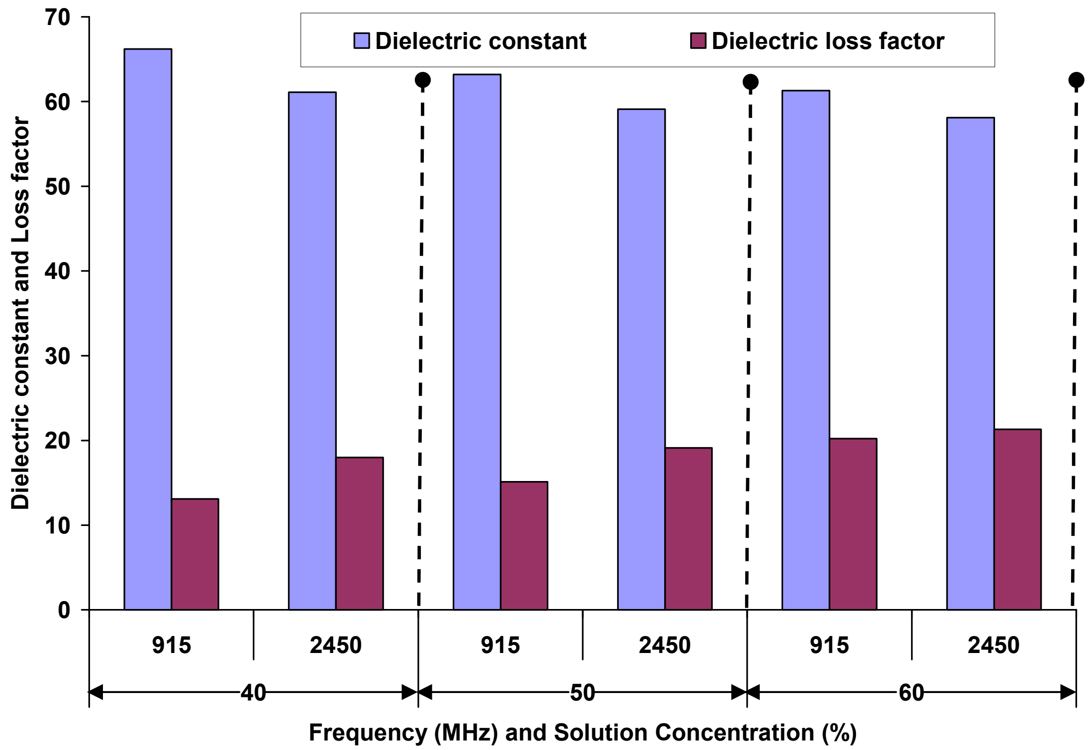

Figure 5.10 Osmotic dehydration effects on dielectric properties at 40, 50 and 60% high fructose corn syrup concentrations and respective frequencies (915 and 2450 MHz).

5.2.3.2. Effect on Dielectric Loss Factor

The moisture content-dielectric loss factor relationship reported in the literature is complex. Funebo and Ohlsson (1999) indicated that dielectric loss factor of maple syrup peaked at moisture content between 44 and 67% at 2800 MHz. Dielectric loss factor of maple syrup also decreased with increasing moisture content (35 to 98%) at 240 MHz. From Figures 5.9 and 5.10, it can be observed that increasing solute concentration and decreasing moisture content in the berry, resulted in an increase in dielectric loss factor values. For the two-step drying approach, further reduction of moisture was achieved under microwave conditions, as the sugar-infused berry favored improved distribution of microwaves within the material and reduced the drying time and energy.

5.3. Drying Characteristics

Drying of osmotic dehydration pre-treated and untreated saskatoon berries was done under:

- Microwave-only,
- Convection-only, and
- Microwave-convection combination conditions.

The dryer system described in chapter IV was used for microwave and combination drying whereas, the thin-layer cross flow dryer discussed in chapter 2.3.2.1 was used for convection drying studies. Drying is a crucial step in preservation of saskatoon berries, in bringing the moisture content from 75% (60% after osmotic dehydration) to 25% (or lower) in a very short time after harvest. Combined microwave-hot-air-drying was more effective in reducing the moisture content of saskatoon berries without damaging the quality attributes of the finished product. No similar work has been reported on saskatoon berry drying and in fact, this is the first systematic study reported on dehydration of saskatoon berries. The development of combined microwave-hot-air-drying system to produce high quality dried saskatoons in relatively short time could make significant contribution to the saskatoon berry industry.

Sugar infused into saskatoon berries during osmotic pre-treatment reduced drying rates during the second drying period, and also osmotic dehydration reduced the total energy consumption on top of the preferential sensory characteristics of the final product. One energy-efficient drying technology was osmotic dehydration in combination with the above-mentioned drying operations. Such a hybrid technology was particularly advantageous when drying berries because a significant fraction of moisture was removed non-thermally with simultaneous infusion of desirable solutes. On the other hand, thermal drying after osmotic dehydration was necessary to reduce moisture content to its final value.

5.3.1. Drying Time

Drying temperature trends with time is shown in Figures 5.11 and 5.12 for berry samples subjected to different drying conditions (60, 70 and 80^{o}C). Higher drying temperatures reduced the required drying time in all of the conditions in Table 5.2. It is apparent that drying rate decreased continuously with drying time. The results indicated that diffusion was most likely physical mechanism governing moisture movement in saskatoon berries. The results were generally in agreement with some literature studies on drying of various food products (Venkatachalapathy, 1998). Microwave drying alone without hot air resulted in lower drying times than convection-only drying but combination drying was more effective than microwave-only or convection conditions. The drying time in microwaves can be reduced by 1.15 times at 60^{o}C and 2.36 times at 70^{o}C drying temperature when compared to convection drying.

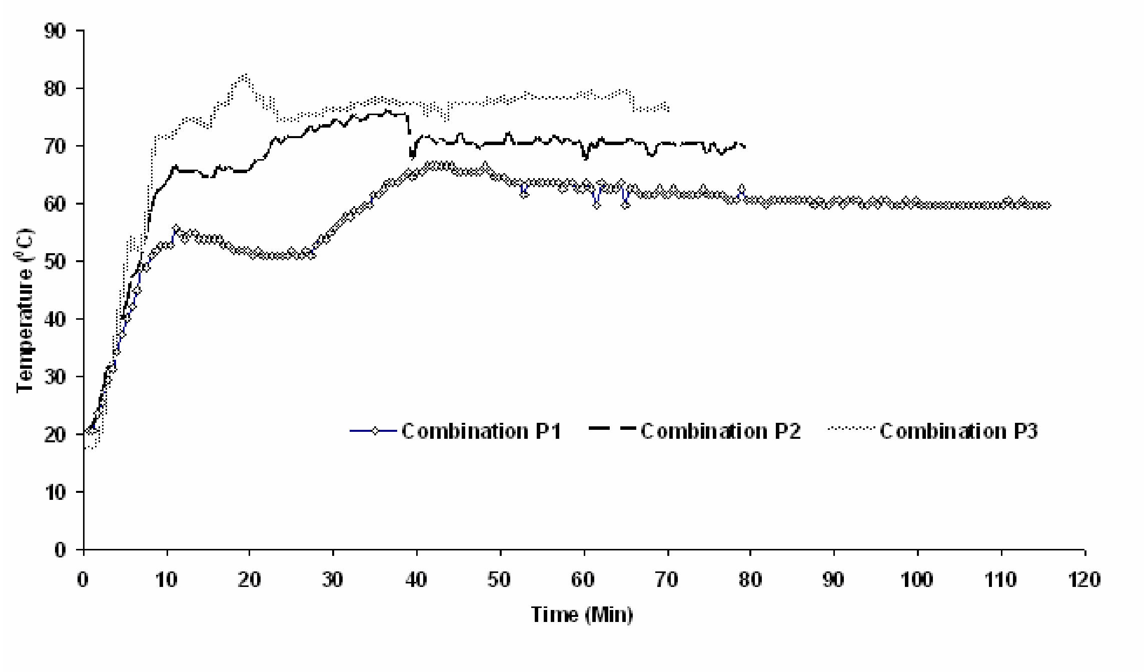

Figure 5.11 Drying temperature trends at combination P1, P2 and P3 levels (60, 70 and 80^oC respectively) and its effect on drying time.

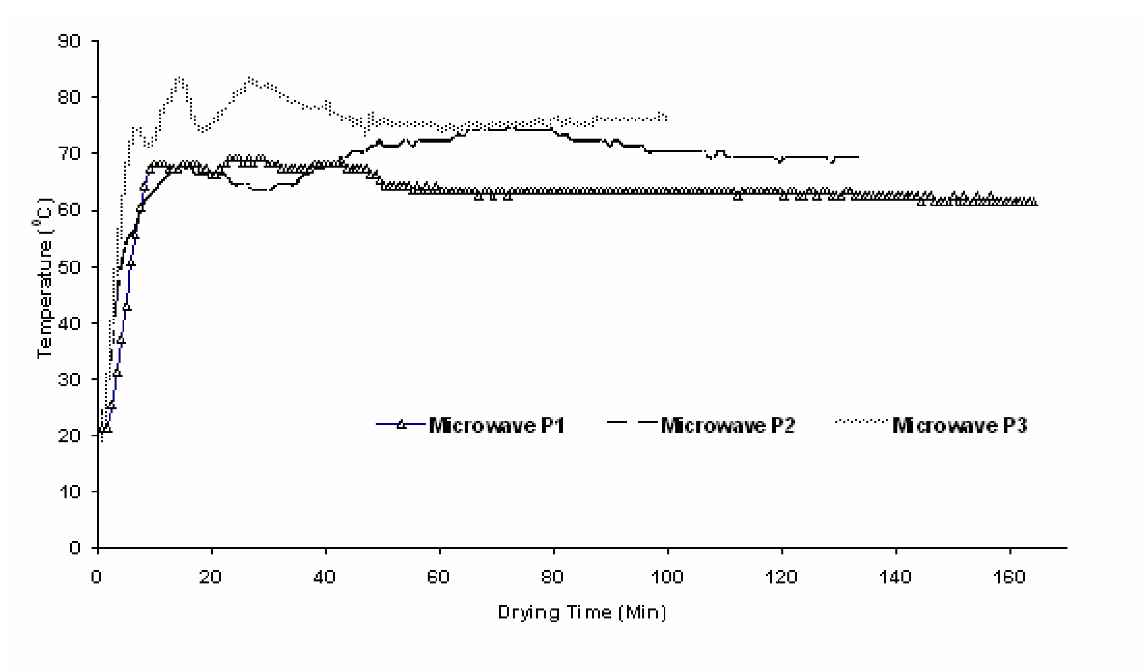

Figure 5.12 Drying temperature trends at microwave P1, P2 and P3 power levels (60, 70 and 80^oC respectively) and its effect on drying time.

Drying time varied from 26 to 200 min (Table 5.3) for the range of experimental parameters. The drying time, in general, decreased with the increase in microwave power level and further reduced the drying time during combination drying. The decrease in drying time being more with the increase in power level, in comparison to the increase in temperature indicating that the effect of microwave power level was more significant than temperature in reducing the drying time.

Table 5.3 Drying time and drying rate for untreated saskatoon berries

Microwave	**Mean Drying Time (min.)**	**Drying Rate (% MC/min.)**
Product temperature of 60^oC	165.67	0.31
Product temperature of 70^oC	58.33	0.87
Product temperature of 80^oC	44.33	1.15
Combination		
Product temperature of 60^oC	116.67	0.44
Product temperature of 70^oC	52.00	0.98
Product temperature of 80^oC	40.00	1.28
Convection		
Product temperature of 60^oC	192.33	0.27
Product temperature of 70^oC	138.33	0.37

5.3.1.1. Effect of Product-drying-temperature

Convection drying time of untreated berries at 60^oC product temperature was 192 min. to dry the berries from 76% to 25% moisture content and at product temperature of 70^oC the drying time reduced to 138 min. Microwave-combination drying reduced drying time by 1.64 and 2.65 times to that required for convection at the same product temperatures, respectively. This can be attributed to the heating effect of microwaves to accelerate the diffusion of moisture from the center of the product to the periphery and with surrounding hot-air conditions moisture removal from the surface was also enhanced. These results explain that the drying air heats the berry surface and minimizes the heat loss from the berry that is volumetrically heated by microwave energy. Therefore, the majority of the heat generated in berry by microwave energy could be used to heat and evaporate the water in the berry efficiently. This results in a better diffusion process contributing to an overall reduction in drying time and savings in energy.

As shown in Figure 5.11, in combination drying of untreated berries the drying time was reduced as the product drying temperature increased. The temperature trend in Figure 5.11 and Figure 5.12 shows that, the temperature rises in the first few minutes and then it tends to stabilize after the moisture content of the produce decreases. In the initial stages of drying, the moisture content is very high resulting in higher microwave absorption as expected and observed. During combination drying, because of the higher drying rates the temperature stabilizes faster than in microwave drying.

5.3.2. Effect of Drying Mode

The drying time was reduced by nearly 45% in combination drying compared to convection drying, for untreated and treated berries. Microwave drying also reduced the drying time considerably over convection drying in both the cases. The moisture content in the sample at different intervals was plotted against time (Figure 5.13 and Figure 5.14) as moisture curves for treated and untreated berries, respectively. The curves indicate the higher drying rate with microwave-only and combination drying over convection drying at any given time. The hot air drying method had a short constant rate period followed by a falling rate period. This was also reflected in the slight case hardening of the product. Microwave and combination drying had only a falling rate period in both cases. Combination drying had a higher falling rate indicating a higher rate of mass transfer, which resulted in a shorter drying time over hot-air and microwave drying. In general, the time required to reduce the moisture content to any given value was dependent on the drying conditions, being highest at microwave P1 (60°C) and lowest at combination P3 (80°C).

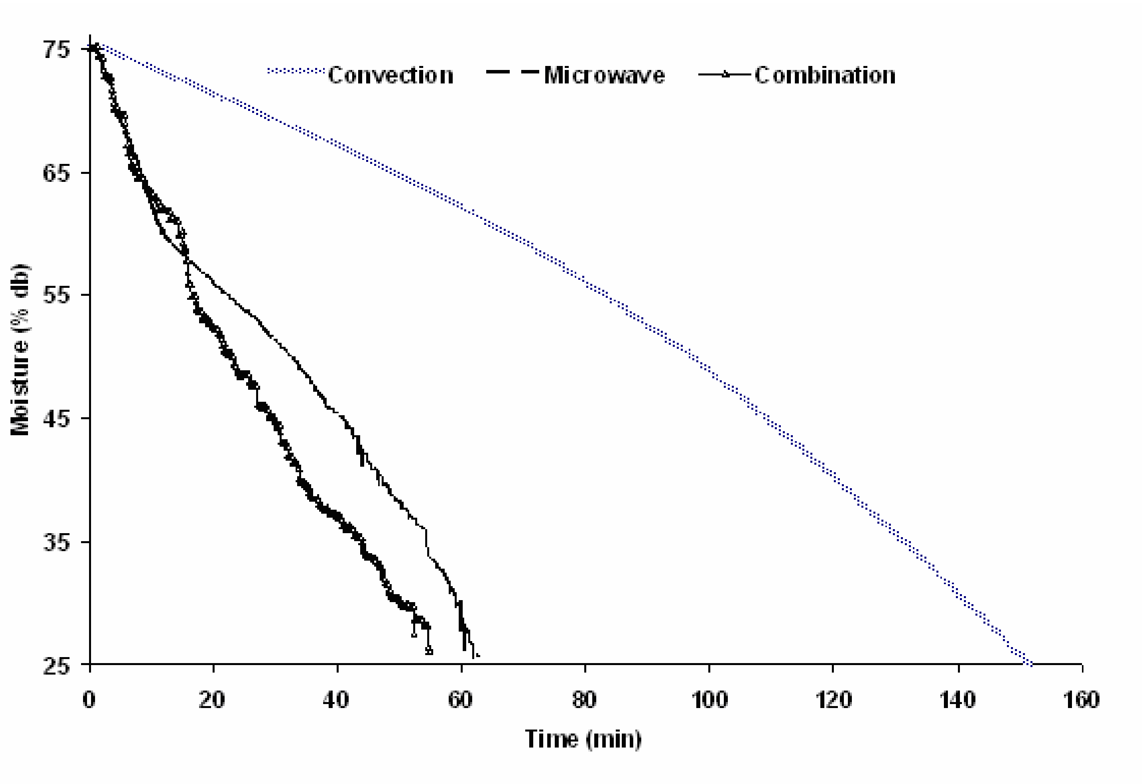

Figure 5.13 Drying of untreated berries at 70°C under microwave, convection and combination drying conditions.

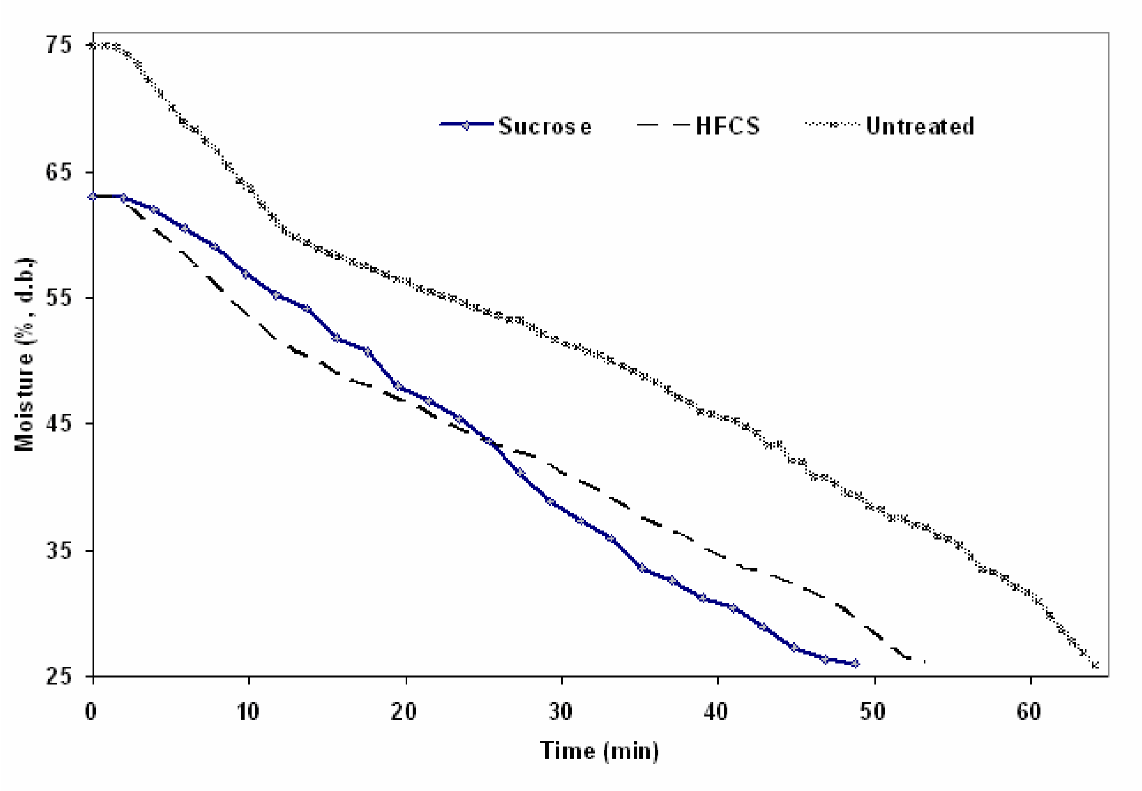

Figure 5.14 Microwave drying of osmotically treated and untreated berries at 70°C.

The drying rates for microwave and combination were higher in the beginning of the drying process and gradually reduced as the drying process progressed. The reason for this was because of more radiation being absorbed in the center, resulting in a faster moisture transfer compared to the diffusion rate from the outer surface. Also, this resulted in a moisture build-up towards the product surface during the initial period of the run. The drying rates increased with increase in microwave power, other conditions remaining the same and thus reducing the drying time.

5.3.3. Effect of Osmotic Dehydration on Drying

Osmotic dehydration as a pre-treatment for drying reduces moisture content by up to 17% which reduces the total drying time, as shown in Table 5.4, to dry the berries to 25% final moisture content.

Table 5.4 Drying time and drying rate for osmotic dehydration of saskatoon berries with sucrose (60% and 24h).

Microwave	**Mean Drying Time (min)**	**Drying Rate (% MC/min)**
Product temperature of 60°C	117	0.44
Product temperature of 70°C	52	0.99
Product temperature of 80°C	33	1.55
Combination		
Product temperature of 60°C	78	0.66
Product temperature of 70°C	37	1.38
Product temperature of 80°C	28	1.84
Convection		
Product temperature of 60°C	132	0.39
Product temperature of 70°C	88	0.58

The effect of osmotic dehydration using sucrose and high fructose corn syrup on the drying curves of saskatoon berries at 70°C under microwave conditions is shown in Figure 5.14. The average moisture content (db) is plotted versus time, t (min) for untreated and treated samples. No constant drying period was observed at any of the conditions studies. It can be observed that treatment with sucrose or high fructose corn syrup removed up to 10 or 19% of the initial moisture content for saskatoons that were soaked in 40, 50 and 60% brix solutions, respectively. There is a reduction of drying time for treated berries by 15-20% of that required for microwave drying of untreated berries. This can be attributed to solvent distribution within the material to cause uniform heating and also the osmotic dehydration itself reduced the moisture content of the initial sample.

Secondary motivations for applying combined osmotic and microwave dehydration as a pre-treatment were:

- Possibility to produce unique (new) products with better taste;
- Improved flavor characteristics and/or increased nutritional value;
- Prevention of oxidation of the product and color stabilization;
- Improvement of the texture of the product such as higher final bulk volume of the product compared to heated air dehydration or microwave dehydration without osmotic pre-treatment;
- Due to shrinkage and weight loss after drying, storage and transport costs are reduced drastically; and
- Dried saskatoon berries after osmotic dehydration have various industrial applications such as bakery foods, nutraceutical industry etc.

5.4. Modeling of Drying Process

Many researchers have adopted due to the consideration of simplicity and accuracy, empirical models for drying data. The simple type of drying model assumes that rate of exchange in moisture content is proportional to the difference between moisture content and Equilibrium Moisture Content (EMC) of the material. The moisture content data at different microwave, combination and convection temperature (power levels) were fitted against drying time, using the various models discussed in Chapter IV.

5.4.1. Evaluation of Thin-layer Drying Equation

Most of the researchers cited in the previous section adopted the fit standard error and the coefficient of determination, R^2 as the criteria to evaluate the goodness of fit of the drying equation. Recently, residual plots have been adopted to evaluate more thoroughly the adequacy of the drying models. If the model can explain the observed values, the residuals would randomly distributed due to possible measurement errors. If the fixed error exists in the predicted model, the residual plots will indicate a significant pattern.

5.4.2. Data Analysis

Five thin-layer drying models were selected to evaluate the best fit to the drying data. R^2 and standard error values for these equations are presented in Table 5.5; from these, the Midilli equation gave the best curve fit (R^2=0.99) for all convection (Figure 5.18) and microwave combination drying results whereas, the modified Page equation consistently gave the best fit (R^2=0.98) for microwave drying results as shown in Figure 5.17. In general, the modified Page equation, the Sharma equation and the Midilli equation fit the combination-drying data very well with good R^2 value as shown in Figure 5.15, Figure 5.16 and Figure 5.19.

Table 5.5 Coefficient of determination and standard error values for different equations.

	Modified Page Model		Sharma's Model		Midilli Model	
	R2	Std. Error (S.E)	R2	Std. Error	R2	Std. Error (S.E)
Microwave _P2	0.98	1.15	-	-	-	-
Microwave_P1 (Sucrose OD)	0.98	1.21	-	-	-	-
Microwave_P2 (Sucrose OD)	0.97	2.04	-	-	-	-
Microwave_P3 (Sucrose OD)	0.97	1.39	-	-	-	-
Combination_P1 (Sucrose OD)	-	-	0.99	0.50	0.99	0.18
Combination_P2 (Sucrose OD)	0.95	2.08	0.99	0.82	0.99	0.84
Combination_P3 (Sucrose OD)	0.97	1.67	0.99	0.24	0.99	0.13
Combination_P2	0.98	1.04	-	-	0.98	1.25
Convection_P2	0.99	0.73	-	-	0.98	2.22
Convection_P1 (Sucrose OD)	0.95	2.42	-	-	0.99	0.42

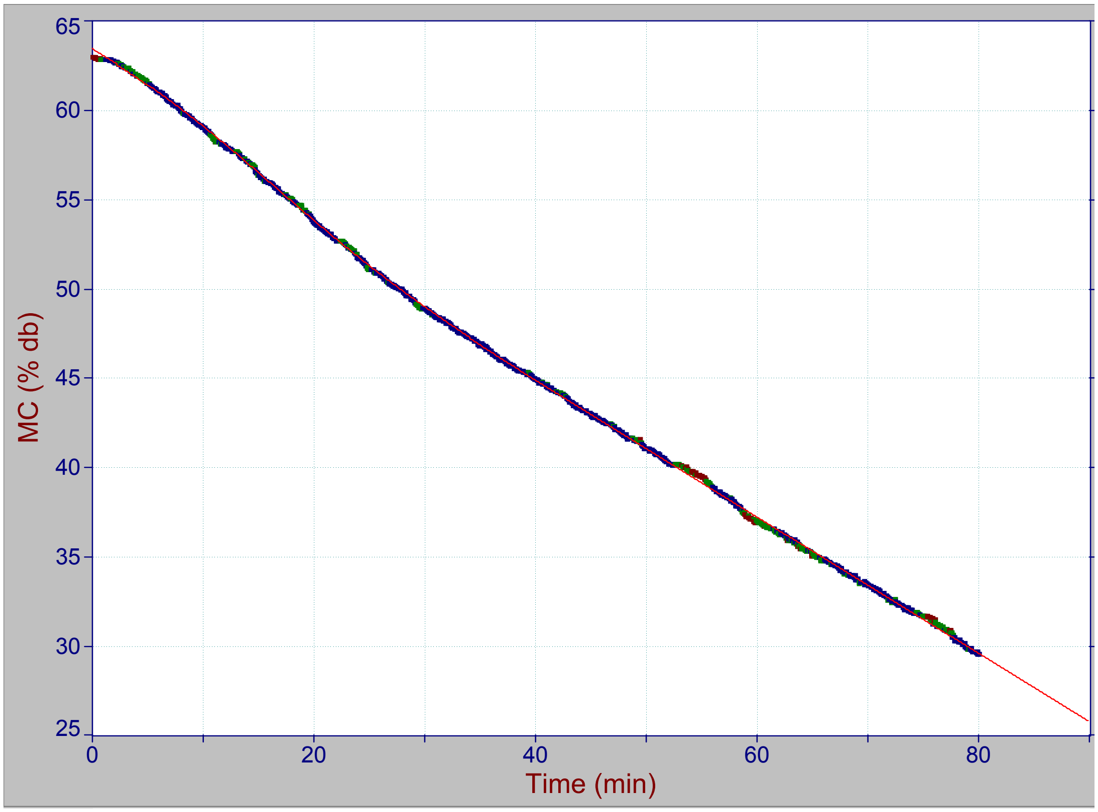

Figure 5.15 Midilli equation drying curve fit for sucrose osmotic dehydration combination drying at 60°C.

For combination drying data of saskatoon berries after osmotic dehydration, the Midilli equation fitted very well with R^2 of 0.999 standard error of 0.129.

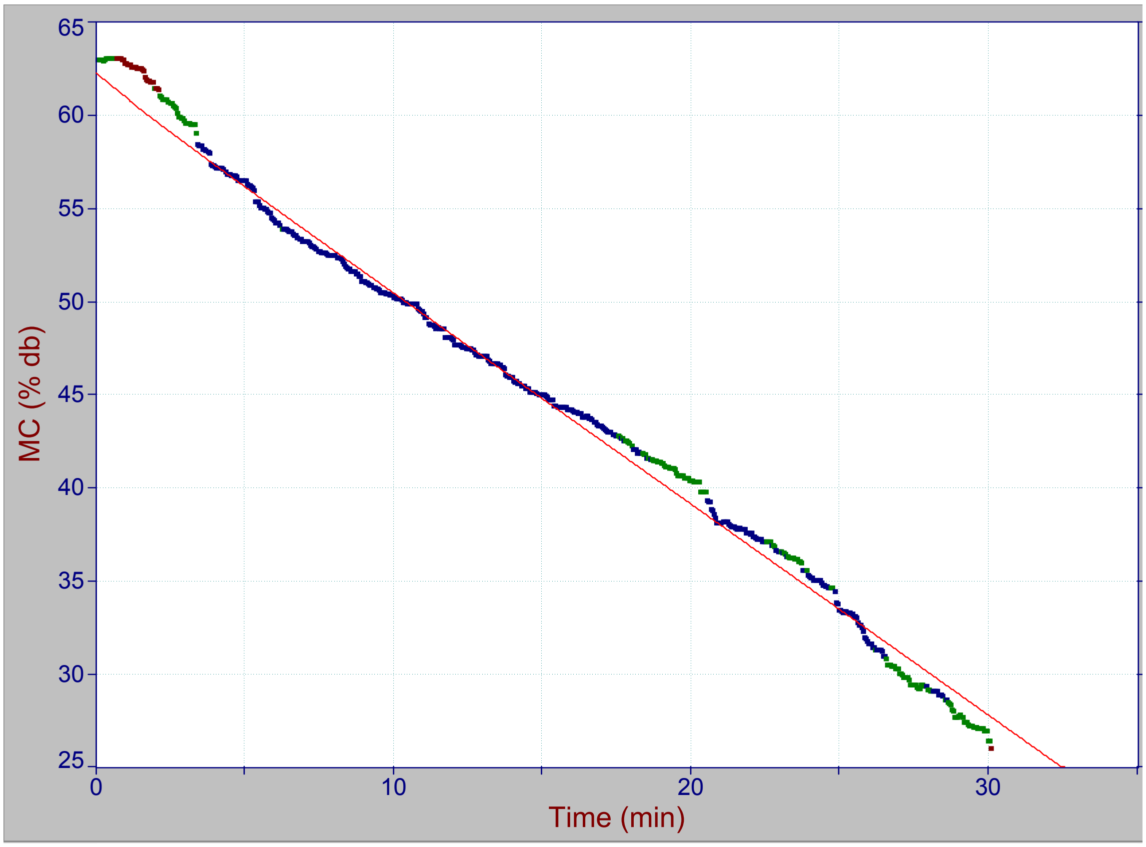

Figure 5. 16 Modified drying equation drying curve fit for sucrose combination drying at 80°C.

For combination drying data of saskatoon berries after osmotic dehydration, the modified drying equation fitted well with R^2 of 0.986 and standard error of 1.273.

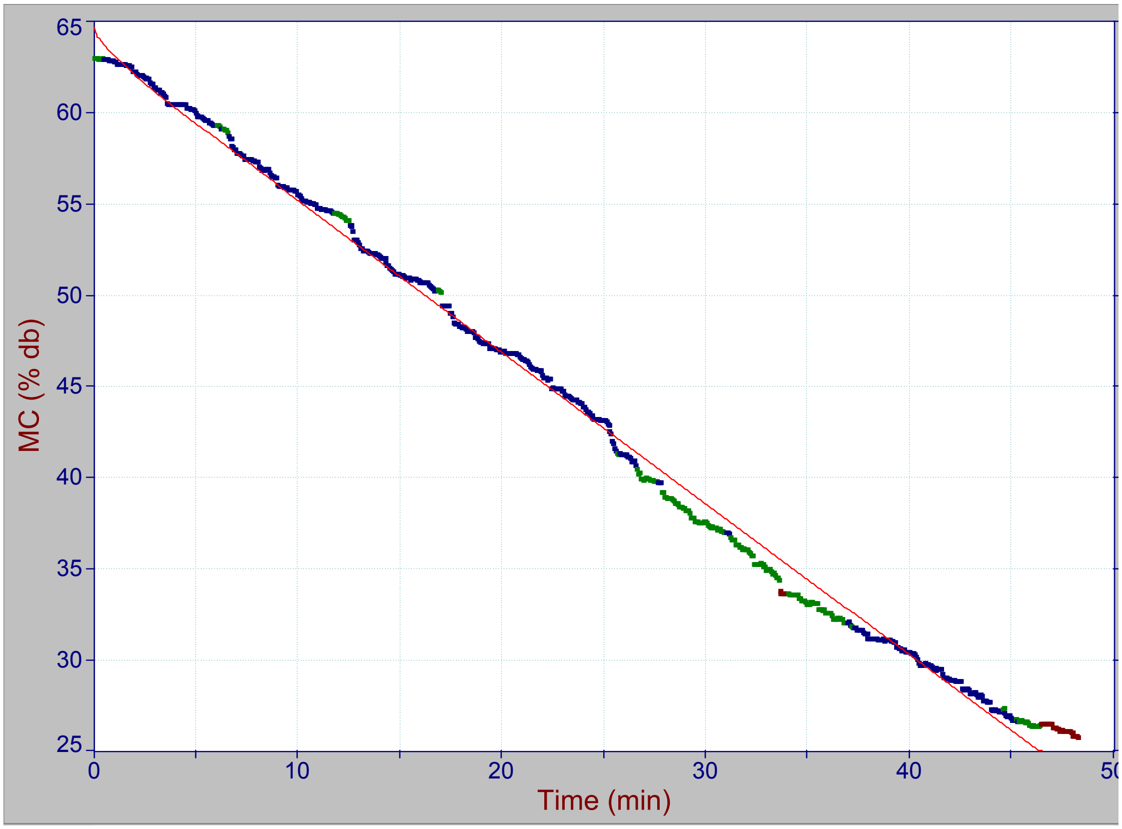

Figure 5.17 Midilli equation drying curve fit for sucrose osmotic dehydration microwave drying at 70°C.

For microwave drying data of saskatoon berries after osmotic dehydration, the Midilli drying equation fitted well with R^2 of 0.995 and standard error of 0.788.

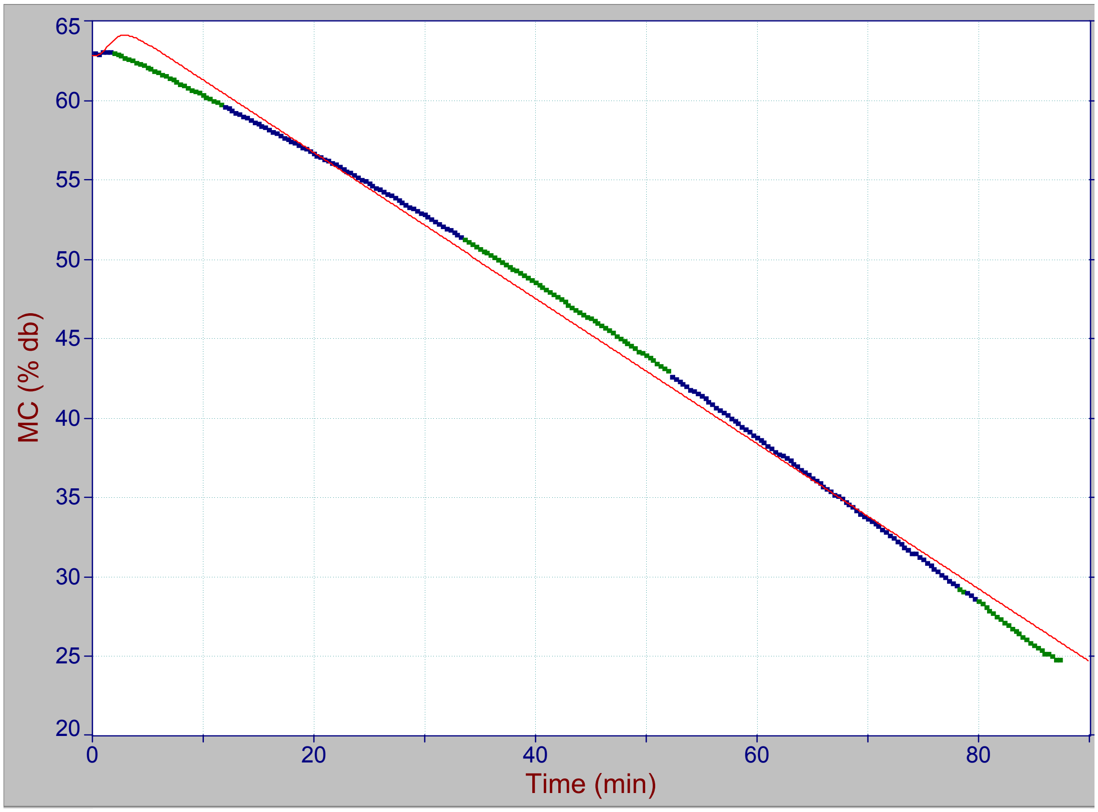

Figure 5.18 Midilli equation drying curve fit for sucrose osmotic dehydration convection drying at 70^{o}C .

For convection drying data of saskatoon berries after osmotic dehydration, the Midilli drying equation fitted well with R^2 of 0.995 and standard error of 0.782.

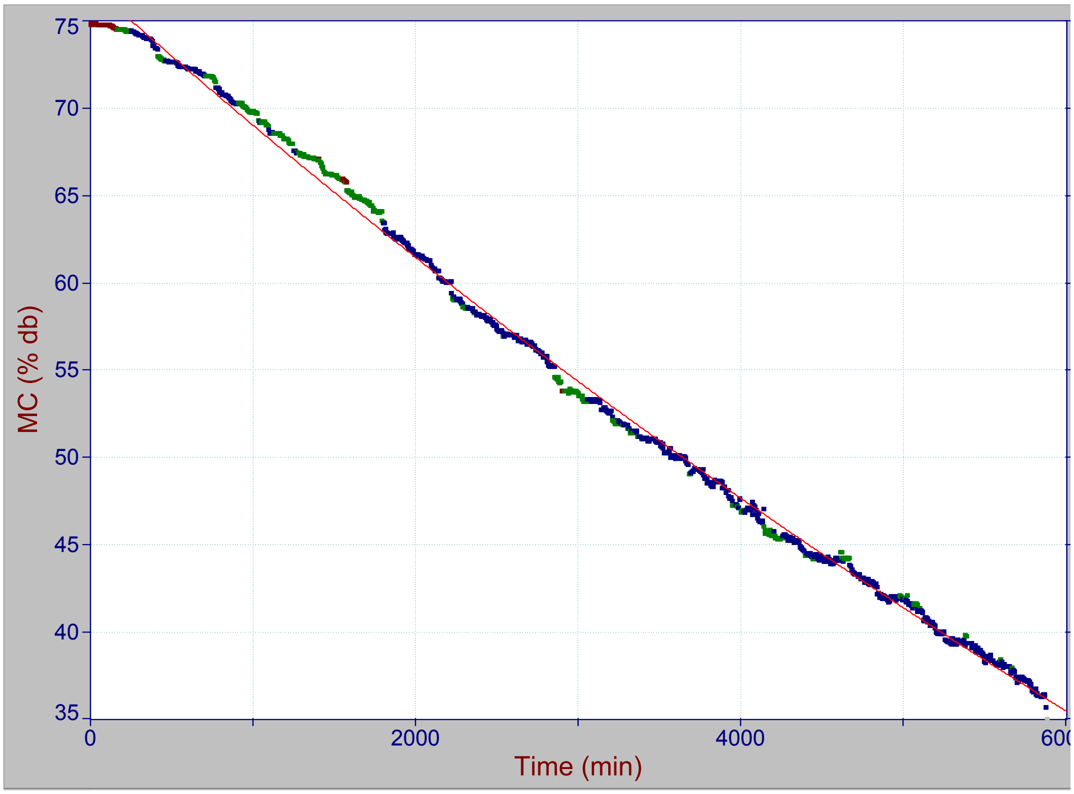

Figure 5.19 Sharma's equation drying model curve fit for combination drying method at 60°C.

For combination drying data of saskatoon berries, the Sharma equation fitted well with R^2 of 0.998 and standard error of 0.579.

5.4.3. Quality Analysis

Dehydrated saskatoon berries were analyzed for the quality changes that might have occurred due to all the different treatments. Re-hydration ratio and color changes were the two main quality parameters considered.

5.4.3.1 Rehydration Ratio

Changes in the original dimensions and shape occur simultaneously and water diffusion affects the rate of the moisture loss during drying. Researchers have pointed out that the volume change process is one of the main sources of error for drying simulation models of biological products. There is significant volume shrinkage during the drying process of high moisture content products such as vegetables (Hatamipour and Mowla, 2002).

Untreated saskatoon berries dried under microwave at 60^{o}C had a rehydration ratio 0.24 that reduced with increasing the product temperature to 70^{o}C and 80^{o}C (Table 5.6).

Table 5.6 Rehydration ratios of sucrose osmotic dehydrated berries at different drying conditions

	Treatments	**Rehydration Ratio**
1	**Microwave dried**	
	At product temperature of 60^{o}C	0.42
	At product temperature of 70^{o}C	0.40
	At product temperature of 80^{o}C	0.39
2	**Combination dried**	
	At product temperature of 60^{o}C	0.43
	At product temperature of 70^{o}C	0.40
	At product temperature of 80^{o}C	0.40
3	**Convection dried**	
	At product temperature of 60^{o}C	0.43
	At product temperature of 70^{o}C	0.43
	At product temperature of 80^{o}C	0.42

In general, the rehydration ratio decreased with increase in product temperatures during drying. As Potter and Hotchkiss (1995) reported, increasing the temperature caused distortion of cells and capillaries in plant tissue, which may lead to textural changes, thus lowering the water absorption and adsorption characteristics and affecting rehydration ability and rehydration ratio. Osmotic dehydration with sucrose and high fructose corn syrup increases the rehydration ratio by around twice that of untreated berries. Osmotic dehydrated berries with high fructose corn syrup solution had significantly ($P<0.05$) higher rehydration ratio when compared to sucrose solution. The drying method did not have a significant effect on the rehydration ratio (Table 5.7).

Table 5.7 Rehydration ratio of microwave-dried berries with and without osmotic dehydration.

	Treatments	Rehydration Ratio
1	**Untreated**	
	At product temperature of 60^oC	0.24
	At product temperature of 70^oC	0.22
	At product temperature of 80^oC	0.21
2	**Osmotic dehydration with Sucrose**	
	At product temperature of 60^oC	0.42
	At product temperature of 70^oC	0.40
	At product temperature of 80^oC	0.39
3	**Osmotic dehydration with HFCS**	
	At product temperature of 60^oC	0.47
	At product temperature of 70^oC	0.47
	At product temperature of 80^oC	0.46

5.4.3.2 Color Analysis

HunterLab colorimeter values of dried saskatoon berries are shown in Table 5.8. The Hunter 'L' measures lightness and varies from 100 for perfect white to zero for black, approximately as the eye would evaluate it. Hunter 'a' measures redness when positive and greenness when negative and 'b' measures yellowness when positive and blueness when negative. The Hunter 'L', 'a', 'b' values for saskatoon berries decreased with the increase in drying temperature during all drying modes. The total color difference was minimal for convection drying, but for microwave and combination drying, the values were around 4 to 5.

Table 5.8 Hunterlab colorimeter parameters of untreated and sucrose pretreated berries under microwave, convection and combination drying conditions

Sample	ΔL	Δa	Δb	ΔEab
Untreated				
Microwave P1	-0.96	-1.41	0.67	1.83
Convection P2	-1.21	-1.38	0.01	1.84
Convection P3	-2.46	-2.23	-0.84	3.42
Sucrose Pretreated				
Microwave P2	-1.92	-2.00	-0.65	2.85
Microwave P3	-3.86	-3.29	-1.72	5.36
Convection P1	-0.62	-2.20	-0.46	2.34
Convection P2	-2.52	-1.56	-0.88	3.09
Combination P2	-2.29	-2.37	-0.83	3.40
Combination P3	-3.32	2.79	0.11	4.34

Table 5.8 revealed that the greatest color difference with all treatments was obtained at the highest power level. The greater heating resulted in faster darkening, with some possibility of occurrence of imperceptible burnt spots.

Microwave dried berries at 60^oC product temperature gave least total color difference of 1.83.

5.5 Summary

The laboratory scale microwave combination dryer was successfully developed for drying of saskatoon berries under both microwave and microwave combination conditions. Microwave combination drying resulted in lowered drying time and also with increase in microwave power levels, drying time was reduced significantly. Osmotic dehydration as a pretreatment to drying reduced up to 15% moisture from the berries and also introduced solutes.

VI. CONCLUSIONS

Production of saskatoon berries as a commercial crop has gained importance in North America and is being exported to other countries for consumption and processing because of its unique sensory characteristics, nutraceutical value and consumer acceptance. This also calls for new post-harvest techniques for shelf life extension and further value-added processing in the manufacture of new saskatoon berry based products. Freezing is the only post-harvest technique reported to date to preserve the berries for year-long consumption. Therefore, microwave and microwave combination drying technique following the osmotic dehydration step, were explored in this study as a post-harvest preservation technique for saskatoon berries.

i. The microwave-convection combination dryer system was developed and successfully tested. The temperature and moisture loss data acquisition systems had minimal problems to record real-time drying data.

ii. The developed drying system with the modified settings can be used for drying / dehydration studies of other agricultural / food materials (e.g. blueberries, beef etc.).

iii. The data obtained from drying of untreated and treated saskatoon berries showed that microwave and microwave combination drying proves to be a faster way of bringing moisture content to safer levels and also preserve the product quality.

iv. The reported drying characteristics of saskatoon berries dried under microwave, microwave-convection conditions were reasonable in comparison to the reported literature, on similar fruit types.

v. Microwave drying of saskatoon berries at product temperatures of 60^{o}C and 70^{o}C after osmotic dehydration retained their quality attributes in the same range, but drying time at 70^{o}C was about 50% less than at 60^{o}C drying time.

vi. Osmotic dehydration of saskatoon berries with high fructose corn syrup sugar solution had 3% less moisture after 24 h period compared to sucrose sugar solution treatment and this difference was significant.

vii. Drying after osmotic dehydration reduced the drying time in all drying conditions studied because of the structural changes that may have occurred at the surface (semi-permeable membrane) giving rise to higher diffusion rates.

viii. Microwave drying had relatively higher drying rates than convection and this was due to the higher dielectric loss factor value in osmotic dehydrated berries that favored microwave absorption.

ix. Microwave combination drying was able to reduce the drying time by up to 20% than microwave-only.

x. LabView programs were developed for real-time temperature and weight-loss measurement and data acquisition.

6.1. Recommendations for Future Work

i. Drying studies with fresh saskatoon berries during the harvesting season can add more value to this research in developing a new post harvest technique for saskatoon berries,

ii. Drying characteristics study at very low microwave power levels and to compare the quality characteristics of the final product is suggested,

iii. Control of microwave power to the lowest possible level with a variable rheostat and solid-state relay circuit and the temperature data can be acquired from Fiso signal conditioner. Installation of a filament transformer to the magnetron circuit to keep the filament to continuously run is a prerequisite,

iv. Sample holder rotation system on the horizontal axis with 180^o turn on either side could improve the microwave distribution with in the material and more even drying of the berries, and

v. Modeling of drying data and heat and mass transfer simulation using FEM-Lab or advanced simulation software is also suggested.

REFERENCES

Adapa, P.K., S. Sokhansanj and G.J. Schoenau. 2002. Performance study of re-circulation cabinet dryer using a household dehumidifier. *Drying Technology* 22(8): 1673-1689.

Albert, H, B and G. J. Liebermann. 1972. *Engineering Statistics,* 2nd edition. Englewood Cliffs, NJ: Prentice Hall Publishers.

AOAC Standard. 1990. 930.04 - Moisture content in plants. In *Official Methods of Analysis,* 2nd edition, 69-81. Arlington, VA: Association of Official Analytical Chemists Inc.

Argaiz, A., A. L. Malo, E. Palou and J. Welti. 1994. Osmotic dehydration of papaya with corn syrup solids. *Drying Technology* 12(7): 1709-1725.

Beaudry, C. 2001. Evaluation of drying methods on osmotically dehydrated cranberries. Unpublished M.Sc. thesis. Montreal, QC: Department of Agricultural and Biosystems Engineering, McGill University.

Bouraout, M., P. Richard and T. Durance. 1994. Microwave and convective drying of potato slices. *Journal of Food Process Engineering* 17: 353-363.

Buffler, C. R. 1993. *Microwave Cooking and Processing: Engineering Fundamentals for the Food Scientist.* New York, NY: Van Nostrand Reinhold Publishers.

Engelder, D. S. and C. R. Buffler. 1991. Measuring dielectric properties of food products at microwave frequencies. *Microwave World* 12(4): 6–15.

Funebo, T. And T. Ohlsson. 1998. Microwave-assisted air dehydration of apple and mushroom. *Journal of Food Engineering* 38 : 353-367.

Funebo, T. and T. Ohlsson. 1999. Dielectric properties of fruits and vegetables as a function of temperature and moisture content. *Journal of Microwave Power and Electromagnetic Energy* 34(1): 42-54.

Grabowski, S. and A.S. Mujumdar. 1992. Solar-assisted osmotic dehydration. In: *Drying of Solids*, ed. A.S. Mujumdar, 367-404. New York, NY: International Science Publisher.

Grabowski, S., A.S. Mujumdar, H.S. Ramaswamy, and C. Strumillo. 1994. Osmo-convective drying of grapes. *Drying Technology* 12(5): 1211-1219.

Green, R.C. and G. Mazza. 1986. Relationships between anthocyanins, total phenolics, carbohydrates, acidity and color of saskatoon berries. *Canadian Institute of Food Science and Technology* 19:107-113.

Hatamipour, M. S. and D. Mowla. 2002. Shrinkage of carrots during drying in an inert medium fluidized bed. *Journal of Food Engineering* 55(3): 247-252.

Huxsoll, C. C. 1982. Reducing the refrigeration load by partial concentration of food prior to freezing. *Food Technology* 5: 98-102.

Kostaropoulos, A.E. and G.D. Saravacos. 1995. Microwave pretreatment of sun-dried raisins. *Journal of Food Science* 60: 344-347.

Khraisheh, M. A., T. J. R. Cooper and T. R. A Magee. 1997. Microwave and air drying I. Fundemental considerations and assumptions for the simplified thermal calculations of volumetric power absorptions. *Journal of Food Engineering* 33: 207-219.

Lenart, A. P. and P. Lewicki. 1990. Osmotic dehydration of apples at high temperature. In *International Drying Symposium' 89*, eds. A. S. Mujumdar and M. Roques, 665-681. New York, NY: Hemisphere Publishing Co.

Lewicki, P. and A. Lenart. 1990. Energy consumption during osmo-convection drying of fruits and vegetables. In: *Drying of Solids*, ed. A.S. Mujumdar, 354-366. New York, NY: International Science Publisher.

Mantius, H. L. and P. R. Peterson. 1995. Fruit extraction and infusion. USA-Patent No. 5419251: 320 861.

Maskan, M. 2000. Microwave/air and microwave finish drying of banana. *Journal of Food Engineering* 44: 71-78.

Masi, P. and M. Riva. 1988. Modeling grape drying kinetics. In *Preconcentration and Drying of Food Materials,* ed. S. Bruin, 203-214. Amsterdam, The Netherlands: Elsevier Science.

Mudgett, R.E., E. C. To and D.I. Wang. 1974. Dielectric Properties of food materials. *Journal of Microwave Power* 9: 303–315.

Mazza, G. 1979. Development and consumer evaluation of a native fruit product. *Canadian Institute of Food Science and Technology* 12(4):166-169.

Mazza, G. 1982. Chemical composition of saskatoon berries (*Amelanchier alnifolia* Nutt.). *Journal of Food Science* 47:1730-1731.

Mazza, G. and M.W. Hodgins. 1985. Benzaldehyde, a major aroma component of saskatoon berries. *Horticultural Science* 20:742-744.

Mazza, G. 1986. Anthocyanins and other phenolic compounds of saskatoon berries (*Amelanchier alnifolia* Nutt.). *Journal of Food Science* 51: 1260-1264.

Mazza, G. and C.G. Davidson. 1993. Saskatoon berry: A fruit crop for the prairies. In *New Crops*, eds. J. Janick and J.E. Simon, 516-519. New York, NY: Wiley Publishers.

Mudgett R E. 1986. Electrical properties of foods. In *Engineering Properties of Foods,* eds. M.A. Rao and S. S. H. Rizvi, 389-457. New York, NY: Marcel Dekker, Inc.

Mujumdar, A. S. 1995. Convective transport in infrared drying. In *Drying'92,* ed. A. S. Mujumdar, 695–703. Amsterdam, The Netherlands: Elsevier Science.

Nelson, S. O. 1973. Electrical properties of agricultural products - a critical review. *Transactions of ASAE* 16: 384–400

Ponting, J. D. and D. M. McBean. 1970. Temperature and dipping treatment effects on drying rates and drying times of grapes, prunes and other waxy fruits. *Food Technology* 4: 633-649.

Potter, N.N. and J.H. Hothchkiss. 1995. *Food Science*, 5th edition. New York, NY: Chapman and Hall Publishers.

Prabhanjan, D.G., H.S. Ramaswamy and G.S.V. Raghavan. 1995. Microwave assisted convective air drying of thin layer carrots. *Journal of Food Engineering* 25: 283-293.

Raghavan, G.S.V., V. Orsat and M.S.Venkatesh. 2005. Microwave Processing of Foods. *Stewart Postharvest Review* 1(2): 1-8.

Ramaswamy, H.S. and F. Nsonzi. 1998. Convective air-drying kinetics of osmotically pre-treated blueberries. *Drying technology* 16(5): 743-759.

Ranganna, S. 1986. *Hand Book of Analyses of Quality Control for Fruits and Vegetables.* New Delhi, India: Tata McGraw Hill Publishing Co. Ltd.

Ratti, C. and A. S. Mujumdar. 1995. Infrared drying. In *Handbook of Industrial Drying,* ed. A. S. Mujumdar, 567–588. New York, NY: Mercel Dekker Inc.

Reddy, L. N., V. Meda and M.D. Pickard. 2004. Combined convection, microwave and infrared processing of agricultural materials. ASAE Paper No. 046100. St Joseph, MI: American Society of Agricultural Engineers.

Reddy, L. N., V. Meda and B. Shrestha. 2005. Dielectric properties of saskatoon berries (Amelanchiar alnifolia) at different pretreatment and osmotic conditions. Paper No. MB04-110. Winnipeg, MB: Canadian Society for Bioengineering.

Reddy, L. N. and V. Meda. 2005. Osmotic dehydration and combination drying technique for prairie fruits. *In Proceedings of International Microwave Power Institute*, 71-74, Seattle, WA. July 13-15.

Reach and Discover. 2005. Agricultural Research and Innovation in Alberta. Issue 4 Spring. http://www.fundingconsortium.ca/rdmag/rd05s_00.pdf (2008/01/14)

Risman, P.O. 1991. Terminology and notation of microwave power and electromagnetic energy. *Journal of Microwave Power and Electromagnetic Energy* 26: 243 – 250.

Sharma, G. P., R. C. Verma and P. Pathare. 2005. Thin-layer infrared radiation drying of onion slices. *Journal of Food Engineering* 67: 361-366.

Somogyi, L,P. and B.S. Luh. 1986. Dehydration of foodstuffs. In *Commercial Fruit Processing,* 2nd Edition, eds. J.G. Woodroof and B.S. Luh, 353-405. Westport, CT: AVI Publishing Company.

Somogyi, L.P, H.S. Ramaswamy and Y.H. Hui. 1996. *Processing Fruits: Science and Technology – Biology, Principles and Applications,* 14-24. Boca Raton, FL: CRC Press.

Tulasidas, T.N., G.S.V. Raghavan and E.R. Norris. 1993. Microwave and convective drying of grapes. *Transactions of ASAE* 36(6): 1861-1865.

Turner, N.J., C. L.C. Thompson, M.T. Thompson and A.Z. York. 1990. *Thompson Ethnobotany,* 253-257. Victoria, BC: Royal British Columbia Museum.

Turner, N.J. 1997*. Food Plants of Interior First Peoples.* Vancouver, BC: UBC Press.

Van Arsdel, W. B., M. J. Copley, A. I. Morgan. 1973. *Food Dehydration*, 2nd edition. Westport, CT: AVI Publishing Co.

Venkatachalapathy, K. 1998. *Combined osmotic and microwave drying of strawberries and blueberries*. Ph. D. Thesis, Montreal, QC: Department of Agricultural and Biosystems Engineering, McGill University.

Venkatesh, M. S. 1996. M. Sc. Thesis: *Cavity perturbation technique for measurement of dielectric properties of some agri-food materials*. Published

M.Sc. thesis, Montreal, QC: Department of Agricultural and Biosystems Engineering, McGill University.

Venkatesh, M. S., E. St-Denis, G. S. V. Raghavan, P. Alvo and C. Akyel 1998. Dielectric properties of whole, chopped and powdered grain at various bulk densities. *Journal of Canadian Agriculture Engineering* 40 (3): 191-200.

Venkatesh, M.S. and Raghavan, G.S.V. 2005. An Overview of Dielectric Properties Measuring Techniques. *Canadian Biosystems Engineering* 47: 715-730.

Yang, C.S.T. and W.A. Atallah. 1985. Effect of four drying methods on the quality of intermediate moisture lowbush blueberries. *Journal of Food Science* 50: 1233-1237.

Yang, A.P.P., C. Wills and C.S.T. Yang. 1987. Use of combination process of osmotic dehydration and freeze drying to produce a raisin type low bush blueberry product. *Journal of Food Science* 52: 1651-1653.

Statistics Canada. 2004. Industry Profile (Canada's Food Processing Industry) http://www.statcan.ca/english/freepub/15-515-XIE/2004001/index.htm (2008/01/14).

Statistics Saskatchewan. 2005. Processing, Fruit Overview http://www.agriculture.gov.sk.ca/Fruit_Overview (2008/01/14).

Canada Foreign Affairs. 2005. Canada's International Market Access Priorities 2005. http://www.dfait-maeci.gc.ca/tna-nac/2005/7_05-en.asp (2007/12/15).

Saskatchewan Agriculture. 2005. Fruit and Vegetable Production Statistics. http://www.agr.gov.sk.ca/docs/statistics/crops/horticulture/fruitveggies040226.pdf (2007/12/15).

Devonian Botanic Garden. http://www.devonian.ualberta.ca/natvgrdn.html (2008/01/14).

Prairie Plant System Inc. 2007. Saskatoon Berries (Amelanchiar alnifolia Nutt.) http://www.prairieplant.com/saskatoon-berries.htm (2008/01/14)

Saskatchewan Chamber of Commerce. 2005. Intensification comes in a Variety of Forms. http://www.saskchamber.com/documents/259Action_Saskatchewan_Special_Feature_11.pdf (2008/01/14).

Riverbend Plantation. 2005. http://www.saskatoonberry.com (2008/01/14).

APPENDIX

This section includes all the additional data for drying, dielectric properties, preliminary studies, scanning electron microscope images and also digital images of microwave dryer system with individual instrumentation. Temperature trends explained in Section 5.3.2 are presented at other drying conditions.

Appendix A1. Microwave Combination Drying at 60, 70 and 80^oC

Drying data (weight, g) for untreated and osmotically dehydrated berries at different product drying temperatures (60, 70 and 80^oC) under microwave-convection combination conditions with respect to time are shown in this part of the appendix.

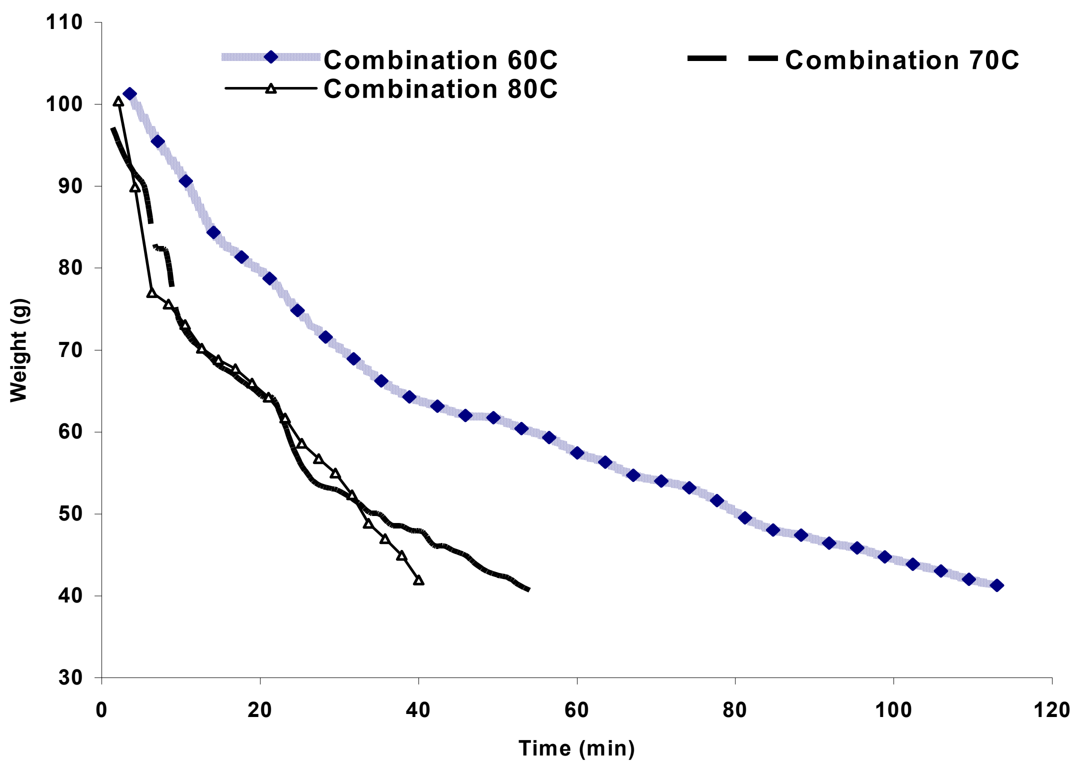

Figure A1 Microwave combination drying of untreated saskatoon berries at 60, 70 and 80^oC temperatures and corresponding weight loss plotted against time (min).

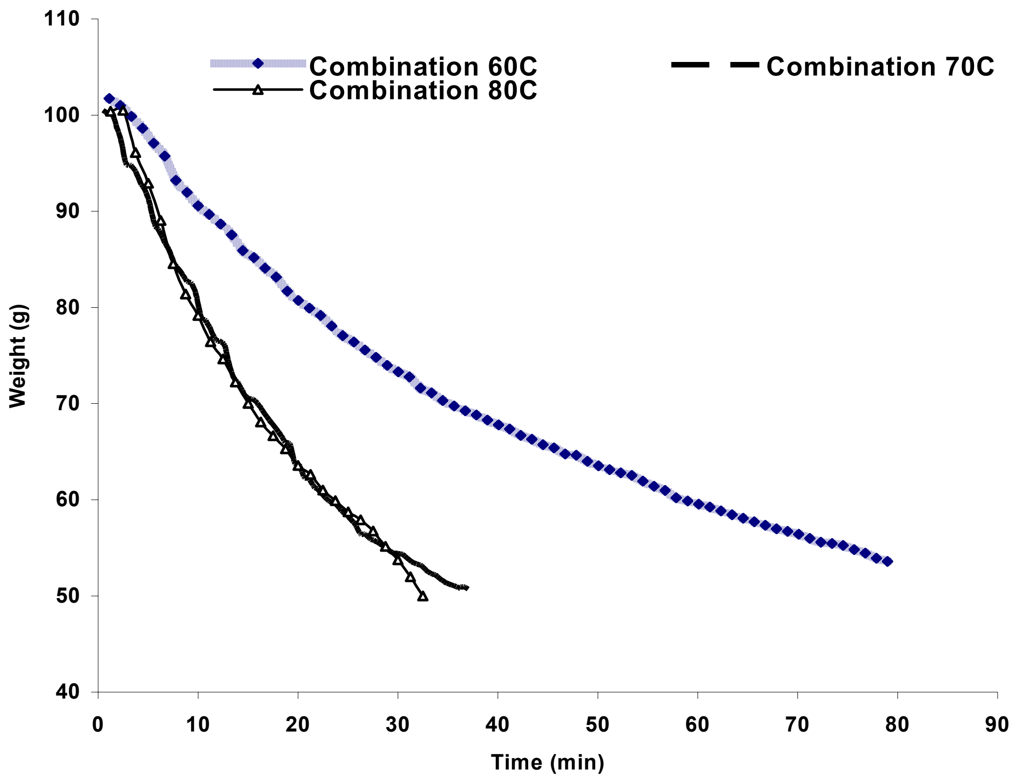

Figure A2 Microwave combination drying (weight, g) of sucrose osmotic dehydrated saskatoon berries at 60, 70 and 80^{o}C temperatures and corresponding weight loss plotted against time (min).

Appendix A2. Microwave drying at 60, 70 and 80°C

Drying data (weight, g) for untreated and osmotically dehydrated berries at different product drying temperatures (60, 70 and 80°C) under microwave conditions with respect to time are shown in this part of the appendix.

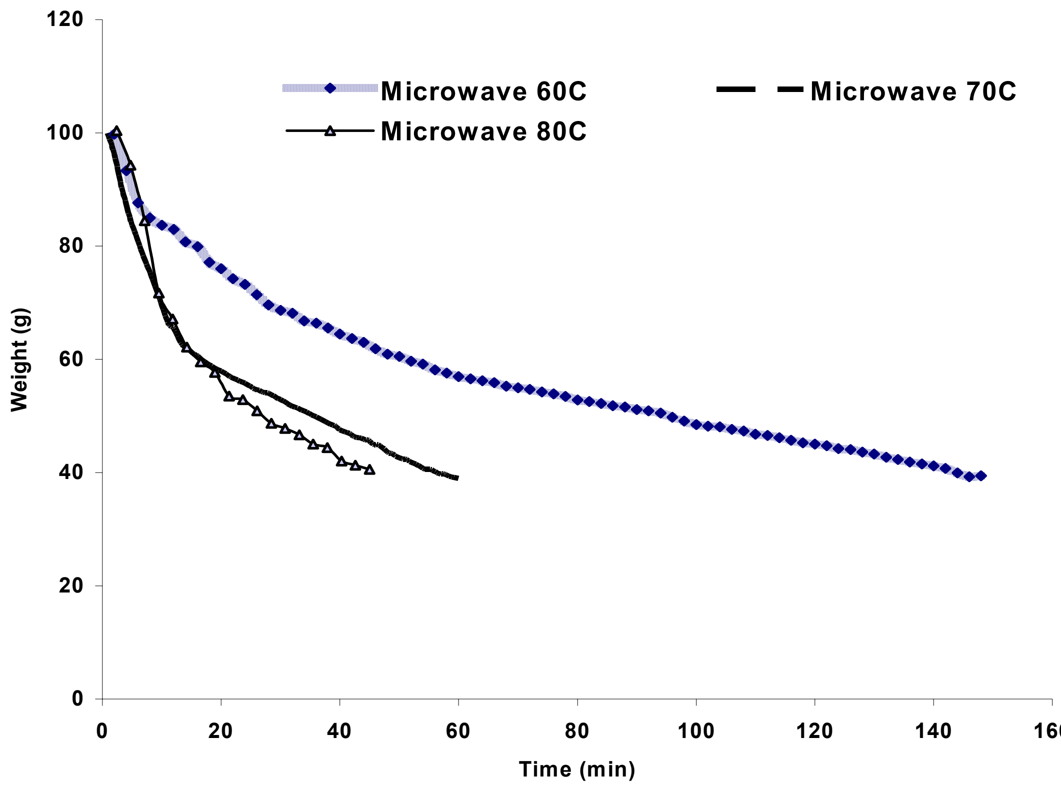

Figure A3 Microwave drying (weight, g) of untreated saskatoon berries at 60, 70 and 80°C temperatures and corresponding moisture loss plotted against time (min).

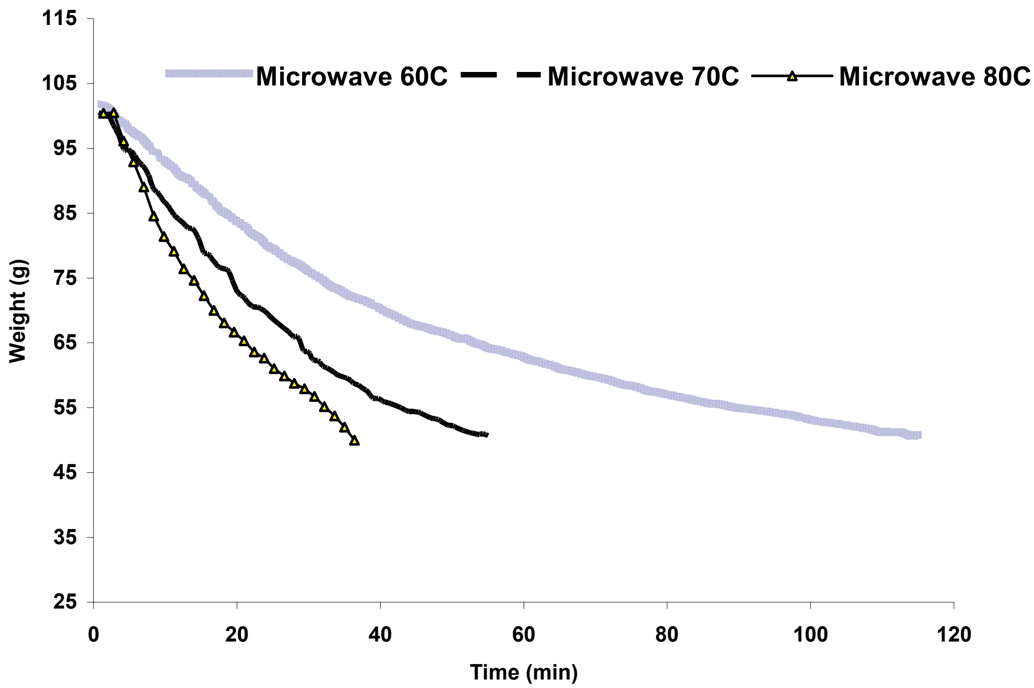

Figure A4 Microwave drying (weight, g) of sucrose osmotic dehydrated saskatoon berries at 60, 70 and 80^oC temperatures.

Appendix A3. Convection drying at 60, 70 and 80°C

Drying data (weight, g) for untreated and osmotically dehydrated berries at different product drying temperatures (60, 70 and 80°C) under convection conditions with respect to time are shown in this part of the appendix.

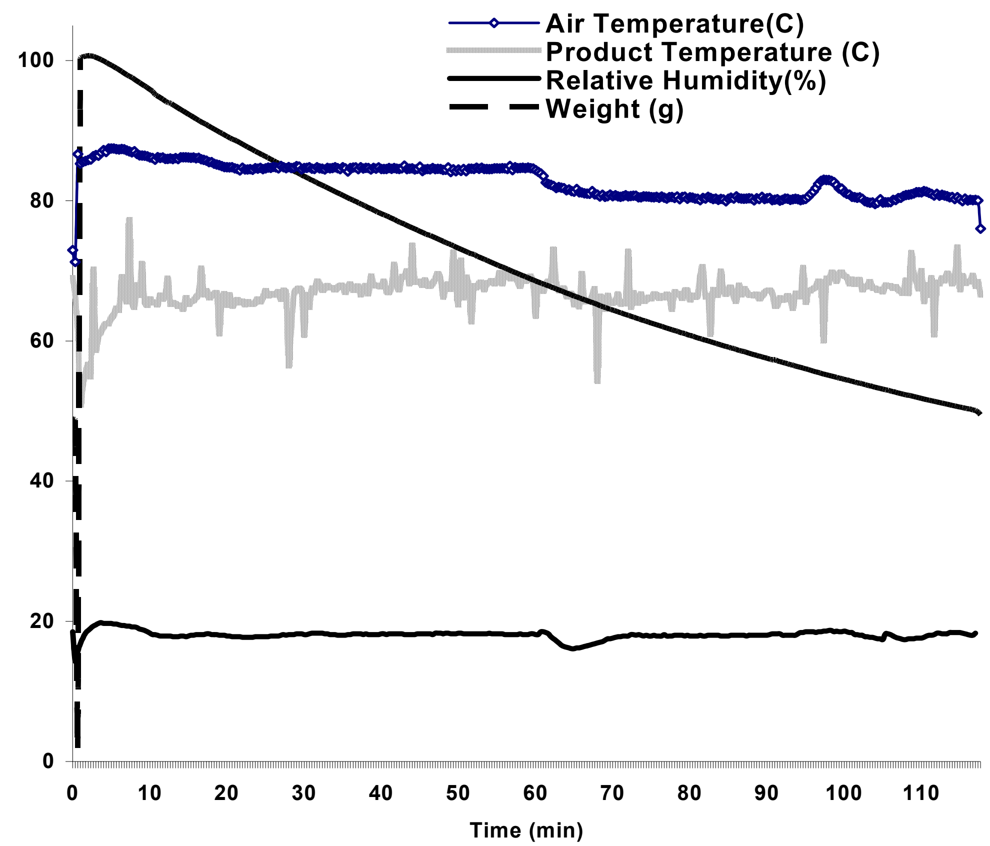

Figure A5 Convection drying (weight, g) of sucrose osmotic dehydrated saskatoon berries at 60°C temperature.

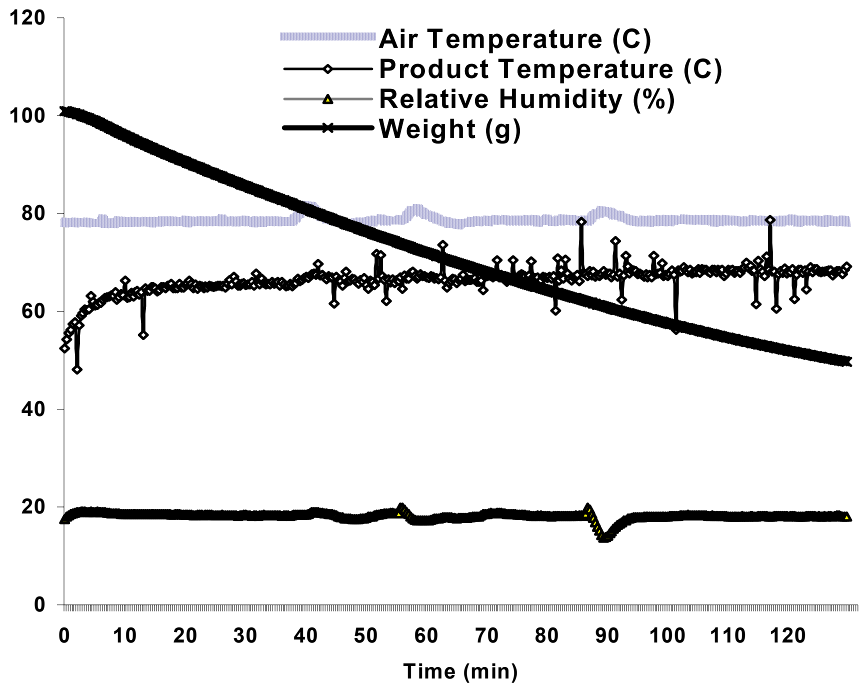

Figure A6 Convection drying (weight, g) of high fructose corn syrup osmotic dehydrated saskatoon berries at 60^{o}C temperature.

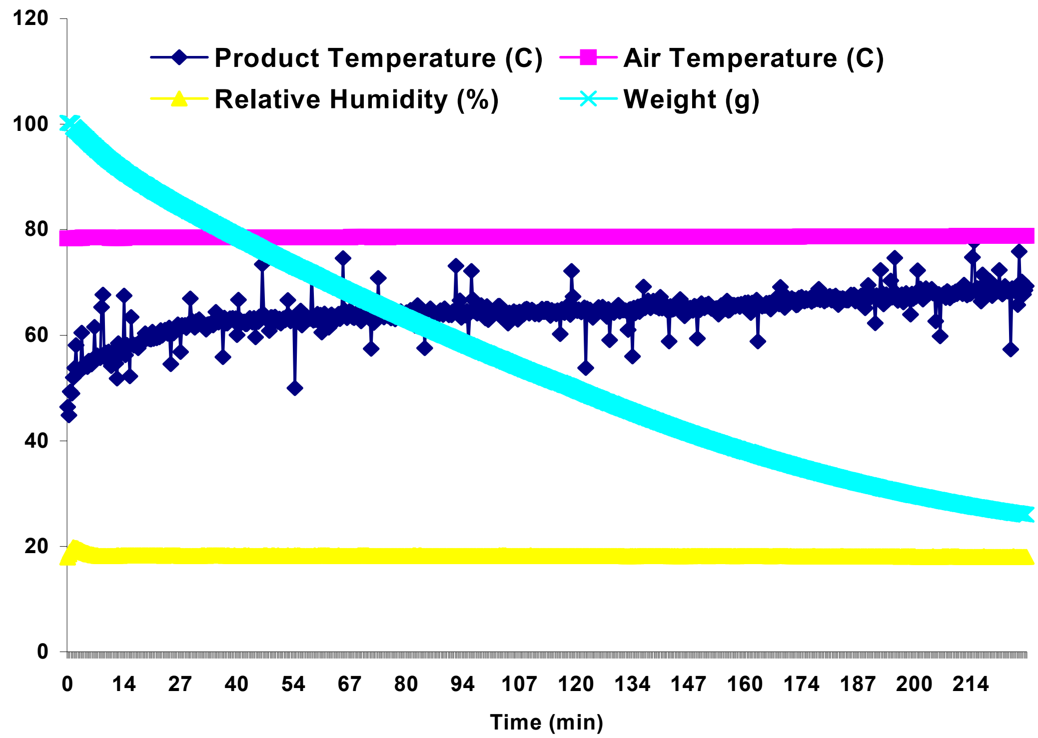

Figure A7 Convection drying (weight, g) of untreated saskatoon berries at 60°C temperature.

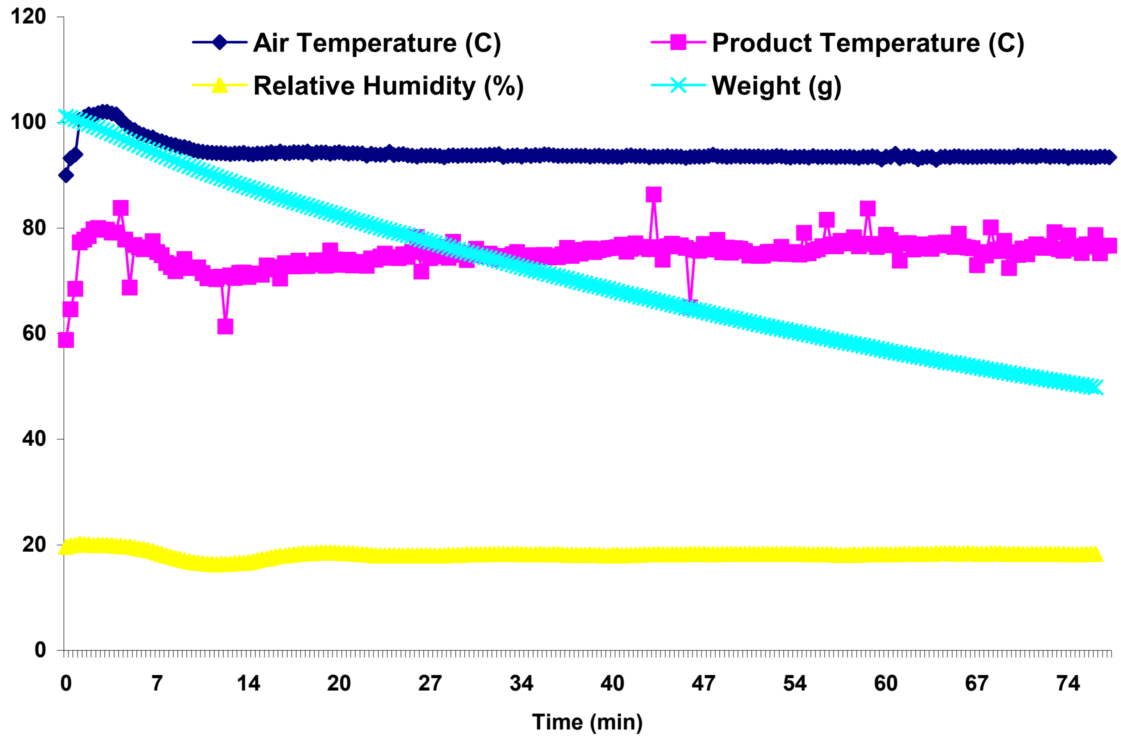

Figure A8 Convection drying (weight, g) of sucrose osmotic dehydrated saskatoon berries at 70^{o}C temperature.

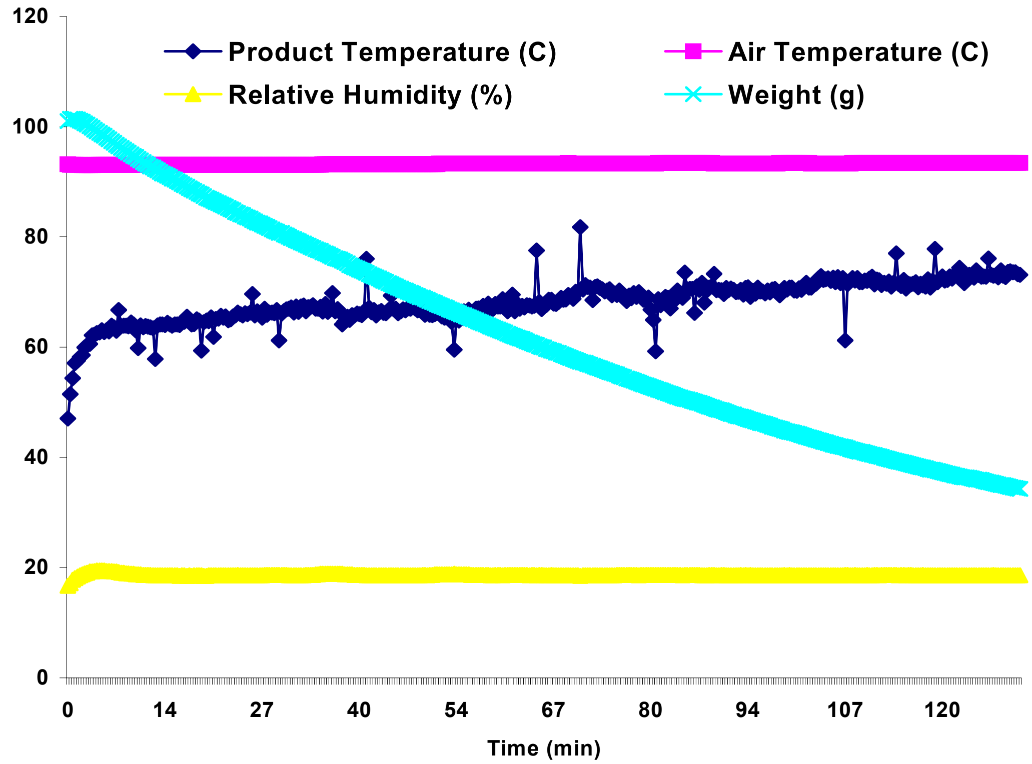

Figure A9 Convection drying (weight, g) of untreated saskatoon berries at 70^{o}C temperature.

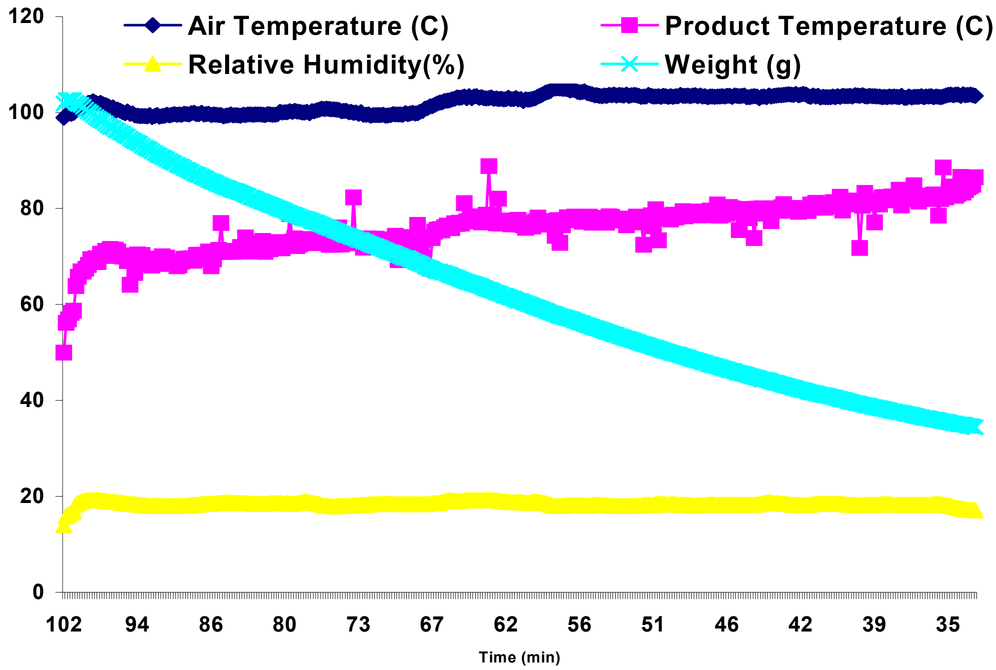

Figure A10 Convection drying (weight, g) of untreated saskatoon berries at 80^{o}C temperature.

Appendix A4. Temperature trends during microwave drying at 60°C.

Temperature variation at microwave power level P1 (refer Table 4.1) with time at different locations of the sample holder.

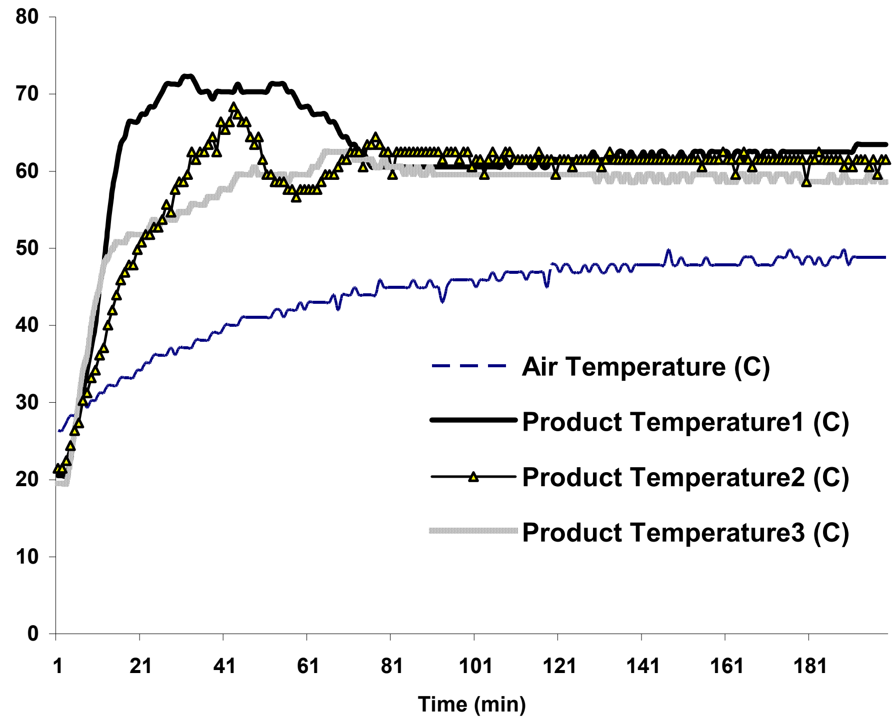

Figure A11 Microwave drying product temperatures of high fructose corn syrup treated saskatoon berries at 60°C product temperature and corresponding air temperature (°C) plotted against time (min).

Note: Product temperatures are at three different locations on the sample holder.

Appendix B1. Microwave drying of fresh blueberries

Fresh blueberries in microwave environment and rupture due to high power treatment.

Figure B1 Blueberries disintegrated structure after low power microwave drying.

Appendix C1. Dielectric properties of saskatoon berries

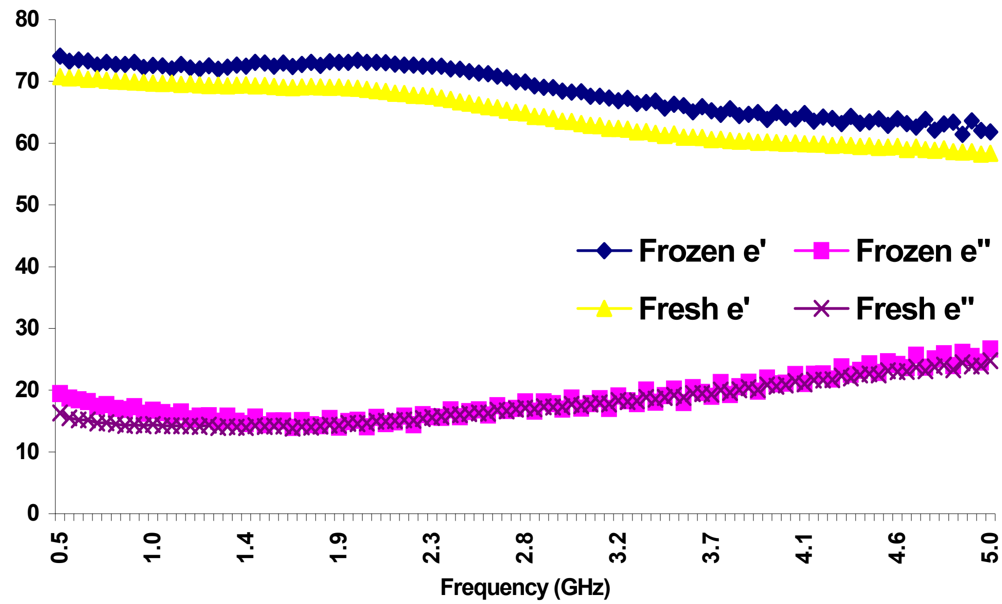

Figure C1 Dielectric properties of frozen saskatoon berry syrup.

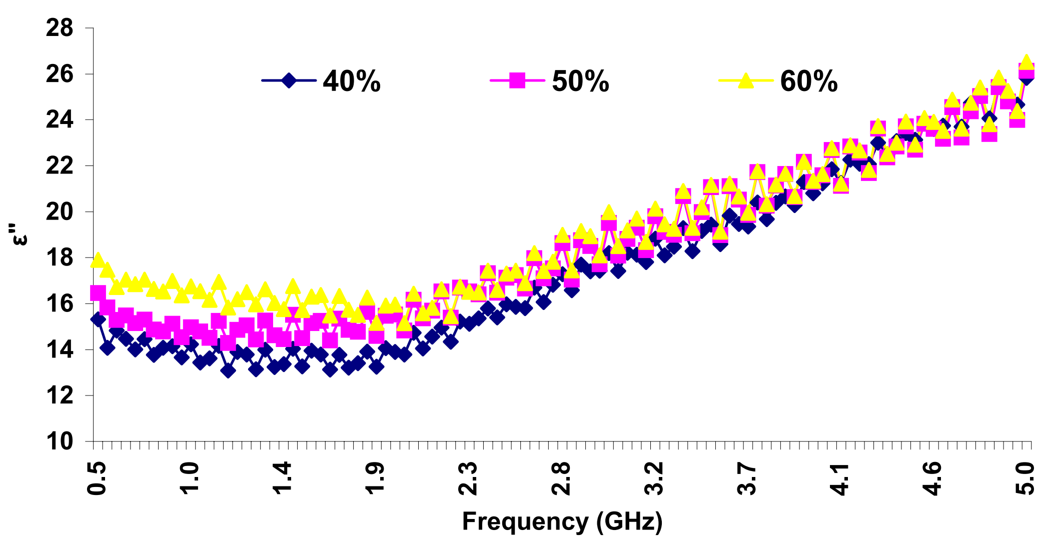

Figure C2 Dielectric loss factor variation of saskatoon berry syrup after osmotic dehydration with 40, 50 and 60% sucrose sugars solutions.

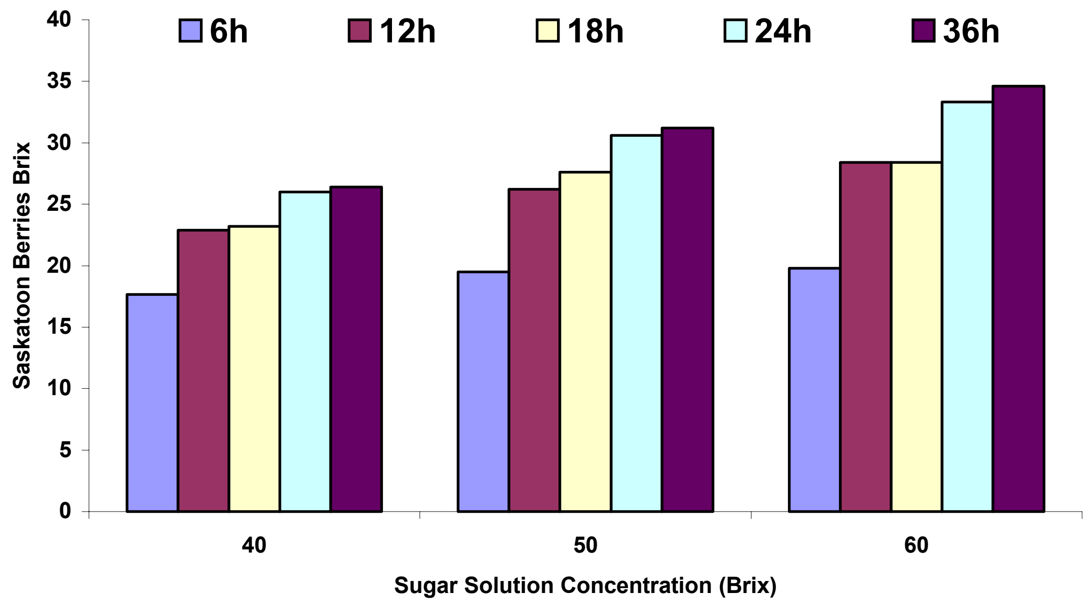

Figure C.3 Effect of high fructose corn syrup Concentration on Osmotic Dehydration.

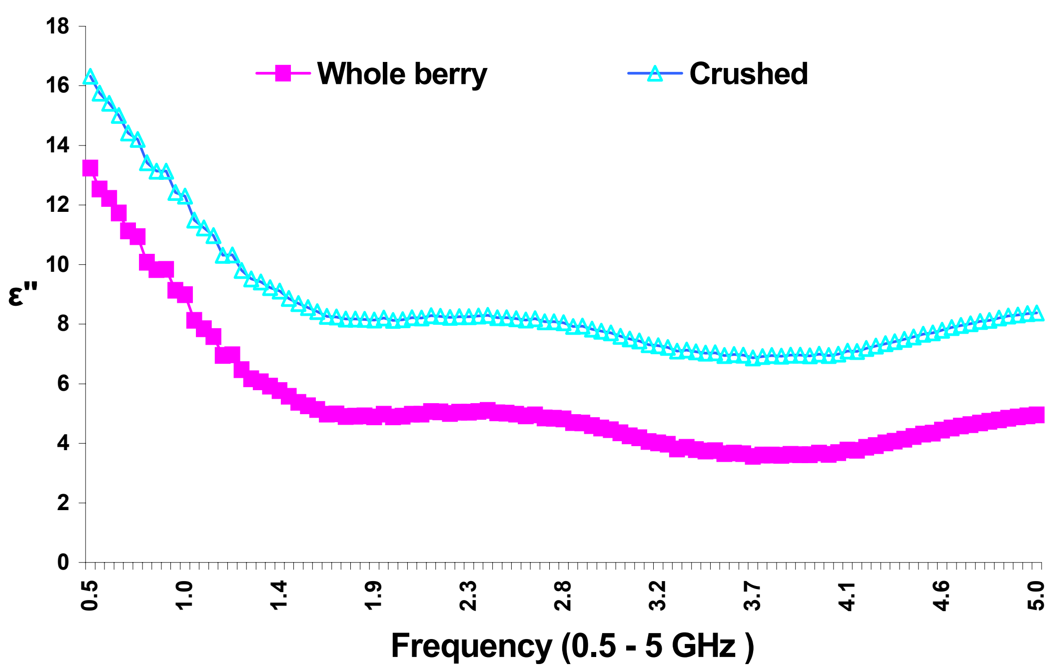

Figure C4 Dielectric loss factor (ε") variation with frequency of Fresh saskatoon berries.

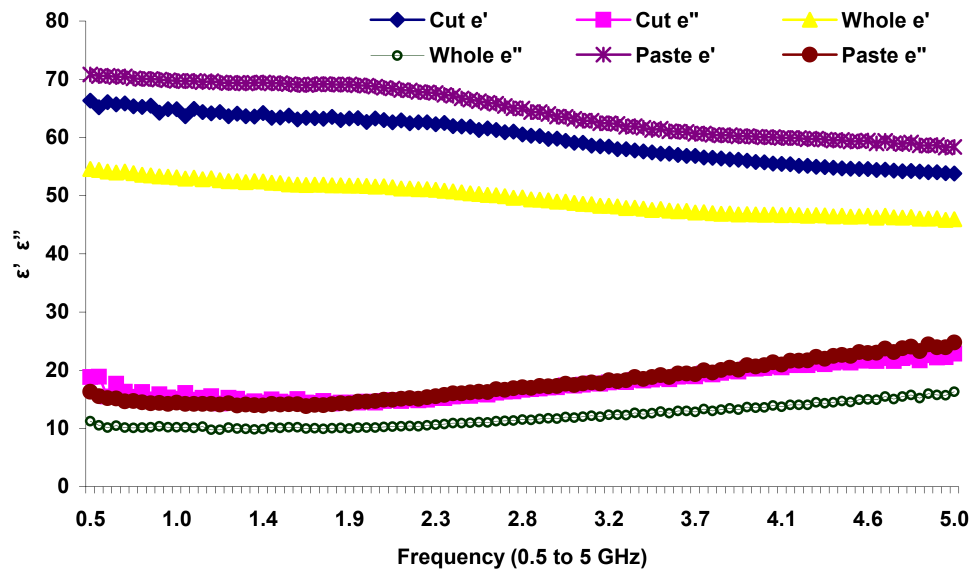

Figure C5 Dielectric properties of fresh whole, cut and syrup of berries.

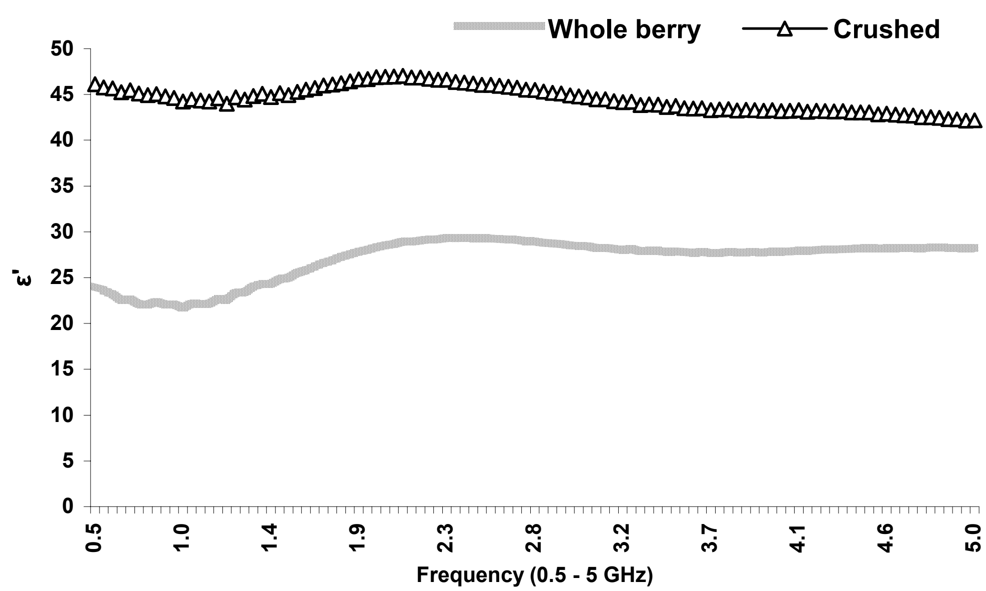

Figure C6 Dielectric constant (ε') variation with frequency of frozen saskatoon berries (whole and crushed).

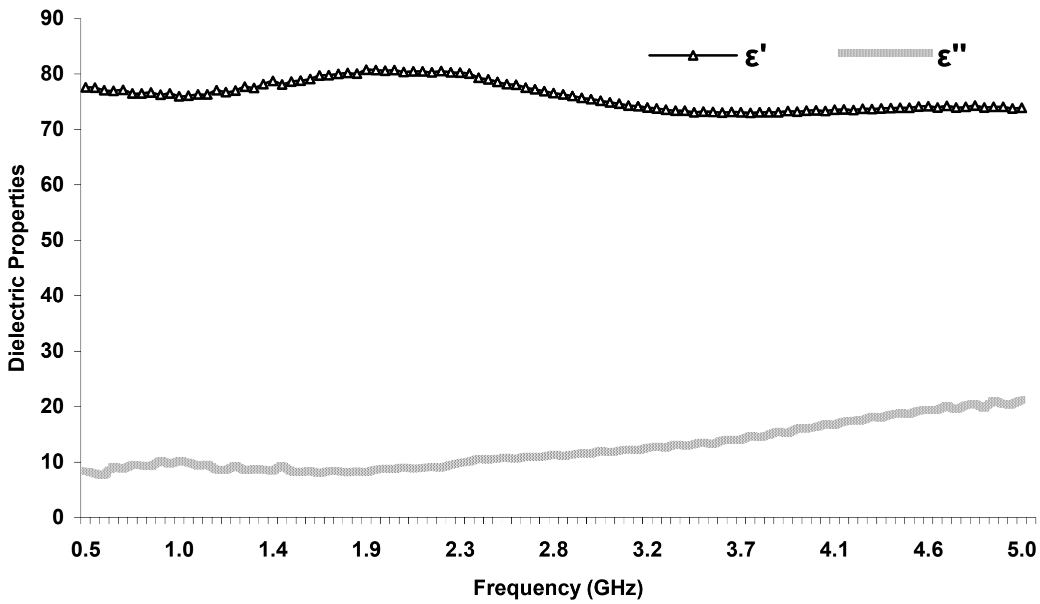

Figure C7 Dielectric constant and Loss factor variation with frequency of water.

Appendix D1. Scanning Electron Microscope images of saskatoon berries

Figure D1 Scanning electron microscope image of osmotically dehydrated berries with 50% sucrose solution.

Appendix E1. Digital Images of Experimental Setup

Figure E1 Frozen saskatoon berries.

Figure E2 Thawed saskatoon berries placed in polycarbonate sample holder.

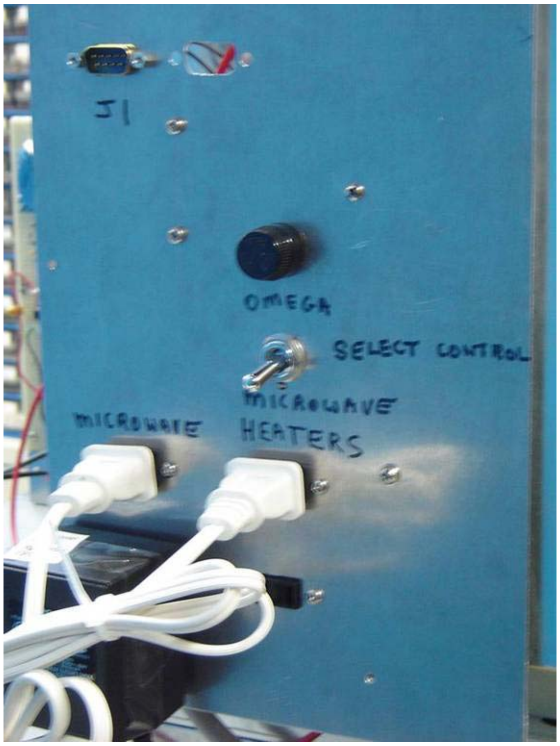

Figure E3 Panel to switch between preset and modified settings.

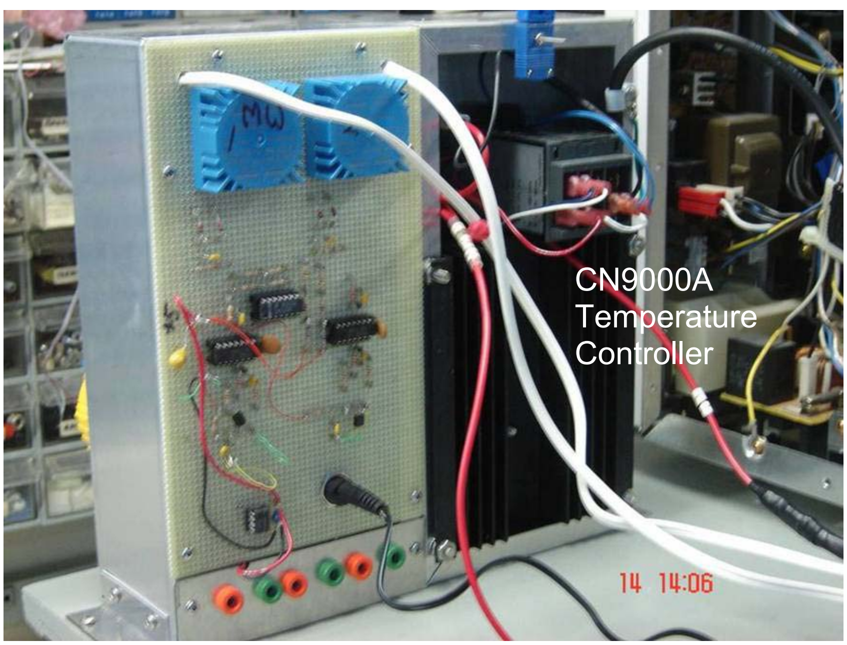

Figure E4 Front panel with temperature controller and setup to monitor convection and microwave run-time.

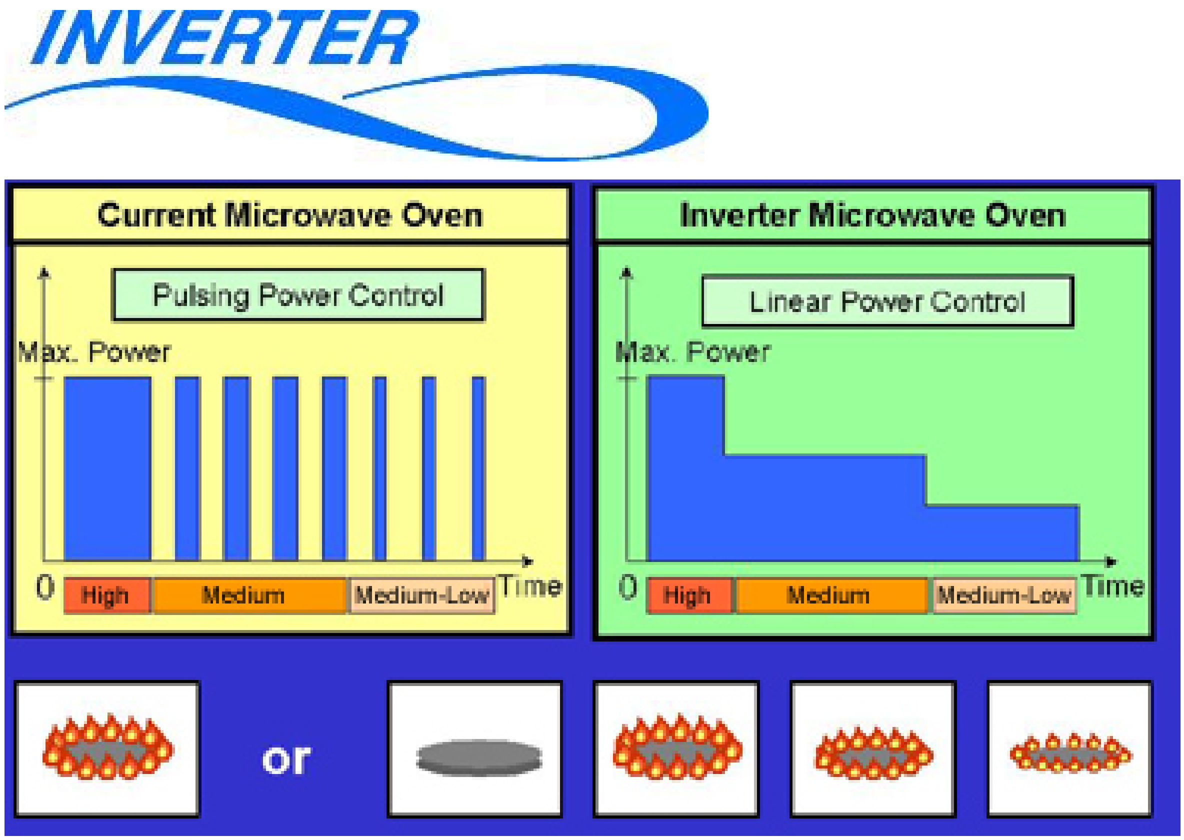

Figure E5 Inverter technology built in the Panasonic microwave-convection system.