EVALUATION OF DRYING METHODS ON OSMOTICALLY DEHYDRATED CRANBERRIES

by

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ABSTRACT

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Over the last few years, cranberry production in Canada and in Québec has increased significantly. Some producers are therefore looking for alternatives in order to offer a product with an added value, such as dried cranberries. The use of dried cranberries has also increased, since these small fruits are found in processed products such as breakfast cereals, granola bars and bakery preparations. This creates a need to evaluate drying characteristics of cranberries by testing different drying methods.

Since cranberry skin is thick and has low porosity, skin pretreatments were considered before drying in order to facilitate water diffusion. Mechanical and chemical pretreatments were considered, by cutting the fruits in half, by making pin holes in each cranberry, and by dipping the fruits in an alkaline solution.

A second pretreatment seemed necessary when drying cranberries in order to reduce their tartness. Cranberries were osmotically dehydrated, by immersing them in osmotic solutions of sucrose or high fructose corn syrup. The mass transfers involved in such a dehydration are a flux of water from the fruits to the solution, a gain of sugar from the solution to the fruits, and some loss of soluble substances from the fruits to the solution. Various parameters were considered during the osmotic dehydration, such as the osmotic agent, the fruit to sugar ratio (on a mass basis), and the duration of dehydration.

Once the pretreatment conditions were selected, four drying methods were tested on the pretreated cranberries. These methods included hot air drying, freeze-drying, vacuum drying and a combination of hot air and microwaves. A quality evaluation of the

dried samples was also performed, including evaluation of overall appearance, taste, color, water activity, rehydration capacity and texture.

Overall results included the importance of osmotic dehydration prior to drying in order to reduce the tartness of the cranberries; the advantage of freeze-drying when rehydration capacity of the fruits is considered; the disadvantage of using freeze-drying based on texture of the final products; and the acceptable or superior attributes of microwave dried cranberries, including color, taste and texture.

RÉSUMÉ

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ÉVALUATION DE MÉTHODES DE SÉCHAGE SUR DES CANNEBERGES DÉSHYDRATÉES PAR OSMOSE

Depuis quelques années, la production de canneberges a augmenté d'une manière significative au Canada, particulièrement au Québec. Certains producteurs veulent donc promouvoir un produit à valeur ajoutée, la canneberge séchée. L'utilisation des canneberges séchées a également augmenté depuis quelques années puisque ce nouveau produit se retrouve dans plusieurs aliments transformés tels les céréales, les barres de type granola et les préparation pour boulangerie. Cette nouvelle demande en canneberges séchées crée un besoin d'examiner les techniques disponibles pour le séchage de ce fruit.

La canneberge, ayant une peau très peu poreuse et relativement épaisse, semble nécessiter un pré-traitment avant même de la faire sécher. Les pré-traitements mécaniques et chimiques ont été considérés, soit la rupture de la peau de la canneberge (en coupant le fruit en deux ou en perçant de petits trous dans la peau), et le trempage du fruit dans une solution alcaline, ce qui promouvoit la diffusion de l'eau durant le séchage.

Un second pré-traitement s'est avéré nécessaire avant le séchage des canneberges afin de réduire le goût amer des fruits. Les canneberges sont plongées dans une solution osmotique, telle une solution de sucrose ou de fructose, dans le but de déshydrater partiellement le fruit par osmose et de le sucrer. Les tranferts de masse présents lors d'une telle déshydratation par osmose comprennent le transfert d'eau provenant des fruits jusqu'à la solution osmotique, le transfert de la substance osmotique vers le fruit, ainsi que le transfert de substances solubres provenant du fruit jusqu'à la solution osmotique. Différents paramètres ont été considérés lors de la déshydratation par osmose, tels l'agent osmotique, le rapport fruit:sucre et la durée de la déshydratation.

Lorsque les conditions de pré-traitement ont été établies, quatre méthodes de séchage ont été testées sur la canneberge pré-traitée. Ces méthodes, soit l'air chaud, le séchage sous-vide, la lyophilisation et la combinaison air chaud et micro-ondes, offrent différents avantages et inconvénients qui dépendent souvent de la nature du produit séché. Ces caractéristiques ont été déterminées pour la canneberge, à travers l'évaluation de la qualité des fruits séchés. L'apparence générale, le goût, la couleur, l'activité de l'eau, la capacité de ré-hydratation ainsi que la texture des échantillons séchés ont été évalués.

Les resultats obtenus indiquent l'importance d'une déshydratation par osmose précédant le séchage afin de diminuer le goût amer des canneberges; l'avantage d'utiliser la lyophilisation lorsque le produit final doit avoir une bonne capacité de ré-hydratation; le désavantage d'utiliser la lyophilisation lorsqu'une texture semblable à celle du produit commercial est désirée; et les attributs acceptables ou supérieurs des canneberges séchées par micro-ondes lorsque la couleur, le goût et la texture sont considérés.

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FORMAT OF THESIS

This thesis is submitted in the form of original papers suitable for journal publication. The thesis format has been approved by the **Faculty of Graduate Studies and Research, McGill University,** and follows the conditions outlined in the **"Guidelines Concerning Thesis Preparation,** section 7, **Manuscripts and Authorship"** which are as follows:

> "The candidate has the option, subject to the approval of the Department, of including as part of the thesis the text, or duplicated published text (see below), or original paper, or papers. In this case the thesis must still conform to all other requirements explained in Guidelines Concerning Thesis Preparation. Additional material (procedural and design data as well as descriptions of equipment) must be provided in sufficient detail (e.g. in appendices) to allow a clear and precise judgment to be made of the importance and originality of the research reported. The thesis should be more than a mere collection of manuscripts published or to be published. It must include a general abstract, a full introduction and literature review and a final overall conclusion. Connecting texts which provide logical bridges between different manuscripts are usually desirable in the interest of cohesion.
>
> It is acceptable for the thesis to include as chapters authentic copies of papers already published, provided these are duplicated clearly on regulation thesis stationary and bound as an integral part of the thesis. Photographs or other materials which do not duplicate well must be included in their original form. In such instances, connecting texts are mandatory and supplementary explanation material is almost always necessary.
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> The inclusion of manuscripts co-authored by the candidate and others is acceptable but the candidate is required to make an explicit statement on who contributed to such work and to what extent, and supervisors must attest to the accuracy of the claims, e.g. before the Oral Committee. Since the task of the Examiners is made more difficult in these cases, it is in the candidate's interest to make the responsibilities of authors perfectly clear. Candidates following this option must inform the Department before it submits the thesis for review."

The work reported here was performed by the candidate and supervised by Dr. G.S.V. Raghavan of the Department of Agricultural and Biosystems Engineering, Macdonald Campus of McGill University, Montreal. The research project was conducted in the Department of Agricultural and Biosystems Engineering, Macdonald Campus of McGill University, Montreal, except the freeze-drying experiments which were performed in the Département des sols et de génie agroalimentaire, Université Laval, Sainte-Foy. The authorship for the papers are 1) C. Beaudry, G. S. V. Raghavan, C. Ratti, and T. J. Rennie, 2) C. Beaudry, G. S. V. Raghavan, and T. J. Rennie, 3) C. Beaudry, G. S. V. Raghavan, C. Ratti, and T. J. Rennie for the papers in Chapters 4, 5, and 6, respectively.

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NOMENCLATURE

a_s	Area per unit volume (m^2/m^3)
a_w	Water activity
$a_{w\ equil}$	Water activity at equilibrium
$a_{w\ fruit}$	Water activity of the fruit
$a_{w\ soln}$	Water activity of the hypertonic solution
a^*	Chromacity coordinate (redness or greenness)
a^*_{sample}	Chromacity coordinate of dried sample
$a^*_{standard}$	Chromacity coordinate of fresh sample
A	Microwaves cycling period of 30 s ON / 30 s OFF
A_s	External area (m^2)
b^*	Chromacity coordinate (yellowness or blueness)
b^*_{sample}	Chromacity coordinate of dried sample
$b^*_{standard}$	Chromacity coordinate of fresh sample
B	Microwaves cycling period of 30 s ON / 60 s OFF
C^*	Chromacity index (saturation index)
DE	Drying efficiency (MJ/kg of water)
D_{eff}	Effective moisture diffusivity (m^2/s)
e_w	Evaporative rate in mass transfer of moisture
E	Electric component of an electromagnetic wave
EO	Ethyl oleate
F:S	Fruit to sugar ratio (mass basis)
h_g	Heat transfer coefficient
h^o	Hue angle in chromacity
H	Magnetic component of an electromagnetic wave
HFCS	High fructose corn syrup
k_g	Mass transfer coefficient
K_2CO_3	Potassium carbonate molecule
L^*	Chromacity coefficient (lightness)
L^*_{sample}	Chromacity coefficient of dried sample

$L^*_{standard}$	Chromacity coefficient of fresh sample
m	Local moisture content (dry basis)
m_{dh}	Mass of a dehydrated sample (g)
m_{rh}	Mass of a rehydrated sample (g)
m_s	Mass of dry solids (kg)
mc	Moisture content (% wet basis)
M_{dh}	Moisture content of a dried sample (% wet basis)
M_{in}	Initial moisture content of a sample before drying (% wet basis)
MW	Microwaves
n_w	Drying rate
NaOH	Sodium hydroxide molecule
p_v	Water vapor partial pressure
q_c	Heat flux (W/m^2)
R	Universal gas constant (0.082057 L.atm/K/mol)
R	Drying rate (kg water/h/m^2)
RF	Radio frequency
RR	Rehydration ratio
t	Time (s)
tanδ	Loss tangent
T	Absolute temperature (K)
w.b.	Wet basis in moisture content
X	Free moisture content (kg water/kg dry solids)
Δa*	Difference in chromacity coordinate a* between fresh and dried cranberries
Δb*	Difference in chromacity coordinate b* between fresh and dried cranberries
ΔL*	Difference in chromacity coefficient between fresh and dried cranberries
ΔE	Total color difference between fresh and dried cranberries

Greek

ε	Complex dielectric constant or electric permittivity complex
ε'	Dielectric constant
ε''	Loss factor
ρ_s	Density of dry solids (kg/m^3)
$\tan\delta$	Loss tangent
μ_i	Chemical potential
μ^o	Chemical potential of a reference state

I. GENERAL INTRODUCTION

During the last century, many advances have taken place in food processing. Several techniques have been developed for the preservation of foods, including smoking, canning, refrigerating and drying the food in question. These methods have been constantly improved in order to apply them to a wide variety of products. Consumers want fruits and vegetables to be available on a yearly basis, which can now be found fresh, canned, frozen or dried.

Like most developed countries, Canada needs to diversify its agri-food sector, to produce high quality and high value products. Fruit and vegetable growers realize that one way to be more competitive is to offer a higher quality product and achieve lower post-harvest losses. Agricultural producers therefore have to be aware of advances in food processing and post-harvest technologies in order to efficiently lower these losses.

Through the last few years, there has been an increasing demand for high quality dried berries. These dried fruits are widely used in the bakery industry, for a variety of processed products including muffin mixes, breakfast cereals, yogurts, sauces and snack bars. An example of berries that recently gained popularity is the cranberry. This fruit is available in North America as a fresh commodity from harvest season (around September) until December, and as a frozen or processed commodity the rest of the year. Dried cranberries are now available on the market as a snack food, or within processed products, such as those mentioned above. However, energy efficient drying technologies for cranberries have not been extensively researched.

Around the world, different methods have been used to dry fruits and vegetables. A method such as solar drying is popular in tropical regions of the world, where sunny weather and low investment are required, whereas techniques such as freeze-drying are used in industrialized countries, requiring high investments. Other methods, such as conventional hot air drying, vacuum drying and microwave drying are also being used for a wide variety of food commodities. Drying fruits and vegetables causes a reduction in the water activity of the produce, thus extending storage life.

Every drying method has specific characteristics and should be tested on a certain commodity in order to determine if this method is suitable to dry the commodity. This

selection will depend on the commodity itself and on the associated benefits of using such a technique. For example, the benefits associated with freeze-drying onions might not be as high as those associated with freeze-drying mushrooms, which represent a higher value commodity. Also, some drying methods may simply not be appropriate for certain commodities, such as solar drying applied to cranberries, which are harvested in the fall in North America.

When drying fruits and vegetables, some pretreatments can be used in order to increase the drying rate or the end quality of the product. First, a skin pretreatment can be applied on a waxy fruit in order to facilitate water diffusion through the skin. This skin pretreatment can be chemical or mechanical. For example, chemical pretreatment prior to drying has been used for a variety of commodities such as grapes, cherries and plums (Pangavhane et al., 1999; Tulasidas et al., 1996; Saravacos et al., 1988; Ponting and McBean, 1970). This pretreatment consists of dipping the fruits in an alkaline solution for a certain period of time and temperature. This pretreatment successfully increased the drying rate of such commodities without affecting quality. Mechanical pretreatments have also been investigated (Di Matteo et al., 2000) and are sometimes found more appropriate. Mechanical pretreatments include cutting the fruits in pieces, puncturing the skin in order to expose the interior of the fruit to the surroundings, or performing a surface abrasion on the skin and thus enhancing the diffusion process.

Another pretreatment that can be useful prior to drying fruits and vegetables is partially dehydrating them through osmotic dehydration. By doing this, the moisture content of the commodity is reduced prior to drying, thus resulting in reduced drying energy requirements. Another effect of osmotic dehydration is the addition of an osmotic agent (generally sugar or salt) to the commodity being dehydrated. This is beneficial for a product, such as cranberries, which has a very tart taste.

Once the appropriate pretreatments have been established, different drying methods can be investigated for a product such as cranberries. The benefits of each technique can be determined for the product in question. So far, there has been little research performed on evaluating drying methods on pretreated cranberries.

II. GENERAL OBJECTIVES

This study has the general objective of evaluating drying methods on cranberries. This overall objective can be represented by three main objectives, which consist of:

1. Optimizing pretreatment methods on cranberries prior to drying. These pretreatments include skin pretreatment and osmotic dehydration.
2. Optimizing microwave parameters for cranberry drying. These parameters include power density and cycling period.
3. Testing and comparing four drying methods:
    a. Microwave drying
    b. Hot air convective drying
    c. Freeze-drying
    d. Vacuum drying

    on cranberries that were previously dehydrated through osmosis. This comparison will be based on a quality evaluation of the cranberries dried under the four drying methods. The overall appearance, taste, surface color, texture, water activity and rehydration capacity will be evaluated.

III. LITERATURE REVIEW

3.1 General introduction on cranberries

Native to North America, the cranberry (*Vaccinium macrocarpon*) is an evergreen vine which best grows in acidic bog habitats. Its fruit has been used for many centuries, first by the American Indians as a source of food, medicine, and in their rituals (Eck, 1990). European explorers became interested in this fruit probably because of its benefits in fighting scurvy. Cranberry sauce was introduced as a traditional Thanksgiving food in the 17th century and it is still a North American tradition to eat cranberry sauce with turkey.

3.1.1 Production & characteristics of the fruit

In the last few years, there has been an increase in cranberry production and consumption. The total cranberry acreage in Canada has grown from 3000 acres in 1995 to 7300 acres in 1999 (Brown, 2000). At a total of more than 80 million pounds of cranberries, the Canadian cranberry production now represents 13% of the total North American production (Brown, 2000). In the province of Québec, 4870 tons of cranberries were commercialized in 1997 and this value is expected to increase to 10630 tons in 2005, under a realistic scenario (DREPA/CDAQ, 1999).

One probable cause of the increase in cranberry popularity is the high nutritional value of the fruit. Table 3.1 shows some characteristics of cranberries. Figure 3.1 shows a photograph of a cranberry plant in late September, when the fruits are ready for harvest.

For many years, it was believed that cranberries presented benefits for the urinary system. Recently, research has shown that daily cranberry juice consumption can have a role in treating and preventing urinary tract infections (Kuzminski, 1996). It is reported that cranberry juice could have the ability of inhibiting bacterial adherence to mucosal surfaces (Kuzminski, 1996). These benefits for the urinary system, along with the high vitamin C content in cranberry juice, have probably played a major role in the increase in cranberry juice consumption in North America. In fact, since 1990, cranberry juice consumption has increased around 8% per year in North America (Asselin, 2000).

Table 3.1: Composition and nutritional value of raw cranberries

Ingredient	Raw cranberries
Moisture	88.00 %
Reducing sugars	4.20 %
Acids	2.40 %
Pectin	1.20 %
Fat	0.40 %
Protein	0.20 %
Ash	0.25 %
Fiber	1.60 %
Undetermined	1.75 %
Minerals per 100 g fruit	
Sodium	1 mg
Potassium	71 mg
Calcium	7 mg
Vitamin C per 100 g fruit	10.5-13.5 mg

(Adapted from Eck, 1990 and Kuzminski, 1996)

3.1.2 Harvesting methods

One particular aspect of cranberry production is the way the fruits are harvested. Because cranberry fruits float on the surface of water, the cranberry fields or bogs are flooded at harvesting time. Once the bog is flooded, a machine equipped with a rotating beater is passed over the plants and this forces the fruits to be detached from the plants. Over the years, water harvesting replaced different methods of dry harvesting, such as scooping and hand picking. The main advantages of water harvesting over dry harvesting are the increased harvesting speed, the elimination of harvest losses due to incomplete picking or dropped berries, and the reduction in vine and fruit injury (Eck, 1990). However, recommendations concerning water harvesting include using cold floodwaters (less than 13°C), removing the berries from water within three to four hours, and cleaning and drying the berries as quickly as possible (Eck, 1990). These recommendations were shown to reduce physiological breakdown and fungal infection in water harvested berries. Figure 3.2 shows a photograph of flooded cranberry fields during harvest.

Figure 3.1: Photograph of a cranberry plant at harvesting period

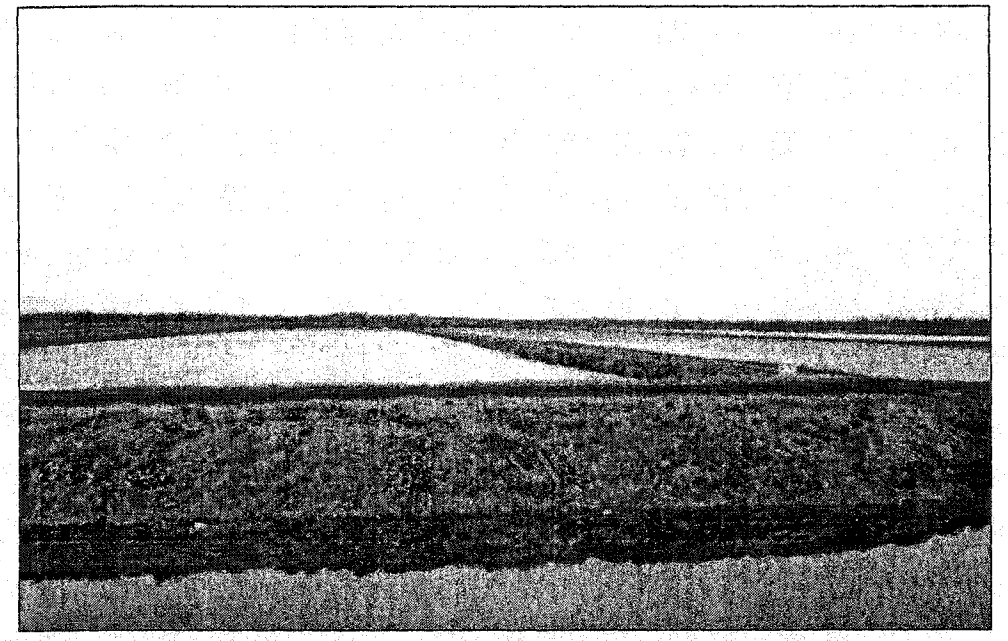

Figure 3.2: Photograph of flooded cranberry fields at harvest

3.1.3 Industry

Over the last few years, the drastic increase in cranberry production in Québec has led to a decrease in the price at which producers can sell their fruits. A 100 pound barrel sold at $85(US) in 1997 was sold at less than $35(US) in 1999 (Dubuc, 1999). This situation has raised interest for value-added products using processed cranberries. Dried cranberries are now available on a yearly basis, along with frozen cranberries, cranberry juices and sauces. The dried fruits are offered as a snack food or are used in bakery products such as breakfast cereals, granola bars, muffin mixes and pastries. The world market for dried cranberries is estimated in the order of $80 million (Brown, 2000). However, very few research projects have studied technologies in cranberry drying. Yongsawatdigul and Gunasekaran (1996) investigated microwave-vacuum drying of cranberries with an osmotic dehydration pretreatment. This procedure required that the fruits were first cut in half prior to the drying process. In this research, cranberries were dried to final moisture content of approximately 15% (wet basis).

3.2 Pretreatments of fruits prior to drying

In order to increase drying rates and/or to improve the quality of the dried product, pretreatments are considered prior to drying fruits and vegetables. These pretreatments can consist of treating the skin of the product, chemically or mechanically, and of partially dehydrating it through osmosis. It is likely that the diffusion of moisture through the skin of the cranberry, being fairly thick and waxy, would be difficult during the drying process if no pretreatment was performed. Some consequences of drying cranberries without pretreating them could be swelling, bursting and bleeding of the whole cranberries. Also, osmotic dehydration of cranberries in a sugar solution would be necessary to decrease the tartness of the fruit. The resulting partially dehydrated fruits could then be dried using different drying methods.

3.2.1 Skin pretreatment

As mentioned before, skin pretreatment of a fruit or vegetable can be done chemically or mechanically. Chemical pretreatment consists of dipping the fruit in an alkaline solution to increase the permeability of the skin in order to enhance diffusion of

water through the skin, whereas mechanical pretreatment consists of mechanically damaging the structure or surface of the fruit. Mechanical pretreatment could consist of cutting the fruit in half, puncturing the skin with pin holes, or performing surface abrasion of the skin. Experiments done on drying strawberries showed that some pretreatment must be done on the fruits because of possible swelling, bursting and bleeding of the fruits during the drying process (Venkatachalapathy, 1998). These experiments showed that puncturing the fruit with a pin did not help in reducing bursting, swelling and bleeding.

Also in these experiments, Venkatachalapathy (1998) showed that dipping the berries in a solution of ethyl oleate (EO) and sodium hydroxide (NaOH) prior to drying increases the drying rate, and does not have an effect on quality. This solution was first found to be effective in reducing drying times by Ponting and McBean (1970), who investigated different dipping treatments on waxy skin fruits such as grapes and prunes. Ponting and McBean (1970) determined that the ethyl esters of fatty acids in the C_{10}-C_{18} range were the most effective dipping material and that EO was the most convenient chemical to handle, along with being very effective. A chemical pretreatment was also used for grapes, which were dried to make raisins (Tulasidas et al., 1996).

According to Di Matteo et al. (2000), the EO contained in an alkaline solution used for pretreating the skin of grapes will penetrate into the waxy layer of that skin, and will cause the formation of many small pores. Saravacos et al. (1988) stated that the action of EO can be explained by its dissolving action on the waxy components and the cell walls of the grapes, and by its wetting (surface active) effect on the resulting porous structure of the grape skin. In their work, Di Matteo et al. (2000) studied the effectiveness of using a mechanical pretreatment, which consisted of performing an abrasion of the grape peel using an inert abrasive material. The removal of the waxy layer from the grape peel was found to be as effective by abrasion than by chemical pretreatment. In fact, the drying rates were found to be similar, however the abrasion pretreatment lead to darker raisins, which is less attractive to consumers.

When examining chemical pretreatments before drying, different variables are of interest. These include the temperature at which the dipping solution is kept, the total

time the fruits are left in the solution, and the concentration of the chemicals used in the experiments.

However, Tulasidas et al. (1996) found that there was no significant difference in the drying times of grapes when pretreated with mixtures of 2% EO in 0.5% NaOH and 3% EO in 0.5% NaOH. The dipping time and the temperature of the solution are often dependent. This means that a shorter dipping time (for example 30 sec) will be associated with a higher solution temperature (for example 80°C), and a longer dipping time (for example 3 min) will be associated with a lower solution temperature (for example 40°C).

3.2.2 Osmotic dehydration

Another process used for fruits and vegetables prior to pasteurization, freezing or drying is osmotic dehydration. It can be defined as a process that consists of placing foods, such as pieces of fruits and vegetables, in a hypertonic solution (Jayaraman and Das Gupta, 1995). A driving force for water removal arises between this hypertonic solution and the food, due to the difference in chemical potential between the two. There are higher osmotic pressure and lower water activity in the hypertonic solution, and the cell wall of the fruit will act as a semi permeable membrane. The water activity, which describes the state of water within foods, is related to the chemical potential as described in Equation 3.1:

$$\mu_i = \mu^o + RT \ln a_w \tag{3.1}$$

where μ_i is the chemical potential, μ^o is the chemical potential of a reference state, R is the universal gas constant, T is the temperature and a_w is the water activity. There will be osmotic dehydration until the water activity in the hypertonic solution comes to equilibrium with the water activity inside the fruit (Barbosa-Canovas and Vega-Mercado, 1996). There is consequently a relation between the water activity at equilibrium and the initial water activity of both the fruit and the hypertonic solution. This relation is shown in Equation 3.2:

$$a_{w\,equil} = a_{w\,fruit} * a_{w\,soln} \tag{3.2}$$

where $a_{w\ equil}$ is the water activity at equilibrium, $a_{w\ fruit}$ is the water activity of the fruit, and $a_{w\ soln}$ is the water activity of the hypertonic solution (Aqualab, 1999).

From this, it can be seen that various mass transfers are involved in osmotic dehydration. The most important aspect will be the water transfer from the fruit to the hypertonic solution, but there will also be an important movement of osmoactive substance from the hypertonic solution into the fruit. Figure 3.3 shows the mass transfers involved in osmotic dehydration.

One important aspect of osmotic dehydration for cranberries is the mass transfer of some osmoactive substances, generally sucrose or fructose, into the fruits. Even though this process may not be desired for some product, it is fundamental for cranberries in order to reduce the tartness of the cranberry. Moreira and Sereno (2000) have proposed a method to control the solute uptake during osmotic dehydration of apple. They have shown that a convective drying step before the osmotic treatment reduced the solute uptake from 75 to 85% with respect to samples subjected to a single osmotic treatment for the same amount of time. They have showed that this pretreatment reduced the solute uptake without increasing total operating time.

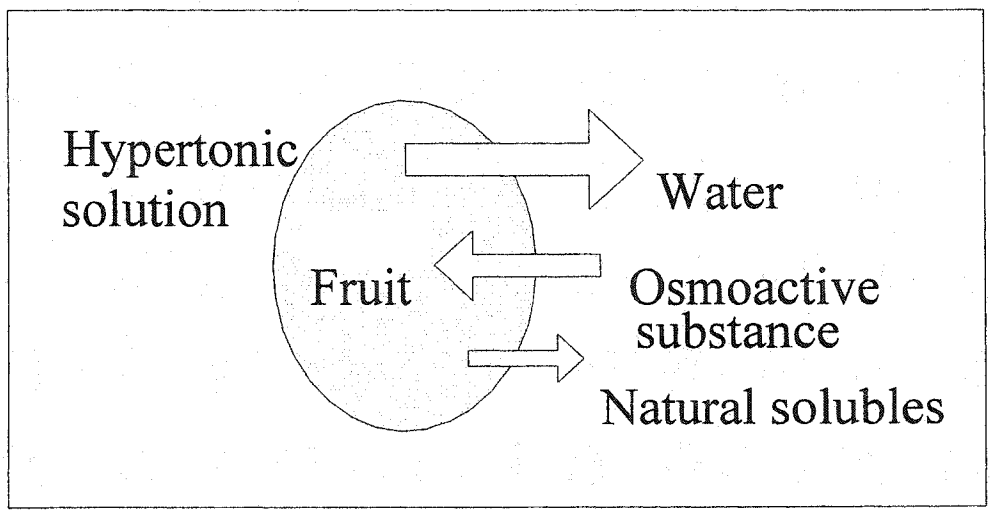

Figure 3.3: Mass transfer in osmotic dehydration
(adapted from Lewicki and Lenart, 1995)

Typically, the rate of mass transfer during osmotic dehydration can be predicted by using Fick's second law of unsteady state diffusion (Nsonzi and Ramaswamy, 1998a, Sablani et al., 2000). Equation 3.3 represents this law as follows:

$$\frac{\partial m}{\partial t} = D_{eff} \nabla^2 m \tag{3.3}$$

where m is the local moisture content (dry basis), t is the time (s), and D_{eff} is the effective moisture diffusivity (m^2/s). This D_{eff} is used to describe the rate of moisture movement when different transport mechanisms occur, as it is difficult to separate each individual mechanism (Sablani et al., 2000). Although this method is not quite sound in theory, it is a practical and convenient way to describe moisture diffusion. Temperature, moisture content and product porosity have an effect on moisture diffusivity (Sablani et al., 2000). An extensive review on this and a list of relationships showing moisture diffusivity as a function of temperature, moisture content and porosity for various products can be found in Sablani et al. (2000).

In osmotic dehydration, there is simultaneous counter-current flow of moisture out of the product and solids into the product. Nsonzi and Ramaswamy (1998a) reported research in which models of the mass transfer process with respect to moisture loss and solids gain using Fick's law were determined. In their study, Nsonzi and Ramaswamy (1998a) evaluated the kinetics of moisture loss and solids gain during osmotic dehydration of blueberries at different temperature and sucrose concentrations. They determined that even though moisture loss and solids gain are both increased with increased temperature and sucrose concentrations, the rates of moisture loss were much higher than the rates of solids gain. They also related moisture and solids diffusivity with temperature and sucrose concentration.

Even though osmotic dehydration cannot dry products to completion, it presents several advantages, such as the minimized heat damage to color and flavor, less discoloration of fruit by enzymatic oxidative browning, better retention of flavor compounds, and less energy consumption since water is removed without phase change (Jayaraman and Das Gupta, 1995). Because osmotic dehydration cannot be considered as a food preservation process by itself, it must be followed by another process, such as freezing, pasteurization or drying, in order to achieve a shelf-stable product. However,

the need to use preservatives such as sulfur dioxide in fruits is practically eliminated by osmotic dehydration (Lewicki and Lenart, 1995). Also, the osmotic dehydration process removes a substantial amount of air from the tissue, thus blanching done before osmotic dehydration is not necessary (Lewicki and Lenart, 1995). Studies have shown that osmotic treatment of fruits and vegetables will alter properties of the final product (Lewicki and Lukaszuk, 2000). The mechanical properties of the dehydrated fruit are modified by the presence of osmoactive substance (i.e. sugars) in the plant tissue. From this, it can be expected that osmotically dehydrated fruits will have different characteristics, such as rehydration capacity, compared to untreated ones.

Even though most osmotic dehydration processes occur at atmospheric pressure, research has shown advantages of using pressures different than atmospheric during dehydration. Studies prove that under vacuum conditions, quicker dehydration kinetics are obtained (Quan Shi and Fito Maupoey, 1993). In his work, Fito Maupoey (1994) determined a model for the vacuum osmotic dehydration operation. Work has also been done on high hydrostatic pressure prior to osmotic dehydration. Rastogi et al. (2000) determined that osmotic dehydration of high hydrostatic pressure-treated foods is faster than that of untreated foods. When using a high hydrostatic pressure treatment prior to osmotic dehydration, there are significant changes in the tissue architecture, resulting in increased mass transfer rates during osmotic dehydration.

In the osmotic dehydration process, variables of interest are the hypertonic agent used (it can be solid, such as granular sugar, or liquid, such as sucrose solutions or high fructose corn syrup), the concentration and temperature of the agent, and the time the produce is left in the hypertonic agent. In his research on strawberry drying, Venkatachalapathy (1998) showed that combining the fruit samples with granular sugar under a fruit to sugar ratio of 4:1 at room temperature, resulted in a clear drying time advantage over conventional drying with no osmotic dehydration. It was also shown that the period of osmotic dehydration should not exceed 24 hours, after which time off-odors developed. Under these conditions, the moisture content (under wet basis) of strawberries went from initially 89% down to 53% through osmotic dehydration.

Yongsawatdigul and Gunasekaran (1996) studied microwave-vacuum drying of cranberries and used an osmotic pretreatment on the fruits. It was shown that by using

high fructose corn syrup at a 1:1 fruit to sugar ratio at room temperature and for 24 hours, the moisture content (wet basis) of the cranberries decreased from 87% initially to 76% and 62% for a 30°Brix and a 60°Brix fructose solution respectively.

In their work, Bolin et al. (1983) have shown that syrup penetration rate into a fruit piece was faster with high fructose corn syrup (HFCS) than with a sucrose solution. The conditions used for the osmotic dehydration were a 1:4 fruit to sugar ratio for both a sucrose solution and HFCS kept at 70°Brix and 70°C, for dehydration times of 0.5, 1, 3, 5, and 7 hours. From this, the use of sucrose and HFCS lead to a solids gain of 8.8% and 13.6% and a moisture loss of 65% and 70%, respectively, for apples left in the osmotic solution for 7 hours.

One more characteristic that can be considered when dealing with osmotic dehydration is its energy aspects. One important portion of the energy consumption in osmotic dehydration is the need of reconstituting the hypertonic solution, which is being diluted as the fruits are losing water (Lewicki and Lenart, 1995). Two different methods are generally used in order to reconstitute the osmotic solution: the diluted solution can be re-concentrated by adding more osmoactive substance and may be reused several times; or the diluted solution can be passed in an evaporator in order to eliminate the water in the osmotic solution (Lewicki and Lenart, 1995; Bolin et al. 1983). It was estimated that dissolution of osmoactive substance in the hypertonic solution needs some 1kJ/kg of water being removed from the fruit. Hence, this process affects energy consumption in osmotic dehydration on a negligible basis (Lewicki and Lenart, 1995). Energy consumption in osmotic dehydration under industrial conditions is estimated to be between 100 and 2400 kJ/kg of water removed, depending on the temperature of the hypertonic solution and the method in which the surplus solution is managed (Lewicki and Lenart, 1995). This is at least less than half the energy required for convection drying, which can be in the range of 5 MJ/kg of evaporated water (Lewicki and Lenart, 1995).

3.3 Drying processes

Over the last century, many drying processes have been designed for a wide range of products. Each drying method presents characteristics, which can be beneficial for

specific products being dried. Mujumdar (1992) reports that drying competes with distillation as the most energy-intensive unit operation due to the high latent heat of vaporization of water, and because the most common drying medium, hot air, is quite inefficient. Drying can be defined as the process of thermally removing volatile substances (usually moisture) in order to yield a solid product (Mujumdar and Menon, 1995). Mujumdar and Menon (1995) also report that when a wet product is being thermally dried, two processes occur at the same time:

i. Energy transfer (mostly heat transfer) from the environment in order to evaporate the surface moisture
ii. Transfer of the internal moisture to the surface of the product and therefore its evaporation due to process i

From these two processes, it is easy to conclude that the rate at which drying will occur will depend on the rate of the two processes. Furthermore, the rate of heat transfer at the boundary layer will vary depending on the mode of heating. These modes include conduction, convection, and radiation, and can be briefly explained as follows:

conduction refers to the heat transfer that occurs across a stationary medium (solid or liquid) when a temperature gradient exists in this stationary medium,

convection refers to the heat transfer that occurs between a surface and a moving fluid when there is a temperature gradient between them, and

radiation occurs between two surfaces at different temperature in the absence of an intervening medium, since all surfaces of finite temperature emit energy in the form of electromagnetic waves (Incropera and DeWitt, 1981).

It is therefore very important to understand which mode of heat transfer is involved in specific drying processes. The different manners in which heat can be supplied correspond to different types of dryers. For example, contact or indirect dryers refer to conduction heat transfer, direct dryers refer to those using convection heat transfer, and microwave or radio frequency electromagnetic fields dyers refer to radiation heat transfer. Over 85% of industrial dryers are of the convection types using hot air or direct combustion gases as the drying medium and over 99% of the application involve removal of water (Mujumdar, 2001). As mentioned above, different modes of heat transfer imply different phenomenon during the drying process. Convection and

conduction will provide heat at the surface of the drying material where heat will diffuse inside the material through conduction. The moisture contained inside the material must then travel to the boundary of the material and it can then be carried by the drying medium, or through the application of vacuum for non-convective dryers (Mujumdar, 1995). Drying processes, using radiative heat transfer, will generate heat inside the material being dried due to the interaction between the microwave or dielectric energy and the material.

Moisture movement in food materials can be caused by a combination of different transport mechanisms listed below (Crapiste and Rotstein, 1997):

- Capillary flow due to gradients of capillary suction pressure.
- Liquid diffusion due to concentration gradients.
- Vapor diffusion due to partial vapor-pressure gradients.
- Viscous flow due to total pressure gradients, caused by external pressure of high temperature.

Other mechanisms, such as thermal diffusion, surface diffusion, and flow due to shrinkage pressure or gravity forces may have a minor contribution to mass transfer, but are generally not considered in food drying (Crapiste and Rotstein, 1997). Under convective drying, the heat flux, q_c, and the evaporation rate, e_w, should have the following form (Crapiste and Rotstein, 1997):

$$\text{Heat transfer} \rightarrow \quad q_c = h_g \left(T_{sf} - T_g\right) \tag{3.4}$$

$$\text{Mass transfer} \rightarrow \quad e_w = k_g \left(p_{vsf} - p_{vg}\right) \tag{3.5}$$

where h_g and k_g are the heat and mass transfer coefficients, T is the temperature, and p_v is the water vapor partial pressure. Heat transfer coefficients for different conditions are found in engineering literature or can be calculated from drying experiments (Ratti and Crapiste, 1995).

A drying process will generally be composed of two well-defined periods: a constant rate period and a falling rate period (Ratti and Crapiste, 1992), as shown in Figure 3.4. Section A to B of the curve, called the constant rate period, represents the

removal of unbound (free) water from the product. The drying rate of this period is generally determined by environmental conditions, such as the temperature, humidity and air velocity (Barbosa-Canovas and Vega-Mercado, 1996) and on the transport mechanism in the boundary layer between the product and the heating medium. Sections B to C and C to D are the falling rate period, where the drying rate is decreased, as bound water is now being removed. The drying rate of the falling rate period is governed by the physical properties of the product, the temperature and its moisture content (Mujumdar and Menon, 1995). In general, the drying rate, n_w, is defined by Equation 3.6 (Crapiste and Rotstein, 1997):

$$n_w = -\frac{m_s}{A_s}\frac{dX_m}{dt} = -\frac{\rho_s}{a_s}\frac{dX_m}{dt} \tag{3.6}$$

where m_s and ρ_s are the mass and density of dry solids, A_s and a_s are the external area and the area per unit volume, respectively, X_m is the moisture content of the material, and t is time.

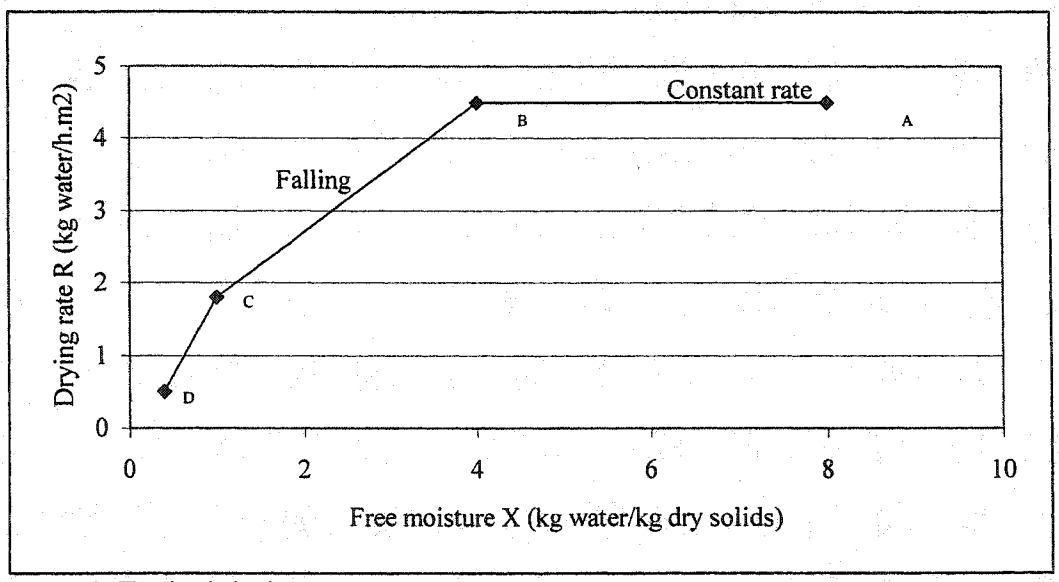

Figure 3.4: Typical drying rate curve (Adapted from Barbosa-Canovas and Vega-Mercado, 1996).

Drying kinetics are an important factor needed for dryer design (Ratti and Crapiste, 1992). Models are being established in drying processes in order to predict drying rates and temperature distribution. Mathematical models used in the design and control of the process parameters during drying can range from very simple to extremely complicated (Khraisheh et al., 2000). The goals of the models should be defined

extensively since their complexity will often depend on the target to be reached. Under certain conditions, results obtained from mathematical models generally compare well with experimental results (Hernandez et al., 2000; Khraisheh et al., 2000; Ghiaus et al., 1997; Ratti and Crapiste, 1992). Various parameters need to be considered when establishing a mathematical model, such as air temperature and velocities, samples specifications (such as size, chemical and physical properties), and dryer conditions (such as microwave power, degree of vacuum).

One method to preserve fruits and vegetables is through drying. Most fresh commodities, containing generally more than 80% of water for fruits and vegetables, are highly susceptible to spoilage through microorganisms growth and moisture-mediated deteriorative reactions. Drying fruits and vegetables represents a challenge due to various factors involved, such as the diversity of forms, the types of tissue forming the structural framework, and the chemical and physical properties of tissues influencing quality (Jayaraman and Das Gupta, 1995).

Even though several types of drying methods are commercially used for fruits and vegetables, three basic types of drying processes are generally applied: sun and solar drying, atmospheric drying (batch and continuous processes), and subatmospheric drying. Atmospheric drying methods include cabinet, tunnel, fluidized bed, spray and microwave heated dryers, whereas subatmospheric drying methods include vacuum and freeze-drying (Jayaraman and Das Gupta, 1995). Conventional hot air drying or freeze-drying are often used for small fruits. Freeze-drying is generally preferred due to the higher end quality of the product, but represents one of the most expensive drying methods. Alternatives for drying small fruits are vacuum drying, microwave drying, and combinations of freeze and microwave drying, vacuum and microwave drying, osmotic and vacuum drying and osmotic and freeze-drying (Venkatachalapathy, 1998).

Commercially available cranberries seem to be conventionally dried using hot air after being osmotically dehydrated. Yongsawatdigul and Gunasekaran (1996) have studied the effectiveness of a combination of osmotic dehydration, vacuum and microwave drying on cranberries. In their study on different drying methods applied to blueberries, Yang and Atallah (1985) investigated combined hot air and microwave

drying, hot air drying, freeze-drying, and vacuum drying. They suggested that the results they obtained could be applied to other small fruits, such as cranberries.

3.3.1 Microwave drying

One alternative to drying foodstuffs is microwave technology. Microwave heating occurs between 300 MHz and 300 GHz, and the wavelengths range from 1 mm to 1 m (Schiffmann, 1995). All bodies in the universe, above absolute zero temperature, emit electromagnetic waves, and all electromagnetic waves are characterized by their wavelength and frequency. An electromagnetic wave is a blend of an electric component, E, and a magnetic component, H. E and H are perpendicular to each other and both are perpendicular to the direction of travel (Schiffmann, 1995). When the electromagnetic wave passes through a material, its frequency remains the same but its wavelength changes, affecting the depth of penetration of the wave.

Another important aspect to grasp is that microwaves are a form of energy and not heat. In fact, heat is generated internally because of this microwave energy, and the heating is instantaneous due to the radiative heat transfer (Venkatachalapathy, 1998). Heat is manifested by the interaction of microwaves with the material, through different mechanisms such as ionic conduction, dipolar rotation, and interaction of electromagnetic fields with material (Schiffmann, 1995).

In ionic conduction, the ions present in the food are charged units and are caused to move in the direction opposite to their own polarity by the electric field. This movement causes the ions to collide with un-ionized water molecules, giving up kinetic energy, and since this occurs millions of times per second, large numbers of collisions and transfers of energy occur (Schiffmann, 1995). There is therefore a two-step energy conversion in using microwaves: the electric field energy is converted to induced ordered kinetic energy, which in turn is converted to disordered kinetic energy, at which point it can be regarded as heat.

In dipolar rotation, water molecules, which are dipolar in nature, are influenced by the rapidly changing polarity of the electric field. Even though these dipoles are normally randomly oriented, the electric field attempts to pull them into alignment. As the field decays to zero, the dipoles return to their random orientation until the electric field builds up to its opposite polarity. This re-orientation of the dipoles occurs millions

of times per second, because the electric field builds up and decays millions of times per second. Consequently, when the field is oscillating, the dipoles are constantly rotating, trying to orient according to the applied electrical field, at the same frequency of the field (Schiffmann, 1995; Garcia et al., 1992).

The nature of microwave-material interactions is governed by the dielectric properties of the material, including dielectric constant (ε') and loss factor (ε''), which are related to the complex dielectric constant (or electric permittivity complex) (ε) and to the loss tangent (tanδ) (Sanga et al., 2000). This can be represented by Equations 3.7 and 3.8:

$$\varepsilon = \varepsilon' - j\,\varepsilon'' \tag{3.7}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{3.8}$$

where $j = \sqrt{-1}$, which indicates a 90^{o} phase shift between the real (ε') and imaginary (ε'') parts of the complex dielectric constant (Schiffmann, 1995). The dielectric constant (ε') governs the distribution of the electromagnetic field within the material and provides an indication of the degree at which energy can be stored by the material (Sanga et al., 2000). Similarly, the loss factor (ε'') describes the degree at which energy can be dissipated into the material. The loss tangent is the ratio of dielectric loss to dielectric constant and indicates the microwave energy lost when absorbed by the material. The dielectric properties are affected by parameters such as moisture content, density, temperature, conductivity, specific heat and penetration depth of the material, as well as the frequency of the applied electromagnetic field (Schiffmann, 1995). In food processing, bulk dielectric properties can be considered since microwaves interact with both the food and the air in the inter-particle space (Venkatachalapathy, 1998).

Over the last few decades, it has been recognized that microwave heating can lead to potential economic, engineering and social benefits (Sanga et al., 2000). Some advantages and limitations of microwave drying are presented in Tables 3.2 and 3.3, respectively.

An advantage mentioned in Table 3.2 is the possibility of combining convection heat transfer with microwaves. This combination has been adopted by several food-

processing facilities in order to reduce drying time and improve food quality (Giese, 1992).

Table 3.2: Advantages of microwave drying (Adapted from Sanga et al., 2000 and Schiffmann, 1995)

Advantages	Reasons
Speed	Drying times can be shortened by 50% or more compared to conventional drying
Nondestructive	Drying can be done at low ambient temperatures, leading to lower thermal degradation
Efficiency	The energy couples into the solvent, not the substrate, resulting in higher drying efficiency
Energy savings	Due to the higher speed of drying
Possible combination	Possibility to combine vacuum or convection to microwaves by adding appropriate equipment resulting in higher drying efficiency

Table 3.3: Limitations of microwave drying (Adapted from Sanga et al., 2000)

Limitations	Reasons
Slow introduction in industry	Due to high initial costs, lack of documented energy savings and lack of well-established production operations
Negative sensory changes	Literature reports cases of microwave dried foods having unacceptable color or flavor to consumers
Uneven temperature distribution	The composition of biological material can lead to variations in moisture content within the material
Required sample size and shape	Difficulty in drying big size food because of insufficient microwave penetration and microwave leaking

Microwaves can also be combined with freeze-drying or vacuum drying in order to dry food material. Sanga et al. (2000) report that the combination of microwaves and freeze-drying was found successful in coffee processing and that various studies have shown decreases in drying time by a factor of 3 to 13. Cohen et al. (1992) report that the combination of microwaves with freeze-drying significantly increased drying rates of peas and enhanced rehydration capacity of the dried product. Microwave vacuum dryers are in commercial use for production of fruit juice concentrates, tea powder and enzymes (Sanga et al., 2000). The advantage of adding vacuum with microwaves is the resulting reduced boiling point of water, achieved at lower pressures. Consequently, heat transfer rates are increased and heat-sensitive products can be dried with lower risk of damage.

Drouzas and Schubert (1996) reported that combining microwaves with vacuum drying produced superior quality banana, where degradation due to high temperatures was prevented. A microwave vacuum drying system (MIVAC®) was developed by McDonnell Company in order to commercially dry grain using microwaves and vacuum (Sanga et al., 2000). Yongsawatdigul and Gunasekaran (1996) studied the combination of microwaves and vacuum in order to dry osmotically dehydrated cranberries. They found the storage stability of the resulting product comparable to that of conventionally-dried cranberries. In the present work, osmotically dehydrated cranberries will be dried using a combination of microwaves and hot air.

3.3.2 Hot air convective drying

Fruits and vegetables can be dried using hot air as the drying medium, which is often found as the simplest and most economical method. Based on hot air drying principles, different types of dryers, such as cabinet, tunnel, belt-through, and pneumatic conveyor dryers, have been designed and are now commercially used (Jayaraman and Das Gupta, 1995).

In hot air drying, convectional heat transfer is mainly involved since moving heated air is in contact with the material to be dried. In some types of hot air dryers, both the material and the air will be in movement. This causes various modes of flow such as countercurrent, parallel, combination of countercurrent and parallel, and cross flow (van't Land, 1991). Cabinet dryers, which are generally small-scale dryers for experimental drying of fruits and vegetables, consist of an insulated cavity in which the material is loaded on trays. Heated air is blown through the material by crossflow or through flow by a fan, which previously forced the air through heaters (Jayaraman and Das Gupta, 1995).

In hot air drying, four main factors can affect the rate and total time of drying: the physical properties of the food (particle size and geometry), the physical arrangement of the food with air (crossflow, through flow, tray load), the physical properties of the air (temperature, humidity, velocity), and the design characteristics of the drying equipment (Jayaraman and Das Gupta, 1995). Even though these factors are determined for each specific product, certain ranges can be determined for fruits. For example, air velocities of 2 to 5 m/s are generally used (Barbosa-Canovas and Vega-Mercado, 1996), and

Tulasidas (1994) reports that there is a quality-related upper temperature limit for hot air drying of grapes of 80°C, beyond which browning and other quality defects occur.

The main disadvantages of hot air drying are the non-uniformity obtained in the dried sample (Barbosa-Canovas and Vega-Mercado, 1996), the slower drying rates compared to other drying methods, and the quality of the resulting product, which may be improved by using other drying methods. Research has determined that the taste, color and overall quality of dried berries can be improved by using alternative methods, such as microwave drying (Yongsawatdigul and Gunasekaran, 1996; Tulasidas, 1994; Venkatachalapathy and Raghavan, 1998; Venkatachalapathy, 1998).

3.3.3 Freeze-drying

One major concern about drying processes is the fact that products being dried are generally exposed to high temperature for a certain time. Most drying processes have the disadvantage of altering compounds responsible for aroma and flavor in food due to long exposure to high temperatures. Therefore, some biological materials, such as pharmaceuticals and certain foodstuffs, cannot be heated through common drying processes, which would alter some of their characteristics. However, these products can successfully be dried using freeze-drying, which is also known as lyophilization. Freeze-drying was introduced in the 1940's on a large scale for the production of dried plasma and blood products (Barbosa-Canovas and Vega-Mercado, 1996). Since then, freeze-drying has been used for a wide variety of products and is today's most commonly used drying method for high-value products (Liapis and Bruttini, 1995). Figure 3.5 shows a simple schematic of a freeze-dryer.

Freeze-drying can be defined as a drying process in which the solvent (generally water) and/or the medium of suspension is crystallized at low temperatures and thereafter sublimated from the solid state directly into the vapor phase (Oetjen, 1999). Figure 3.6 shows the phase diagram of water and the area in which this transfer from solid to vapor is possible. From Figure 3.6, it can be seen that water will go directly from solid phase to gaseous phase when the conditions are below the triple point of water. This sublimation process is a complex one, even for pure water, and if the product contains two or more components in true solutions, simplified model substances must be used due to complexity (Oetjen, 1999).

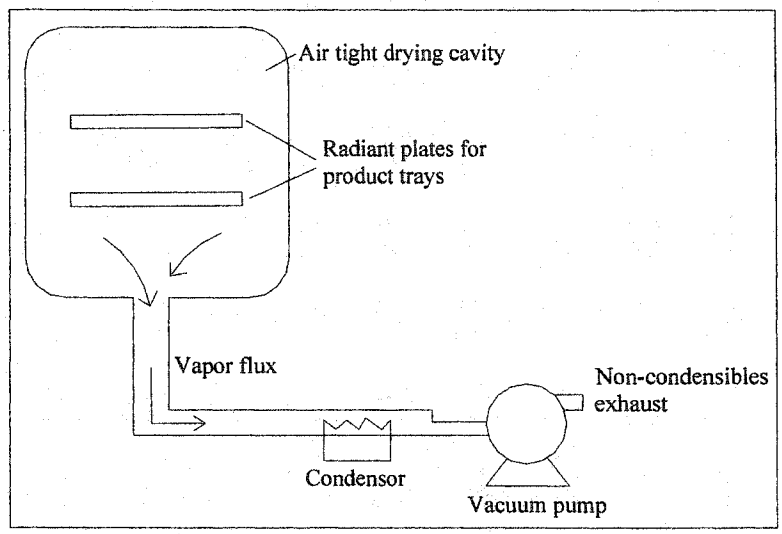

Figure 3.5: Schematic representation of a freeze-dryer

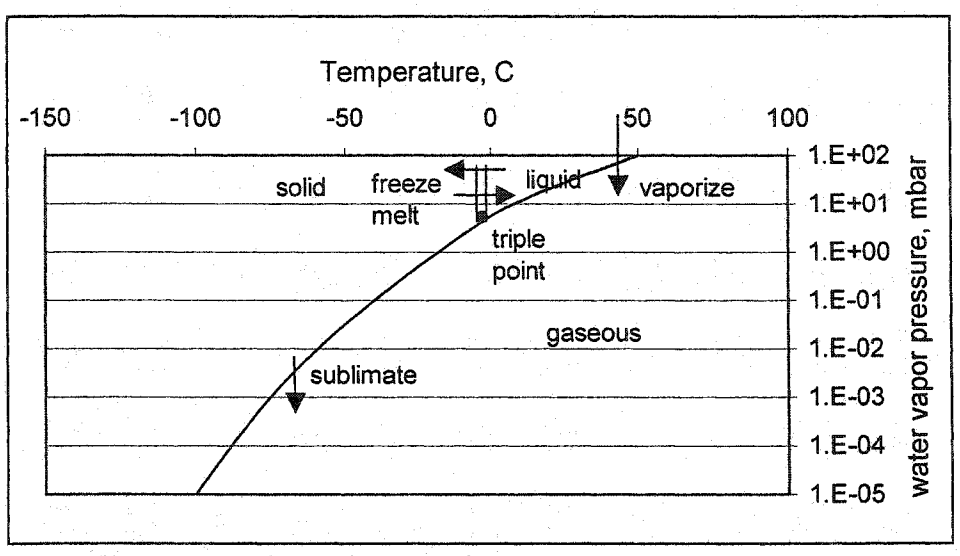

Figure 3.6: Phase diagram of water (Adapted from Oetjen, 1999)

The process of freeze-drying consists of three main stages: freezing, primary drying, and secondary drying. The freezing stage requires a rapid cool down of the temperature of the material in order to obtain fully crystallized water and solids (Oetjen, 1999). The primary drying stage involves sublimation of the ice crystals in the material caused by an applied vacuum. Therefore, the water, present as ice, sublimes when the energy for the latent heat is supplied. This energy can be generated in four forms: radiation of heated surfaces, conduction from heated plates or gases, gas convection, or

dielectric losses in the ice in a high-frequency field (Oetjen, 1999). However, the energy for sublimation is generally supplied by conduction to the frozen product through plates on which the material is placed. The condenser of the freeze-dryer will capture the water vapor in order to prevent its return to the product (Barbosa-Canovas and Vega-Mercado, 1996). This will cause the deposit of frost on the condenser during freeze-drying, which will tend to reduce its heat transfer efficiency. This is the reason why frost must be removed or defrosted, through passing hot air or by using a heating element in the condenser. The secondary drying step begins when no more ice is in the product but moisture is still present as partially bound water. Figure 3.7 shows a schematic of the moisture removal through freeze-drying.

In freeze-drying processes, because the moisture inside the food is removed by sublimation, the pressure inside the freeze-dryer must be less than or near the equilibrium vapor pressure of the frozen moisture. If frozen pure water was processed, sublimation could occur at a temperature at or near 0°C and at an absolute pressure of 611 Pa. However, water in foods exists in a combined state, therefore the material must be cooled below 0°C to keep the water in the frozen state. Under such a process, a temperature around −10°C and an absolute pressure of 267 Pa are commonly used (Liapis and Bruttini, 1995).

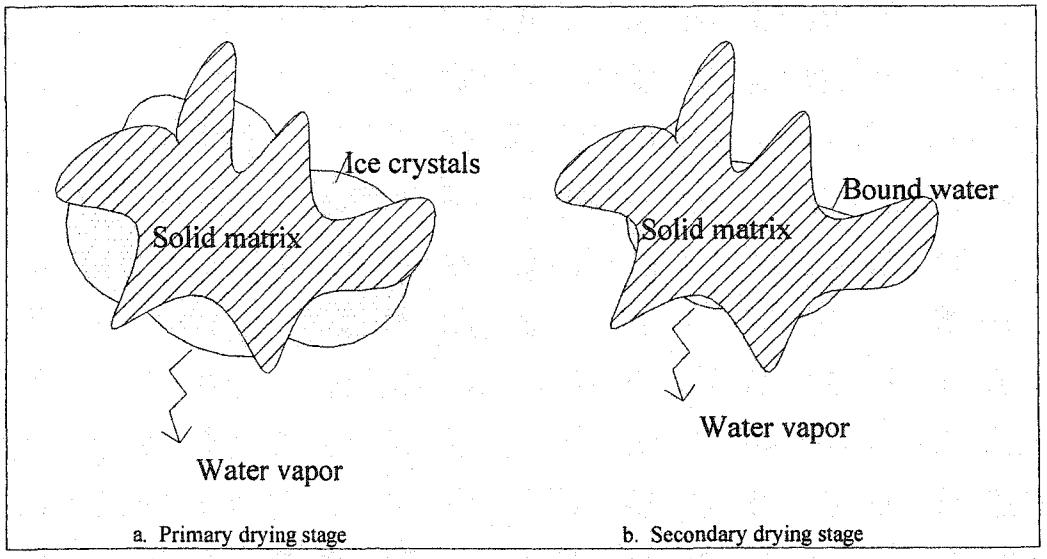

Figure 3.7: Schematic representation of the moisture removal through freeze-drying

Figure 3.8 shows a diagram of a cranberry cut in half, as it is being freeze-dried. As the ice sublimes, the sublimation interface, which started at the outside surface (where x = 0), recedes and a porous layer of dried material remains (Liapis and Bruttini, 1995).

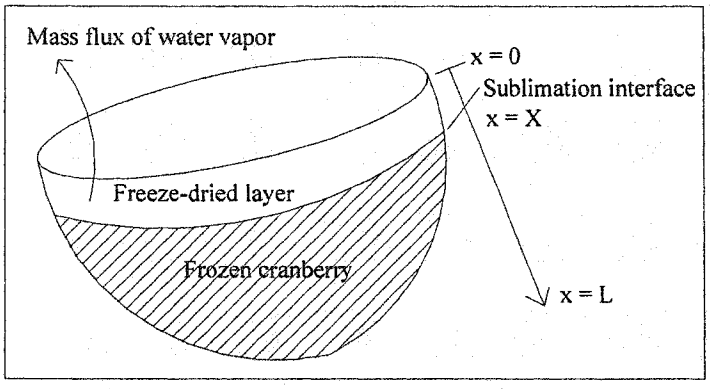

Figure 3.8: Diagram of a cranberry being freeze-dried

By looking at Figure 3.8, it can be expected that freeze-drying will be most useful when the final moisture content of the material is very low. In the case of a half cranberry, as shown in Figure 3.8, drying it to a moisture content around 15 to 20% (wet basis) could lead to a remaining frozen volume where x approaches to L. This could cause future collapse of the resulting dried product. This is why it is preferable to freeze-dry materials to a moisture content approaching zero.

Although freeze-drying implies expensive and sophisticated equipment, its use can be justified because the nature of the final product is hardly altered. Denaturation (decomposition of proteins) and loss of flavor, which occur in hot air drying of foodstuffs, can be prevented in freeze-drying. A good example of this is the distinct taste of spray-dried and freeze-dried coffee found on the market (van't Land, 1991). A variety of high-value products found on the market are freeze-dried. For example, mushrooms and berries, such as strawberries, are usually freeze-dried because they are highly sensitive products. Another important factor of freeze-drying is the structural rigidity afforded by the frozen skin of the product (Liapis and Bruttini, 1995). This rigidity can prevent the collapse of the solid matrix remaining after drying. This is why a freeze-

dried product tends to have a porous and nonshrunken structure with excellent rehydration capacity.

3.3.4 Vacuum drying

In vacuum dryers, the boiling point of water is reduced due to the lower pressure applied around the product. Similar to freeze-drying, vacuum drying is an expensive drying method due to the equipment involved. Figure 3.9 shows a simple diagram of a vacuum dryer used for laboratory experiments. The drying cavity where the product is placed must be heavily constructed to withstand the high vacuum conditions, and other parts of the setup, mainly vacuum pumps and means to collect the moisture (condensers or absorbent materials), also involve moderate or high installation and maintenance costs (Greensmith, 1998). The heat source on the setup shown in Figure 3.9 is in the form of heated plates inside the drying cavity, upon which trays of product are placed.

Vacuum drying has advantages that can justify its high costs, such as offering a product temperature lower than conventional drying methods and preventing oxidation of the product through contact with air (van't Land, 1991).

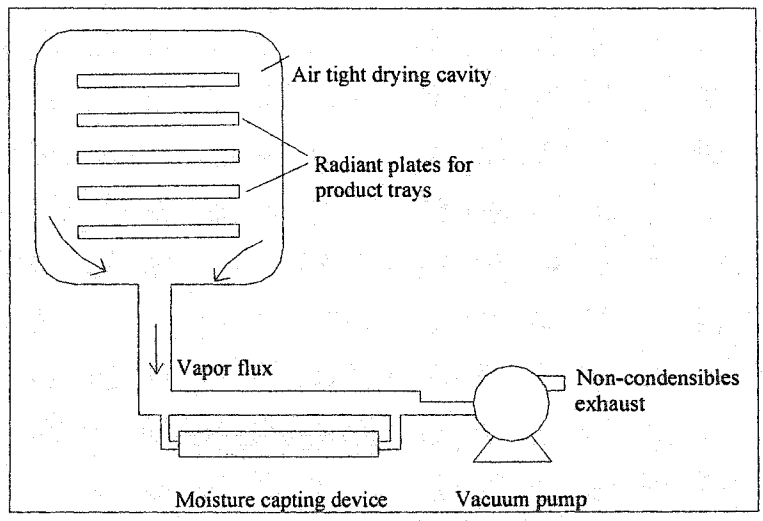

Figure 3.9: Diagram of a vacuum dryer used for laboratory experiments

Vacuum drying has been applied for dehydration of citrus juices, apple flakes, and various heat-sensitive products in which the ascorbic acid retention is important (Sokhansanj and Jayas, 1995). Even though the degree of vacuum and the temperature for drying depend on the sensibility of the product, most vacuum applications use levels

of absolute pressure of 7 kPa (50 mm Hg), at which the boiling point of water is reduced to 39°C (Barbosa-Canovas and Vega-Mercado, 1996).

Through the years, vacuum has been found to be a good method to combine with some other process, such as vacuum osmotic dehydration of fruits (Quan Shi and Fito Maupoey, 1993), microwave-vacuum drying of cranberries (Yongsawatdigul and Gunasekaran, 1996), and as a secondary dryer where the moisture content of a material is initially reduced to 20-25% by a conventional method, and then vacuum is applied to bring the moisture down to 1-3% (Sokhansanj and Jayas, 1995).

3.4 Quality evaluation

In order to determine the characteristics of cranberries dried under various methods, different parameters can be examined through a quality evaluation. These parameters include a sensory evaluation of the overall appearance and taste of the dried sample, along with the measurement of its surface color, texture, water activity and rehydration capacity.

3.4.1 Sensory evaluation

A sensory evaluation is an important part of the quality determination of a food product since it represents the consumer's appreciation of the product (Rennie et al., 2001). Different factors are important to the consumers and can be determined simply by being in contact with the food, such as texture, color and aroma. A scale from 1 to 7 (like extremely to dislike extremely, respectively) can be used, where untrained judges have to evaluate the overall appearance, the aroma, the color and the taste of dried samples. The judges can also be asked to provide any comments or observations they might think appropriate. Venkatachalapathy (1998) used a panel of ten or more untrained judges to perform sensory evaluation of convection, microwave and freeze dried strawberries and blueberries. Rennie et al. (2001) used a visual quality evaluation hedonic scale ranging from 9 to 1, representing visual quality of excellent to extremely poor, respectively.

3.4.2 Surface color determination

Objective measurement of surface color is a very important part of the quality evaluation of a food product. When measured with a colorimeter, the surface color can

be represented by three coordinates, L^*, a^*, b^*. These coordinates provide information on lightness of the material (McGuire, 1992). In the L^*, a^*, b^* color space, the lightness coefficient, L^*, ranges from 0 (black) to 100 (white), and the coordinates $a^*$and b^* locate the color on a rectangular-coordinate grid perpendicular to the L^* axis. On the horizontal axis, a^* indicates red-purple (positive value) and bluish-green (negative value). On the vertical axis, positive b^* indicates yellow and negative b^* indicates blue (McGuire, 1992). The data obtained in terms of L*, a* and b* can be converted to hue angle (h^o), and Chroma C*, an index somewhat analogous to color saturation or intensity (McGuire, 1992). Color difference (ΔE) can also be calculated in order to evaluate the difference in color between the tested material and some standard. The following equations can therefore be used for the surface color analysis (Yongsawatdigul and Gunasekaran, 1996; McGuire, 1992):

$$H^o = \tan^{-1}(b^*/a^*) \tag{3.9}$$

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2} \tag{3.10}$$

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{3.11}$$

where $\Delta L^* = L^*_{sample} - L^*_{standard}$

$\Delta a^* = a^*_{sample} - a^*_{standard}$

$\Delta b^* = b^*_{sample} - b^*_{standard}$

In their study on osmo-convective drying of blueberries, Nsonzi and Ramaswamy (1998b) determined color values of the dried samples in terms of L*, a*, b* values and calculated the total color difference ΔE. Similarly, Venkatachalapathy and Raghavan (1998) determined the total color difference in their study on microwave drying of osmotically dehydrated blueberries. In their study on microwave vacuum drying of cranberries, Yongsawatdigul and Gunasekaran (1996) reported that the color of dried cranberries was caused by red anthocyanins and yellow flavonoids. They refer to surface color of the dried samples through the hue angle (h^o), the Chroma index (C*) and the total color difference (ΔE).

3.4.3 Textural characteristics

Texture is one of the most important quality factors in foodstuffs and is related to the response of the tactile senses to physical stimuli which results from the contact

between the body (mouth, hands) and the food (Urbicain and Lozano, 1997). Textural attributes of materials can be determined by the amount of deformation or distortion caused by specific loads (Riley and Zachary, 1989). This can be represented by stress-strain relations, which are obtained by applying an axial load to a test specimen and measuring the load and deformation simultaneously. A testing machine, such as the Instron Universal Testing Machine (Instron Corporation, MA, USA), can be used to obtain such data. These texture measuring devices are found to have five essential elements: the driving mechanism, a probe element in contact with the food, a system to sense force-direction, a sensor for type and rate of application, and a read-out system (Venkatachalapathy, 1998). The probe element in contact with the food can be of various shapes, such as a flat plunger, shearing jaws, piercing rod, and cutting blade, and the selection of the probe element often depends on the food being sampled.

Empirical and imitative tests, classified as non-fundamental methods, are widely used in the food industry. In some cases, a single texture measuring system (e.g., Instron Universal Testing Machine and Kramer Shear Press) can perform several empirical and imitative tests (Urbicain and Lozano, 1997). In the case of a sample of many individual products, such as peas or dried cranberries, the Kramer shear press is an appropriate alternative to determine textural behavior. Figure 3.10 shows a schematic representation of a Kramer shear press. The mode of operation of such a device is shear, where the force necessary to shear through a food with one or multiple blades results in combinations of stresses. This method can be applied to fruits and vegetables, meat, cheese, and baked goods (Urbicain and Lozano, 1997).

Stress-strain relations are translated through stress-strain diagrams, from which different parameters can be calculated. Figure 3.11 shows a typical stress-strain diagram (or load versus displacement curve). The first part of the stress-strain diagram is commonly represented by a straight line, and Thomas Young, in 1807, suggested that the stiffness of a material could be determined by the stress-strain ratio of that part of the diagram (Riley and Zachary, 1989). This ratio is called Young's Modulus and is the slope of the straight-line portion of the diagram. Two points of the load-displacement curve are shown on Figure 3.11 and identified as yield and break points. The yield point

occurs when there is an appreciable increase in displacement (or strain) with little or no increase in load (or stress) (Riley and Zachary, 1989).

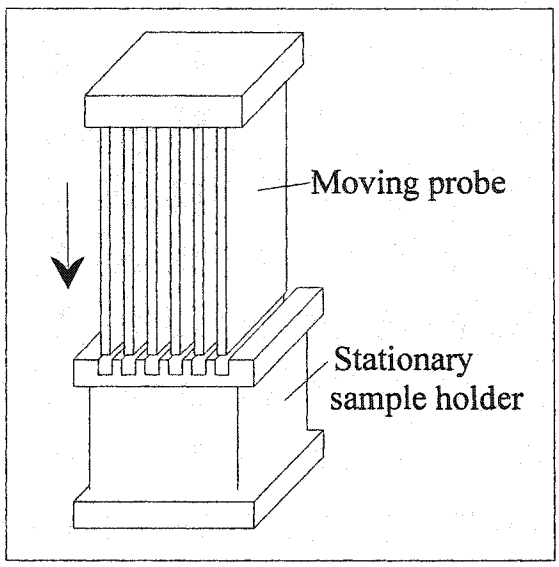

Figure 3.10: Kramer shear press used in compressive testing of dried cranberries

Along with Young's Modulus, other parameters obtained from the load-displacement relation are often of interest, such as the energy involved in different parts of the diagram. Energy characteristics, which can be determined from the area under the load-displacement curve, include energy to yield point, energy to break point, and a toughness parameter (Instron, 1993). This toughness factor is calculated by dividing the energy to break point by the volume of the sample being tested.

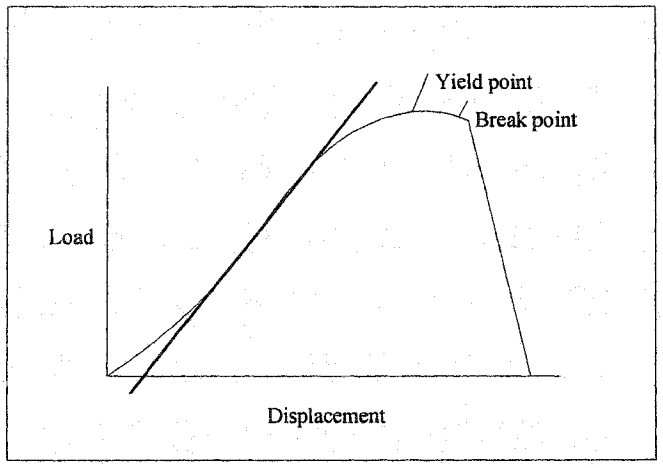

Figure 3.11: Typical diagram obtained from axial testing of a material

In their study on microwave-vacuum drying of cranberries, Yongsawatdigul and Gunasekaran (1996) measured texture of the dried samples using an Instron Universal Testing Machine (Model 1130), equipped with a v-shaped cutter probe. This way, the maximum force required to cut a single cranberry was determined. Nsonzi and Ramaswamy (1998b) determined textural characteristics of osmo-convective dried blueberries using a Lloyd Universal Testing Machine (Model LRX), equipped with a 50 mm diameter probe. The hardness and stickiness were derived from the load-displacement curves as indicators of texture. In their study on microwave drying of osmotically dehydrated blueberries, Venkatachalapathy and Raghavan (1998) determined textural characteristics of the dried samples using the Instron Universal Testing Machine, equipped with a 6 mm diameter probe. They expressed texture as toughness of the tested material, in units of Mega Pascals.

3.4.4 Water activity determination

An important aspect considered in food preservation is the understanding of how the water is bound in the food (Barbosa-Canovas and Vega-Mercado, 1996). The term water activity (a_w) was introduced in the 1950's and describes the state of water present in the food (Barbosa-Canovas and Vega-Mercado, 1996). The water activity of a product can be defined as the measurement of the energy status of water in a system, indicating how tightly water is bound, structurally or chemically, within a substance (Aqualab, 1999). It can indicate the relation between a food and the equilibrium relative humidity of the surrounding atmosphere.

The concept of water activity is of particular importance as an indication of product quality, safety and storability. Water activity can indicate the stability of a food product with respect to microbial growth, chemical and biochemical reaction rates, and physical properties (Barbosa-Canovas and Vega-Mercado, 1996). Through research, it was determined that microorganisms cannot grow in the dehydrated food system when the water activity range is less than or equal to 0.6-0.7, but enzymatic and nonenzymatic reactions may continue at this level of water activity (Jayaraman and Das Gupta, 1995).

Since water activity is a function of temperature, it is important to measure water activity at a constant temperature if comparisons are needed. Furthermore, a relationship

exists between the water activity and the water content of a product. This relationship is called the sorption isotherm, and is unique for each product (Aqualab, 1999).

Water activity can be estimated by using different methods, such as vapor pressure, osmotic pressure, freezing point depression, boiling point elevation, and psychrometric evaluations (through dew point and wet-bulb depression) (Jayaraman and Das Gupta, 1995). For example, vapor pressure can be determined from the dew point of an air-water mixture. The temperature at which the dew point occurs is determined by observing condensation on a smooth, cooled surface such as a mirror (Barbosa-Canovas and Vega-Mercado, 1996). The dew point temperature is subsequently related to the vapor pressure through psychrometrics.

3.4.5 Rehydration capacity measurement

The ability of a dried sample to rehydrate is an important aspect because numerous products need to be partially rehydrated before consumption. One consequence of dehydration is some loss in the ease of rehydration (Potter and Hotchkiss, 1995). This can be explained by physical shrinkage and distortion of cells and capillaries, but mainly by chemical and physicochemical changes at the colloidal level. Furthermore, the effects from heat (through drying) and sugar or salt concentration (through osmotic dehydration) can partially denature proteins, which can no further fully reabsorb and bind water. Other components, such as starches and gums, may also be altered through drying and/or dehydration and become less hydrophilic (Potter and Hotchkiss, 1995). Rehydration is maximized when the disruptions that occurred through drying and/or dehydration are minimized (Venkatachalapathy, 1998). Rehydration capacity is therefore expected to be higher in products that were dried under certain methods, such as freeze-drying, which is known to retain the structure of the product being dried. Freeze-dried foods were found to have an open porous structure that results in fast and high rehydration (Nsonzi and Ramaswamy, 1998b; Yang and Atallah, 1985).

IV. OPTIMIZATION OF SKIN PRETREATMENTS AND OSMOTIC DEHYDRATION ON CRANBERRIES

4.1 Introduction

When drying fruits and vegetables, pretreatments can be used in order to increase drying rates and/or to enhance the quality of the end product. The main pretreatments involve a skin pretreatment and an osmotic dehydration of the food. Skin pretreatments, either chemical or mechanical, are used to enhance the water diffusion through the skin of the product. In a chemical pretreatment, fruits are dipped in an alkaline solution for a given time and temperature, whereas in a mechanical pretreatment, the skin is cut, punctured or grazed. Osmotic dehydration causes a partial dehydration of the commodity, where moisture is removed and osmoactive substance (usually sugar or salt) is gained. The main advantages of osmo-dehydrating a product before drying are the resulting lower drying energy requirements, reduced heat damage to color and flavor, and better retention of flavor compounds.

4.1.1 Skin pretreatment

Skin pretreatment of certain commodities prior to drying has been studied over the last few decades. Even though mechanical pretreatments may be used, most studies focus on chemical pretreatments. This consists of dipping the fruits in an alkaline solution at a given time and temperature. Solutions containing EO ($C_{20}H_{38}O_2$) were found to facilitate water diffusion, thus increasing drying rates on fruits such as grapes, cherries, prunes, strawberries, and blueberries (Tulasidas et al., 1996; Ponting and McBean, 1970; Venkatachalapathy, 1998). Harrington et al. (1978) used scanning electron microscopy and suggested that EO redistributes wax on the surface of treated cherries, thereby enhancing mass transfer of water vapor through the partially dewaxed areas of the cuticle. Saravacos et al. (1988), who studied the effects of EO on the rate of air-drying of foods such as grapes, reported that the action of EO can be explained by its dissolving action on the waxy components and the cell walls of grapes, and by its wetting (surface active) effect on the resulting porous structure of the grape skin.

When studying a chemical pretreatment, different parameters are of interest. These include the time the fruits are left in the solution (called the dipping time), the chemical concentrations of the alkaline solution, and the solution temperature. Saravacos et al. (1988) and Tulasidas et al. (1996) used an EO and NaOH mixture before drying grapes to make raisins. Tulasidas et al. (1996) showed that using a mixture of EO and NaOH (2%EO in 0.5% NaOH) was preferred over EO only (0.5% NaOH) and over a solution of EO in potassium carbonate (3% EO in 2.5% K_2CO_3). Furthermore, Tulasidas et al. (1996) and Venkatachalapathy (1998) both determined that there was no significant difference in the drying times of grapes and strawberries (respectively) when pretreating them with mixtures of 2% EO in 0.5% NaOH and 3% EO in 0.5% NaOH. The lower concentration of EO was thus selected for the pretreatment of the fruits prior to drying in both experiments.

The dipping time and the temperature of the alkaline solution are also important factors to consider. Generally, the dipping time is increased with lower temperatures. Tulasidas et al. (1996) used 2% EO in 0.5% NaOH at 80°C for 30 seconds for pretreating grapes, whereas Venkatachalapathy and Raghavan (1998) used the same concentrations but at a temperature of 40°C for 1 minute when pretreating blueberries. Pangavhane et al. (1999) studied the effects of various pretreatments on grapes including room temperature dipping for 3 minutes and 93°C dipping for 5 seconds. They concluded that hot dipping pretreatment further reduced the drying time but produced raisins with diminished quality compared to those subjected to cold dipping pretreatments.

The main disadvantages of using chemical pretreatments are the consumer reluctance to eat foods that have been chemically treated, the added manipulation required by these pretreatments and the costs associated with them. Mechanical pretreatments are often suggested to replace chemical pretreatments in order to increase drying rates. So far, no literature exists on the chemical pretreatment of cranberries prior to drying. Yongsawatdigul and Gunasekaran (1996) performed a mechanical pretreatment on cranberries, by cutting them in half prior to osmotic dehydration.

4.1.2 Osmotic dehydration

Osmotic dehydration, which can be defined as a process that consists of placing foods, such as pieces of fruits and vegetables, in a hypertonic solution (Jayaraman and

Das Gupta, 1995) is often used before drying foods. In this process, variables of interest are the hypertonic solution used (generally sucrose or glucose solutions or high fructose corn syrup), the concentration and temperature of the solution, and the length of time the produce is immersed in the solution. In his research on strawberry drying, Venkatachalapathy (1998) showed that combining the fruit samples with granular sugar under a 4:1 fruit to sugar ratio at room temperature led to a clear drying time advantage, for both conventional hot-air and microwave drying, over fruits that were not previously osmotically dehydrated. It was also shown that the period of osmotic dehydration should not exceed 24 hours, after which off-odors could be developed. This is probably due to the fact that strawberries are extremely perishable, unlike the majority of other fruits. Under these conditions, the strawberry moisture content (wet basis) decreased from 89% initially, to 53% through osmotic dehydration.

In their work, Bolin et al. (1983) showed that the syrup penetration rate into a fruit piece was faster with high fructose corn syrup (HFCS) than with a sucrose solution. The conditions used for the osmotic dehydration were a 1:4 fruit to sugar ratio for a sucrose solution and HFCS both kept at 70°Brix and 70°C, and for dehydration times of 0.5, 1, 3, 5, and 7 hours. From this, the use of sucrose and HFCS lead to a solids gain in apples of 8.8% and 13.6% and a moisture loss of 65% and 70%, respectively, for a dehydration time of 7 hours.

Yongsawatdigul and Gunasekaran (1996) studied microwave-vacuum drying of cranberries and used an osmotic pretreatment on the fruits. It was shown that by using high fructose corn syrup at a 1:1 fruit to sugar ratio at room temperature and for 24 hours, the cranberry moisture content (wet basis) went from 87% initially, down to 76% and 62% for a 30°Brix and a 60°Brix fructose solution, respectively.

4.2 Objectives

The objectives of this study were to evaluate chemical and mechanical pretreatments on cranberries, to determine the effectiveness of an EO pretreatment on such fruits, to determine appropriate conditions for the osmotic dehydration of cranberries prior to drying them, and to examine the effects of osmotic dehydration on drying characteristics and final quality of cranberries.

4.3 Materials and Methods

All tests were performed on thawed cranberries (*Vaccinium macrocarpon*) of the Stevens cultivar, which were harvested using flooding of sandy soils. The fresh fruits were frozen after harvest and were completely thawed by immersion in ambient temperature water for 1 hour just before being used for dehydration.

4.3.1 Chemical pretreatment

Tests were done using a mixture of 2% EO and 0.5% EO (mass basis). In order to obtain this solution, liquid EO, which was previously kept at a temperature around –20°C, and granular EO were added to distilled water already at the desired temperature. Cold dipping was first performed for 30, 60 and 180 seconds in the alkaline solution left at ambient temperature (23°C ± 1). Three more solution temperatures were tested, 45°C, 65°C and 80°C, again for dipping times of 30, 60 and 180 seconds. After dipping, the fruits were rinsed using cold tap water to remove excess chemicals; they were then wiped gently with absorbent towels and air-dried to remove surface moisture. The treated fruits, along with untreated controls, were placed in granular sugar (2:1 fruit to sugar ratio) for 24 hours for osmotic dehydration. After 24 hours, the fruits were removed from the granular sugar, rinsed with warm tap water and again wiped gently with absorbent towels and air-dried to remove surface moisture. The mass of the samples was recorded and the samples were placed in the drying oven at 70°C until no more mass change was observed for moisture content determination (Boland, 1984).

Different concentrations of EO and EO were then tested. A mixture of 5% EO and 0.5% EO and one of 5% EO and 1.0% EO were used, both at a temperature of 45°C and a dipping time of 1 minute. Again, the treated fruits were rinsed and subjected to an osmotic dehydration as described above.

4.3.2 Mechanical pretreatment

Two mechanical pretreatments were tested on the cranberries; pin holes were performed to break the skin of the cranberries, and other fruits were cut in half. The first method consisted of perforating 15 pin holes per cranberry evenly over the surface and the second method required cutting each fruit in half with a stainless steel blade knife.

The mechanically treated fruits were then subjected to the same osmotic dehydration as the chemically treated ones, and were also compared to untreated controls.

4.3.3 Osmotic dehydration

Once an appropriate skin pretreatment was selected, different factors concerning osmotic dehydration were tested. Two different osmotic agents were used, granular sugar and high fructose corn syrup (HFCS), at different fruit to sugar ratios. The corn syrup used was Invertose 2655, at 76°Brix. The fruit to sugar ratios tested were 4:1, 3:1, 2:1 and 1:1 for granular sugar, and 2:1 and 1:1 for HFCS. Different dehydration times, which are the time the produce is immersed in the solution, were tested. These dehydration times were 12, 24, 36 and 48 hours. All tests were performed at ambient temperature.

After a given dehydration time, the fruits were removed from the osmotic agent, rinsed with warm tap water, gently wiped with absorbing towels and air-dried to remove surface moisture. The Brix content of both the cranberries and the remaining osmotic solution were measured using a hand-held refractometer (Fisherbrand by Fisher Scientific, Nepean, Ont.). The fruits were crushed in order to measure the Brix content of their syrup, and this was also done on untreated fruits in order to determine the Brix content of fresh cranberries. The moisture content of all the samples was taken under AOAC standards, by placing them in the drying oven at 70°C until no change in mass was observed.

Once the osmotic dehydration characteristics were established, two drying methods, freeze-drying and vacuum drying, were tested on both control and dehydrated cranberries. The freeze-drying tests were performed using a laboratory scale freeze-dryer (Unitop 400L, Virtis, USA), shown in Figure 4.1, equipped with twelve 600mL-bottles, shown in Figure 4.2, linked to the main oven cavity where vacuum was applied. The frozen twenty-five grams samples were placed in each bottle and their mass

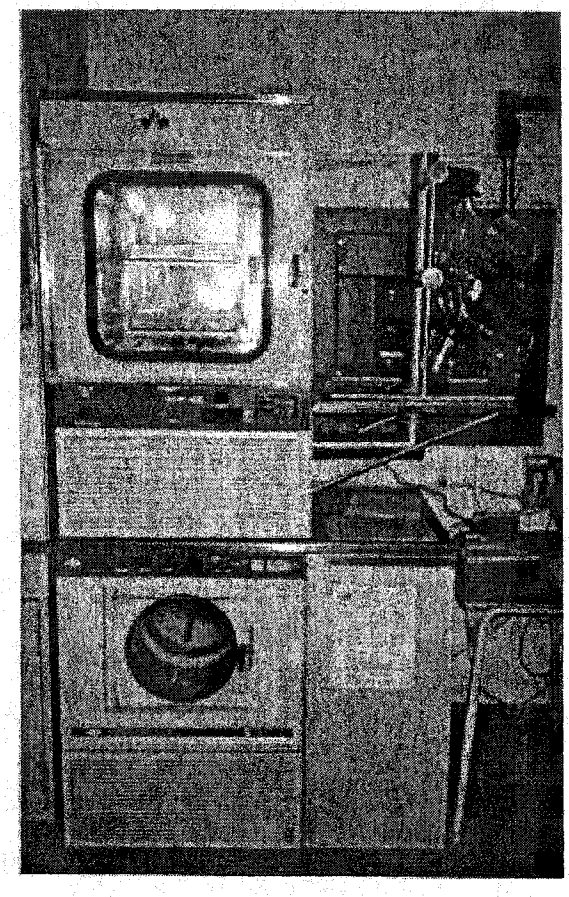

Figure 4.1: Photograph of the freeze-dryer used for drying cranberries

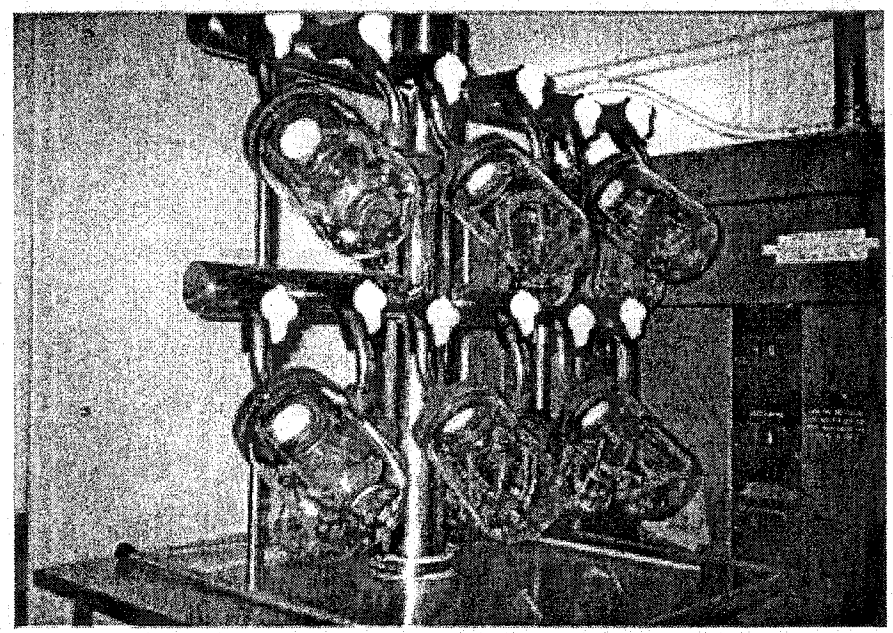

Figure 4.2: Photograph of the bottles connected to the freeze-dryer, where cranberries were placed for drying.

was recorded periodically (every two hours). All freeze-drying tests were thus performed at room temperature. The samples were removed once they reached a moisture content of 15% (wet basis), which is the average moisture content of commercially available dried cranberries. All samples were refrigerated at 4±1°C until quality evaluation. The vacuum drying tests were performed using a laboratory scale VWR Scientific vacuum dryer (John Scientific Inc., Canada), shown in Figure 4.3. The tests were performed at a plate temperature of 70°C and a pressure of about 7 kPa (a vacuum of 94.6 kPa). The mass of the samples (initially 25-g) was measured periodically (every two hours) by breaking the vacuum and stopping the experiment for a brief moment. The samples, placed on an aluminum plate, were removed from the vacuum dryer once they reached a moisture content of 15% (wet basis) and refrigerated at 4±1°C until quality evaluation.

Figure 4.3: Photograph of the vacuum dryer used for drying cranberries.

4.3.4 Quality evaluation

Quality evaluation included sensory evaluation performed by untrained judges who gave a grade according to taste (scale from 1 to 7, with lower number showing greater appreciation). Water activity measurement was performed at 40°C using a water activity meter (Model 3 TE Series, Meyer Service & Supply, Ont., Canada); rehydration ratio was calculated by using Equation 4.1 (Venkatachalapathy, 1998)

$$RR = 10\left(\frac{m_{rh}(100 - M_{in})}{m_{dh}(100 - M_{dh})}\right) \tag{4.1}$$

where RR = rehydration ratio
m_{rh} = mass of rehydrated sample (g)
M_{in} = initial moisture content (%wet basis) of the sample before drying
m_{dh} = mass of the dehydrated sample (g)
M_{dh} = moisture content (%wet basis) of the dried sample

The surface color of the samples was measured by using a chroma meter (Model CR-300X, Minolta camera Co. Ltd., Japan). The three parameters obtained from the measurement, the lightness coefficient L^*, along with the coordinates a^* and b^*, were converted to hue angle (h^o), and Chroma C*, and the total color difference (ΔE) was also calculated in order to evaluate the change in color between the fresh (frozen-thawed) and dried cranberries. The following equations were used (McGuire, 1992):

$$H^o = \tan^{-1}(b^*/a^*) \tag{4.2}$$

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2} \tag{4.3}$$

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{4.4}$$

where $\Delta L^* = L^*_{sample} - L^*_{standard}$

$\Delta a^* = a^*_{sample} - a^*_{standard}$

$\Delta b^* = b^*_{sample} - b^*_{standard}$

4.3.5 Experimental design

All experiments were conducted in triplicate and the data were subjected to analysis of variance. Differences were identified as significant or non-significant based on the Student-Newman-Keuls test and Duncan's multiple range tests for each variable

(i.e. fruit to sugar ratio, dehydration times, osmotic dehydration). A significance level of 0.05 was used in all cases.

4.4 Results and Discussions

4.4.1 Skin pretreatment

No difference was observed in the water loss through the osmotic dehydration of both the untreated and chemically pretreated fruits, under all test conditions. In other words, the use of a mixture of EO and EO at different concentrations, temperatures and for different dipping times was not found to be successful on promoting diffusion of water through the cranberry skin. The moisture content loss through the osmotic dehydration of all samples, which lasted 24 hours, was from 1 to 4% (wet basis), which has no practical advantage. The four different mixture temperatures used, along with the different dipping times, did not appear to affect the cranberry skin. However, dipping the fruits in a solution at 80°C for more than 30 seconds did affect the fruits, in that they started to cook, and their texture was deteriorated. The different concentrations of both EO and EO did not appear to affect the porosity of the cranberry skin. Table 4.1 summarizes the results from the chemical pretreatment.

On examination of the two mechanical pretreatments, making pin holes in each fruit was found unsuccessful (moisture content decreased about 2% w.b.), whereas cranberries cut in half and placed in granular sugar had a moisture content decrease of 24% (w.b.). The conditions of the osmotic dehydration subsequent to each pretreatment were similar; granular sugar was used at a 2:1 fruit to sugar ratio for 24 hours at room temperature. By cutting each cranberry in half, the interior of the fruit was exposed directly to the osmotic agent and the mass transfers involved in the osmotic dehydration were therefore promoted.

4.4.2 Osmotic dehydration

Using both granular sugar and high fructose corn syrup, different fruit to sugar ratios resulted in different moisture content decreases for a dehydration time of 24 hours at room temperature for cranberries cut in half. These results are presented in Table 4.2.

Table 4.1: Moisture content decrease of cranberries through osmosis after chemical pretreatments under various conditions

Mixture used	Temperature of solution (°C)	Dipping time (min)	Moisture content decrease through osmosis (% w.b.)
2% EO 0.5% NaOH	Ambient	0.5-1.0-3.0	1.2-1.4-2.0
2% EO 0.5% NaOH	45	0.5-1.0-3.0	0.9-1.1-1.2
2% EO 0.5% NaOH	65	0.5-1.0-3.0	1.8-3.2-2.1
2% EO 0.5% NaOH	80	0.5-1.0-3.0	3.7-NA*-NA*
5% EO 0.5% NaOH	45	1.0	1.6
5% EO 1.0% NaOH	45	1.0	1.2

* Results are not available due to the cooking of the cranberries under such dipping conditions

Table 4.2: Mean moisture and sugar contents in dehydrated cranberries cut in half for 24 hours at room temperature for different fruit to sugar ratios

Osmotic agent	Fruit to sugar ratio	Final moisture content (%wb)	Sugar content (°Brix)
Granular sugar	1:1	61.1^{b}	31.8^{b}
Granular sugar	2:1	64.4^{c}	28.7^{c}
Granular sugar	3:1	66.8^{d}	25.0^{d}
Granular sugar	4:1	70.7^{e}	22.7^{e}
HFCS	1:1	57.1^{a}	37.4^{a}
HFCS	2:1	63.5^{c}	$30.3^{b,c}$

Duncan groupings: means with the same letters are not significantly different

The Brix content of the dehydrated cranberries increased from 17 to 31°Brix, since fresh cranberries are around 6°Brix. The HFCS, originally at 76°Brix, gained some water from the fruits and thus had a final Brix content between 52 and 57. By recording the mass of each sample before and after the osmotic dehydration, different mass transfer components can be calculated from the following equations:

$$\text{Mass loss} = \frac{\text{initial mass before osmosis} - \text{total mass after osmosis}}{\text{initial mass before osmosis}} * 100 \qquad (4.5)$$

$$\text{Solids gain} = \frac{\text{mass solids after osmosis} - \text{mass solids before osmosis}}{\text{initial mass before osmosis}} * 100 \quad (4.6)$$

$$\text{Moisture loss} = \frac{\text{initial moisture content} - \text{final moisture content}}{\text{initial moisture content}} * 100 \quad (4.7)$$

The equations above were used and Table 4.3 summarizes the different component transfer under specific conditions.

Table 4.3: Component transfer in granular sugar and HFCS in the dehydration of cranberries for 24 hours at room temperature for different fruit to sugar ratios

Osmotic agent	Fruit to sugar ratio	Mass loss (%)	Solids gain (%)	Moisture loss (%)
Granular sugar	1:1	7.8	24.6	31.1
Granular sugar	2:1	3.4	23.2	27.5
Granular sugar	3:1	5.9	20.0	24.7
Granular sugar	4:1	9.6	15.3	20.4
HFCS	1:1	0.8	31.3	35.7
HFCS	2:1	5.9	23.1	28.5

When left in the osmotic agent for 24 hours at room temperature and at the same fruit to sugar ratio (i.e. 1:1), cranberries in HFCS had absorbed more solids and lost more moisture than those in granular sugar. Bolin et al. (1983) report that sucrose, being a disaccharide, would be expected to migrate slower than fructose, which is a monosaccharide, whether the migration mechanism is explained by the conventional diffusion procedure or by the bulk flow theory of Ray (1960). Furthermore, Bolin et al. (1983) reported that research has shown that fructose had a diffusion coefficient 32% higher than sucrose. High fructose corn syrup was found to replace more of the water in the cells of apples than sucrose because of its faster penetration rate. Another important factor to consider is that granular sugar, being a solid, will have a different contact area with the fruits than HFCS, which is a liquid. From the results shown in Table 4.3, it can be noted that there does not appear to be a clear correlation between the fruit to sugar ratio and the mass loss. It is important to realize that mass loss is a function of both the

rates of water and sugar diffusion. This is why having a smaller fruit to sugar ratio (1:1 versus 2:1 HFCS to fruit ratio) may not result in a larger mass loss, as expected.

Once different fruit to sugar ratios were tested and high fructose corn syrup at 1:1 F:S was found to efficiently reduce moisture and increase sugar content in cranberries, different dehydration times were tested. Tables 4.4 and 4.5 report the results obtained.

Table 4.4: Mean final moisture and sugar contents in cranberries dehydrated in HFCS at a 1:1 fruit to syrup ratio for different dehydration times at room temperature

Dehydration time (hours)	Final moisture content (%wet basis)*	Final sugar content (°Brix)*
12	62.6[a]	32.3[a]
24	57.1[b]	37.4[b]
36	50.2[c]	45.2[c]
48	46.4[d]	51.0[d]

*Duncan groupings: means with the same letters are not significantly different

Table 4.5: Component transfer in HFCS at a 1:1 fruit to syrup ratio in the dehydration of cranberries at room temperature for different dehydration times

Dehydration time (hours)	Mass loss (%)	Solids gain (%)	Moisture loss (%)
12	2.0	25.5	29.5
24	0.8	31.3	35.7
36	-2.9	40.0	43.5
48	-4.9	45.1	47.8

When examining Table 4.4, a logarithmic function can be fitted on the available data in order to get an estimation of the maximum moisture content loss and Brix content increase that could be obtained. Figure 4.4 shows logarithmic fit of the data presented in Table 4.4.

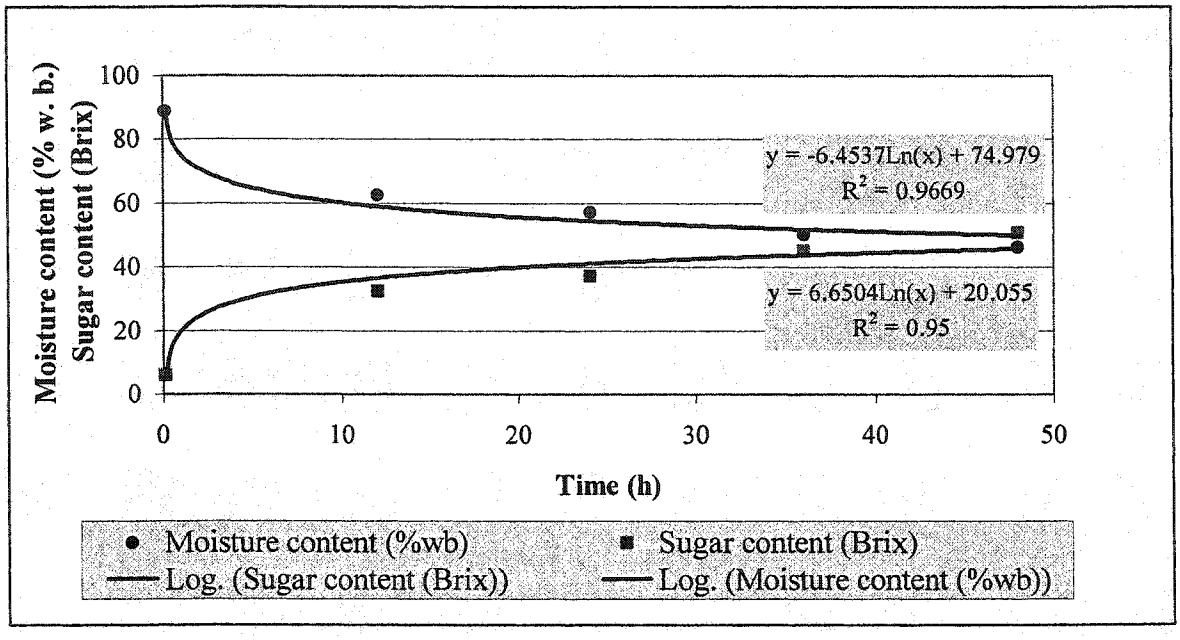

Figure 4.4: Logarithmic function of the moisture content (%wb) and Brix content of cranberries in HFCS at 1:1 F:S, for different times at room temperature

The equations shown on Figure 4.4 are useful for the range of 0 to 48 hours. As observed from Tables 4.4 and 4.5, both the solids gain and the moisture loss increase with an increased dehydration time. However, the subsequent moisture content loss and sugar content increase beyond 24 hours is not justified. The samples left in the corn syrup for 36 and 48 hours had an unacceptable quality after the osmotic process. The fruits became darker and the edges of the cut cranberries started to "blacken" and to oxidize. However, the significant difference in the results for 12 and 36 hours justifies the selection of 24 hours for appropriate osmotic dehydration conditions done at room temperature for cranberries. It can also be noted that with a dehydration time longer than 24 hours, the mass loss observed was negative, i.e. more sugar was gained than water was lost. Figure 4.5 shows a photograph of cranberries being dehydrated by osmosis in high fructose corn syrup under different fruit to sugar ratios.

When dried cranberries, that were not osmotically dehydrated, were compared with cranberries that were first dehydrated, significant differences in their characteristics can be observed. Table 4.6 shows results obtained from both drying methods. Figure 4.6 shows a photograph of freeze-dried cranberries, with no prior dehydration (left) and with an initial osmotic dehydration (right). Osmotically dehydrated (treated) and control samples were freeze-dried to a final moisture content of 15% (wet basis) in 5.7 hrs and 7.6 hrs, respectively. Treated and control samples were vacuum dried to a final moisture content of 15% (w.b.) in 4.6 hrs and 6.8 hrs, respectively. All these drying times were found to be significantly different ($P < 0.05$), based on Duncan groupings. As expected, there is an advantage of performing an osmotic dehydration based on drying times. Figures 4.7 and 4.8 represent drying curves for both osmotically dehydrated and control fruits being dried under two methods.

The sensory evaluation, although not statistically valid, showed that consumers preferred cranberries that were previously osmotically dehydrated. The sugar uptake through this process reduced the tartness of the fruits, which seemed to be necessary for consumer acceptance. The water activity of all dried samples was found to be lower than 0.7, which is often referred to as the limit to intermediate moisture foods (Raoult-Wack et al., 1992).

An important distinction can be made between the osmotically dehydrated cranberries and those that were not previously treated before drying; the rehydration capacity is significantly lower ($P < 0.05$) in osmotically dehydrated cranberries. Since the internal structure of the fruit is disintegrated due to osmotic stress during the osmotic dehydration (Rastogi et al., 2000), the rehydration is not performed as in an undisturbed fruit. Other studies have also confirmed this observation, such as the results obtained by Sereno and Moreira (2000) on the changes of rehydration capacity of osmotically treated apple. The authors reported that in all cases, rehydration capacities were lower with osmotically dehydrated apple, due to structural changes during dehydration and to solute penetration. Also, the lower rehydration ratio of the osmotically dehydrated fruits can be explained by the added solids in the cranberries, which reduced the amount of water being absorbed during rehydration (Nsonzi and Ramaswamy, 1998).

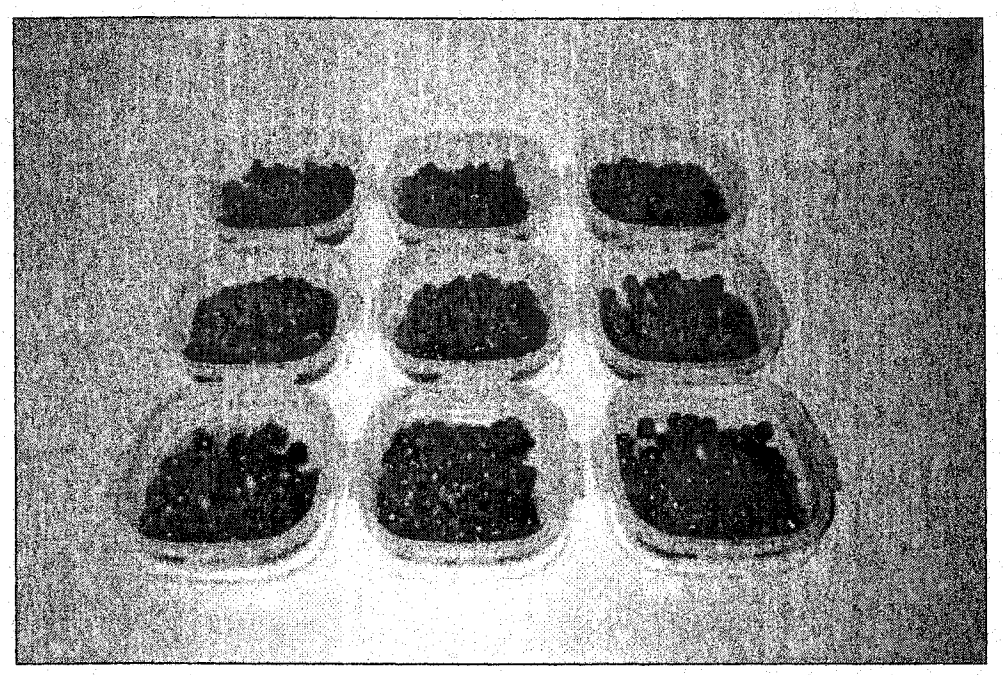

Figure 4.5: Photograph of cranberries being dehydrated by osmosis in high fructose corn syrup under different fruit to sugars ratios.

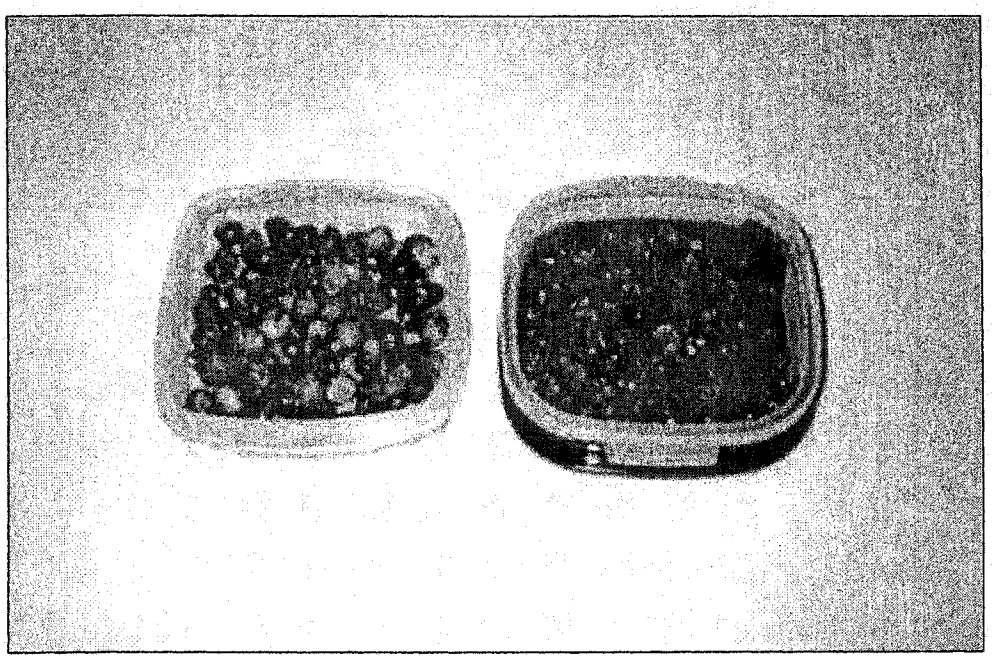

Figure 4.6: Photograph of freeze-dried cranberries, with no prior dehydration (left) and with an initial osmotic dehydration (right)

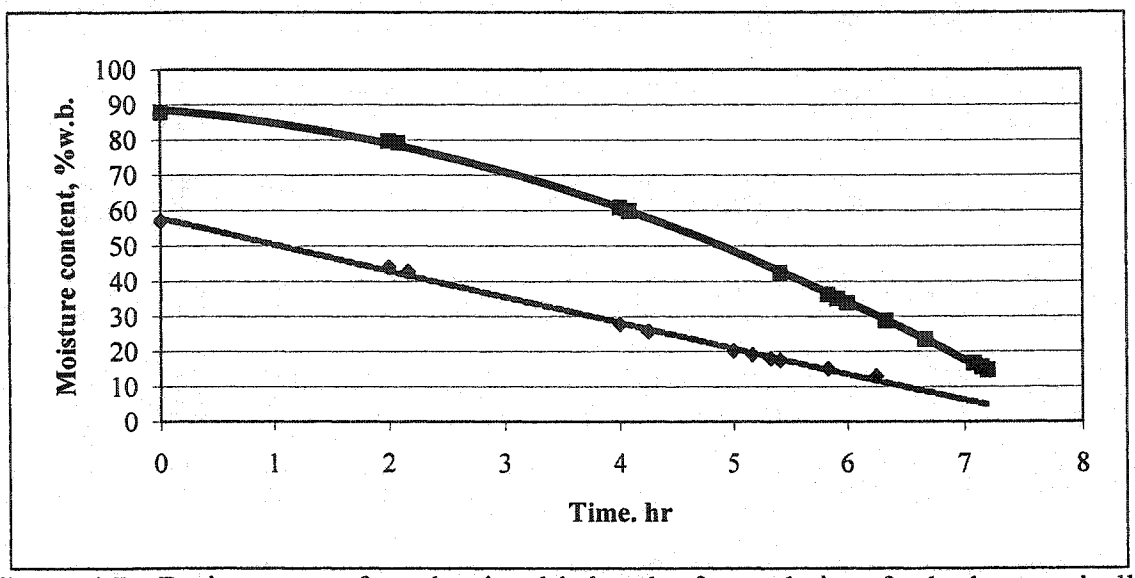

Figure 4.7: Drying curve of cranberries dried under freeze-drying, for both osmotically dehydrated fruits (dotted line) and control fruits (continuous line).

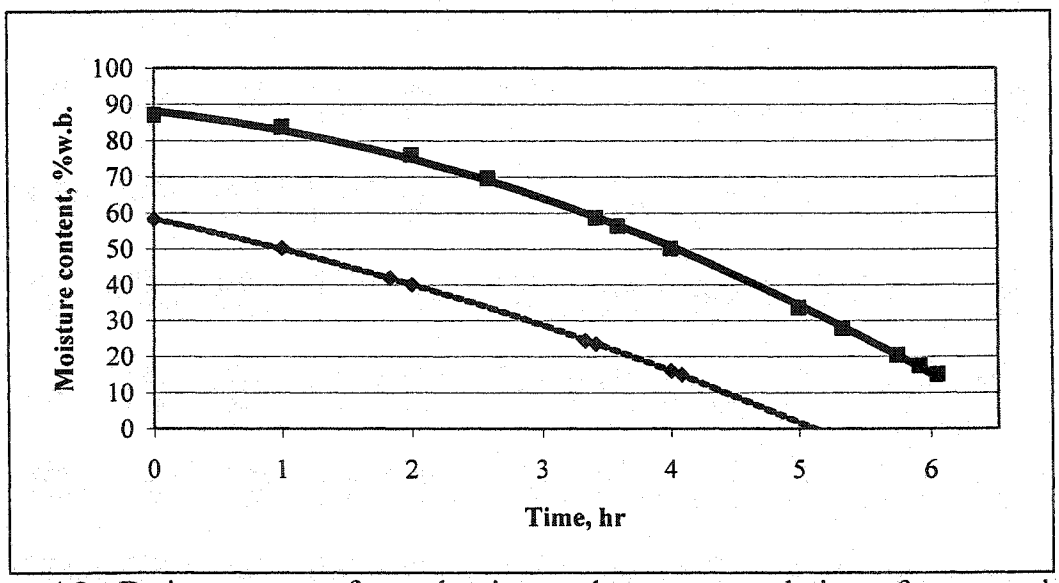

Figure 4.8: Drying curve of cranberries under vacuum drying, for osmotically dehydrated fruits (dotted line) and control fruits (continuous line).

Table 4.6 shows that freeze-dried cranberries that were not osmotically dehydrated have a significantly greater color difference than the other treatments. This was noticeable even by visual inspection of the samples, where the freeze-dried cranberries had a much lighter surface color than the other samples. Furthermore, the values for redness of the freeze-dried fruits, both osmotically dehydrated or not, are higher than the redness values of vacuum dried fruits. It may be explained that

degradation of anthocyanin pigments, which are closely related to redness of fruits (Forni et al., 1993) in cranberries dried by freeze-drying, is less since the temperature is lower than that used in vacuum drying. Anthocyanins are not stable chemically and their exposure to heat treatments can enhance their oxidation, thus resulting in degradation of color (Forni et al., 1993).

Table 4.6: Effect of osmotic dehydration and of two drying methods on sensory evaluation, water activity, rehydration ratio, and surface color.

	Taste	Water activity	Rehydration ratio	Color difference ΔE
Treated and freeze-dried	2.1	0.664	2.0^{c}	4.3^{b}
Treated and vacuum dried	2.3	0.602	1.8^{c}	4.4^{b}
Untreated freeze-dried	5.4	0.568	6.0^{a}	12.5^{a}
Untreated vacuum dried	6.7	0.677	3.5^{b}	6.0^{b}

Duncan groupings: means with the same letters are not significantly different

4.5 Conclusions

Changing the temperature and concentration of the EO and EO mixture, along with changing the time the fruits were dipped in the mixture did not have a significant effect ($P < 0.05$) on promoting water diffusion through the cranberry skin. Mechanical pretreatments were also tested and it was shown that making 15 pin holes in the skin of each cranberry did not have an effect on promoting mass transfer involved in osmotic dehydration. However, cutting the fruits in half did have a significant impact ($P < 0.05$) on the dehydration of cranberries through osmosis. The cut fruits had a moisture content decrease of about 24% (wet basis) when using granular sugar at a fruit to sugar ratio of 2:1 for 24 hours at room temperature.

Changing the osmotic agent and the fruit to sugar ratio when performing osmotic dehydration on cranberries had an effect on moisture loss and solids gain. High fructose corn syrup was found to cause higher solids gain and moisture loss than granular sugar when the fruits were left in the osmotic syrup for 24 hours at room temperature at a fruit to sugar ratio of 1:1.

Changing the time that cranberries remained in the osmotic agent also had a significant effect on both the moisture loss and the solids gain. These two variables increased with an increased dehydration time. However, leaving the cranberries in the osmotic agent for more than 24 hours resulted in fruits having an unacceptable quality at the end of the osmotic process.

Osmotic dehydration also resulted in significant differences ($P < 0.05$) in drying characteristics of cranberries. A significant difference ($P < 0.05$) was observed in drying times, where the shortest drying time was found by using osmotic dehydration prior to vacuum drying. An important difference was observed in the rehydration capacity of the dried cranberries, with osmotically dehydrated fruits having a lower rehydration ratio than untreated fruits. Furthermore, untreated and freeze-dried cranberries had a greater rehydration capacity and color difference than cranberries dried under other conditions. Sensory evaluation performed by judges determined that osmotic dehydration, prior to drying, was necessary for consumer acceptance of cranberries.

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CONNECTING TEXT

Upon determining the pretreatment characteristics of cranberries, the next step was to examine the drying behavior of these fruits when subjected to different drying methods. In this work, one dielectric method was tested, where a combination of microwaves and hot-air was used to dry osmotically dehydrated cranberries to a moisture content of approximately 15% (wet basis). Parameters involved in microwave drying, such as power density and cycling period, were examined and appropriate conditions determined based on drying times and quality of the end product.

V. OPTIMIZATION OF MICROWAVE DRYING OF OSMOTICALLY DEHYDRATED CRANBERRIES

5.1 Introduction

Although they appear as new technologies, microwave and dielectric heating have been used for many years. Over the last decades, there has been an increasing interest in the applications of microwave and dielectric heating in the industry, mainly due to the worldwide energy crisis. This interest may be explained by volumetric heating due to microwave penetration and reduced processing times, which can be translated into energy and economical savings (Sanga et al., 2000).

Today, many research projects have shown the advantages of using microwaves in drying processes (Cohen et al., 1992; Garcia et al., 1992; Tulasidas et al., 1993; Venkatachalapathy and Raghavan, 1998; Yongsawatdigul and Gunasekaran, 1996). Different parameters involved in the microwave drying of foodstuffs can be examined. For example, the power density and the mode in which microwaves are generated (i.e. pulsed or continuous modes) must be examined for specific products.

5.1.1 Microwave drying

Over the last decades, it has been recognized that microwave heating can lead to potential economic, engineering and social benefits (Sanga et al., 2000). Radio frequency (RF) and microwaves (MW) are forms of electromagnetic wave energy, which are used in industrial applications, such as drying of foodstuffs, wood, papers and textile. Radio frequency and microwave have a penetrating effect on the product, which causes volumetric heating. Materials, that are absorbers and transmitters of microwaves, are said to be dielectric, and when subjected to microwaves, heat is generated through the materials.

The mechanisms of dielectric drying can be understood by looking at the dipole orientation at the molecular level; in the absence of an energy field, the molecules of liquid water have a random distribution of the position of their dipoles. However, when an external electrical field is applied around the molecules, the dipoles re-orient with the applied field. Consequently, if the field is oscillating, the dipoles are constantly rotating,

trying to orient according to the applied electrical field, at the same frequency of the field. Because of the inertial interactions among the molecules, heat is generated and is dependent on the frequency of the electrical field (Garcia et al., 1992). The resulting energy is absorbed throughout the volume of the material being dried. In fact, it is the increase in internal pressure that drives out the moisture from the interior of the material to the surface where evaporation occurs (Sanga et al., 2000). Radio frequency and microwave heating is therefore often combined with conventional drying means in order to enhance drying rates.

5.1.2 Power density and cycling period

When applying microwave energy in a drying process, different parameters must be considered. For example, the amount of generated microwaves according to the quantity of material being dried and the mode in which microwaves are generated are important factors. The power density is used to refer to the amount of generated microwaves according to the mass of material being dried. Power density is commonly expressed in units of W/g (Raghavan and Silveira, 2001; Venkatachalapathy, 1998;Tulasidas, 1994).

Microwaves can be generated via two different modes: by using a pulsed or a continuous mode. However, research has shown that continuous heating does not accelerate the rate of water removal when critical moisture content is reached, and that there is no overall advantage of using a continuous mode over a pulsed one (Yongsawatdigul and Gunasekaran, 1996). When using pulsed heating, the microwave generator is turned off for a specific amount of time, and thus different power-on and power-off times can be used. Yongsawatdigul and Gunasekaran (1996) examined two power-on times (30 and 60 s) and three power-off times (60, 90, 150 s) when microwave-vacuum drying cranberries. They determined that a power-on time of 30 s and a power-off time of 150 s were the most suitable settings for maximum drying efficiency.

5.2 Objectives

The objectives of this study were to evaluate the drying characteristics of osmotically dehydrated cranberries under a dielectric method, where microwaves and hot-air are combined to dry osmotically dehydrated cranberries; to determine the

appropriate microwave power density and cycling period; and to perform a quality evaluation on the dried samples.

5.3 Materials and Methods

All tests were performed on cranberries (*Vaccinium macrocarpon*) of the Stevens cultivar, which were harvested using flooding of sandy soils. The fresh fruits were frozen after harvesting and were completely thawed by immersion in ambient temperature water for 1 hour just before being used for dehydration. The fruits were initially cut in half and dehydrated through osmosis, by placing the fruits in high fructose corn syrup (76 °Brix) at a 1:1 fruit to sugar ratio, at ambient temperature and for 24 hours (as determined in Chapter 4). The fruits were then rinsed with warm tap water and gently dried with towels. The samples were then refrigerated at 2°C until used for drying. The mean initial moisture content of fresh (thawed) cranberries was 88.0% (wet basis), and the mean moisture content of the osmotically dehydrated cranberries was 57% (wet basis) before drying.

5.3.1 Microwave drying

The tests were performed using a custom designed laboratory scale convective and microwave dryer, shown in Figure 5.1. The dryer was equipped with a 750 Watts, 2450 MHz microwave generator (item 1). Generated microwaves traveled through a series of rectangular waveguides to the main cavity (item 6), and a circulator (item 2) ensured the absorption of reflected microwaves within the main cavity. Item 3 in Figure 5.1 shows two power meters indicating both the incident and reflected power. Incident power was set according to the tested power density, which was based on the initial mass of the sample. Reflected power was maintained manually around zero during the experiments, via three tuning screws inserted in the top of the wave-guide assembly (item 4). Heated air was continually blown on the sample placed as a single layer on the sample holder (item 7), by a 0.25 kW blower (item 8) placed underneath the drying cavity. Three 2 kW-electrical heaters (item 9) were used to raise the air temperature. The temperature and velocity of the air were maintained constant throughout the tests, at 45°C and 2 m/s, respectively. The mass of the samples (initially 125 g) was monitored during the drying process, as the sample holder was equipped with a strain gage (item 5).

The inlet and outlet air temperature was measured with Type-K thermocouples, and the temperature of the sample was measured using a digital fiber optic thermometer (Nortech Fibronic Inc. Canada) specially appropriate for microwave applications. All temperature, power and mass data were recorded by a data acquisition system (HP34970A – Data Acquisition / Switch Unit, Hewlett-Packard, USA). A computer program was written in HPVEE to monitor the drying process. The sample was removed when it reached a moisture content of 15% (wet basis) and refrigerated at 4±1°C until quality evaluation was performed, one week later. Figure 5.2 shows a photograph of the experimental set-up for microwave and hot-air drying of microwaves.

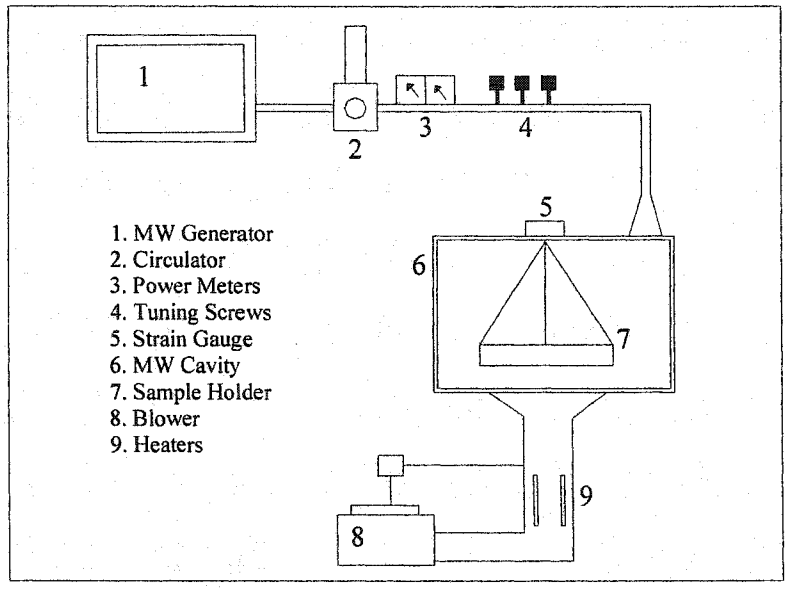

Figure 5.1: Schematic of the experimental set-up for microwave and hot-air drying of cranberries

5.3.2 Power density and cycling period

In order to determine appropriate power density and cycling period, combinations of these parameters were studied. Upon determining the critical limit of power density based on burning of the samples (approximately 1.5 W/g), the selected power densities were 0.75 W/g, 1.0 W/g, and 1.25 W/g based on the sample's initial mass. Two different cycling periods were tested, 30 seconds on/30 seconds off and 30 seconds on/60 seconds off. Osmotically dehydrated cranberries were dried under the six combinations of power density and cycling period, and all experiments were replicated twice. The dried cranberries were subjected to a partial quality evaluation, where overall appearance and

taste were scored by untrained judges, and surface color and texture were also measured. The most appropriate combination of power density and cycling period based on drying time and quality was selected.

5.3.3 Quality evaluation

In this work, three methods were selected to evaluate the quality of the dried cranberries. A sensory evaluation of the samples was performed, along with the measurement of its surface color and texture.

Sensory evaluation of a produce, though subjective, is an important part of quality evaluation since it represents the same procedure that would be used by a consumer (Rennie et al., 2001). The hedonic scale that was used for the sensory evaluation of the dried cranberries is shown in Table 5.1. The main drawback of this method is the subjectivity of the judges involved. Due to the high number of samples evaluated, there was difficulty in having the same judges for all tests. This would have resulted in applicable data for statistical analysis, where judges would have represented a block in a randomized complete block design. However, since judges evaluating samples differed from test to test, the data obtained was not valid for statistical analysis, but was still considered important since it gave an idea of the consumer's preference to the different samples. The judges were asked to evaluate the overall appearance and taste of the samples.

Table 5.1: Sensory evaluation scale

Score	Description
1	Like extremely
2	Like very much
3	Like
4	Neutral
5	Dislike
6	Dislike very much
7	Dislike extremely

Objective measurements, including surface color and texture, were also determined. The color of any dried product is an important factor to consider, as it is one of the main attributes to evaluate quality. The color of dried cranberries is caused by red anthocyanins and yellow flavonoids (Yongsawatdigul and Gunasekaran, 1996). The surface color of the samples was measured by using a chroma meter (Model CR-300X, Minolta camera Co. Ltd., Japan) equipped with a 5 mm diameter measuring area. The measurement was taken on the external side of the cut cranberries and the mean of three measurements at the same location was taken. Five different fruits from the same sample were randomly tested. The instrument was initially calibrated on a Minolta standard-white plate (L = 98.28 a* = -0.05 and b* = 2.32). Each reading provided a value for three coordinates, L^*, a^*, b^*, providing information on lightness directly (McGuire, 1992). The lightness coefficient, L^*, ranged from 0 (black) to 100 (white), the a^* coordinates indicated red-purple color (positive value) or bluish-green color (negative value), and the b^* coordinate indicated a yellow color (positive value) or a blue color (negative value) (McGuire, 1992). Mean color values of cranberries dried under different treatments were compared to those of fresh (frozen-thawed) cranberries, which were considered as a standard. The commercially available dried cranberries were not used as a standard for color because of the unknown processing conditions. Furthermore, different cultivars of cranberries and harvesting times can lead to variations in color. The data obtained were in terms of lightness (L*), redness (a*) and yellowness (b*), but was converted to hue angle (h^o), and Chroma C*, an index somewhat analogous to color saturation or intensity (McGuire, 1992). Color difference (ΔE) was also calculated in order to evaluate the change in color between the fresh (frozen-thawed) and the dried cranberries. The following equations were therefore used for the analysis of surface color (McGuire, 1992; Yongsawatdigul and Gunasekaran, 1996):

$$H^o = \tan^{-1}(b^*/a^*) \quad (5.1)$$

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2} \quad (5.2)$$

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (5.3)$$

where $\Delta L^* = L^*_{sample} - L^*_{standard}$

$\Delta a^* = a^*_{sample} - a^*_{standard}$

$\Delta b^* = b^*_{sample} - b^*_{standard}$

The textural characteristics of the dried samples were determined using the Instron Universal Testing Machine (Series IX Automated Materials Testing System 1.16), shown in Figure 5.3. Compression tests, using a Kramer shear press, shown in Figure 5.4, were performed on 15g samples (for the osmotically dehydrated samples) and 4g samples (for the control sample). These masses were used in order to have a single layer of dried fruits in the 66mm by 66mm Kramer shear press cavity. A 50kN load cell was used and the crosshead speed for all tests was 160 mm/min. Three samples were used, for each condition (i.e. combination of power density and cycling period), and their mean result was determined. Different parameters were obtained, including Young's Modulus and the toughness of the tested samples.

5.3.4 Experimental design

All experiments were conducted in triplicate and the data were subjected to analysis of variance (ANOVA). Differences were identified as significant or non-significant based on the Student-Newman-Keuls test and Duncan's multiple range tests for each variable (i.e. combination of power density and cycling period). A significance level of 0.05 was used in all cases.

5.4 Results and Discussions

5.4.1 Drying time and sensory evaluation

Three power densities, 0.75 W/g, 1.0 W/g, and 1.25 W/g based on the sample's initial mass, were tested along with two different cycling periods, which were 30 seconds ON / 30 seconds OFF (cycling period A) and 30 seconds ON / 60 seconds OFF (cycling period B). Table 5.2 summarizes the results for drying time and sensory evaluation from the six combinations tested. Figure 5.5 shows a photograph of cranberries dried with microwaves at different power levels. It can be noted that the sample on the left was dried with a higher power level (1.25 W/g, cycling period A), and that parts of the sample had a burnt appearance. The quality of this sample was unacceptable, while the sample on the right (dried at 1.0 W/g cycling period B) was acceptable. Figure 5.6 represents the drying curves of the six combinations, where the mean of three replicates was plotted.

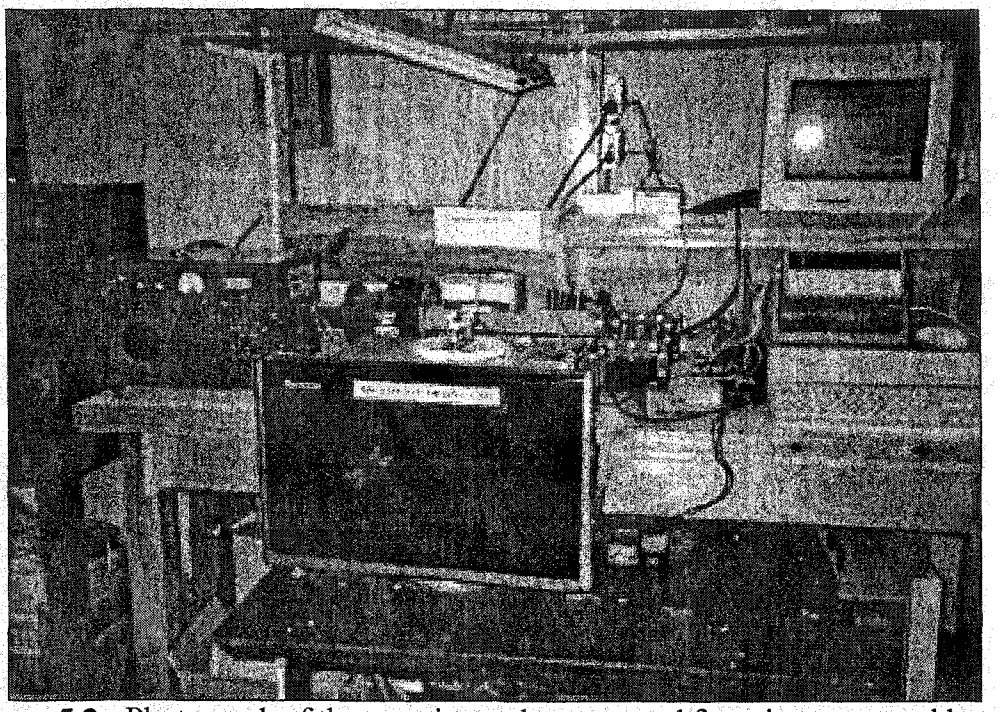

Figure 5.2: Photograph of the experimental set-up used for microwave and hot-air drying of cranberries.

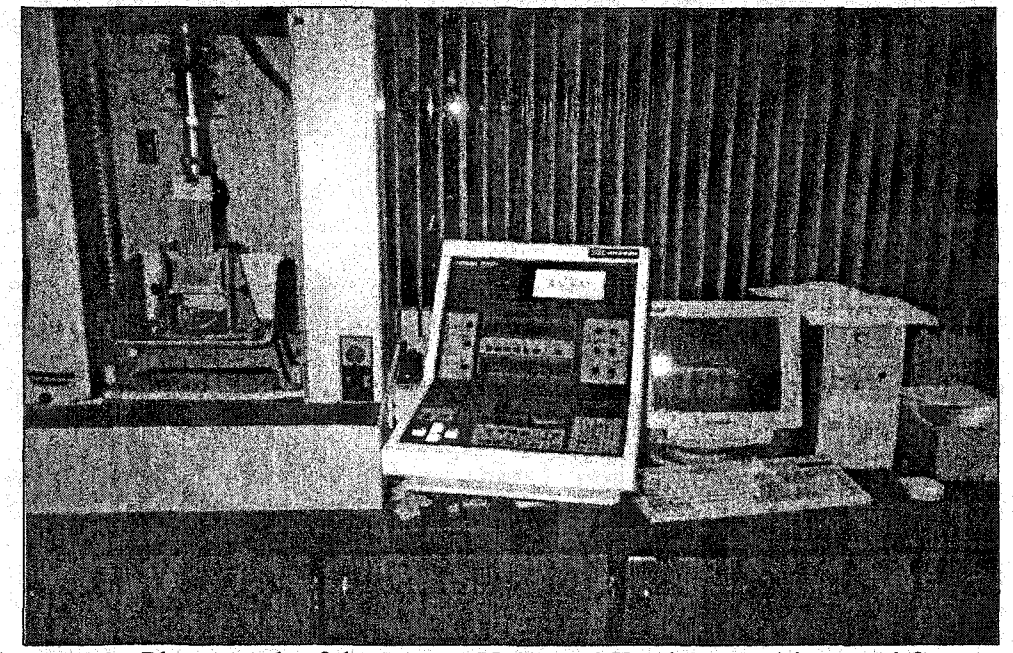

Figure 5.3: Photograph of the Instron Universal Testing Machine used for texture measurements of the samples.

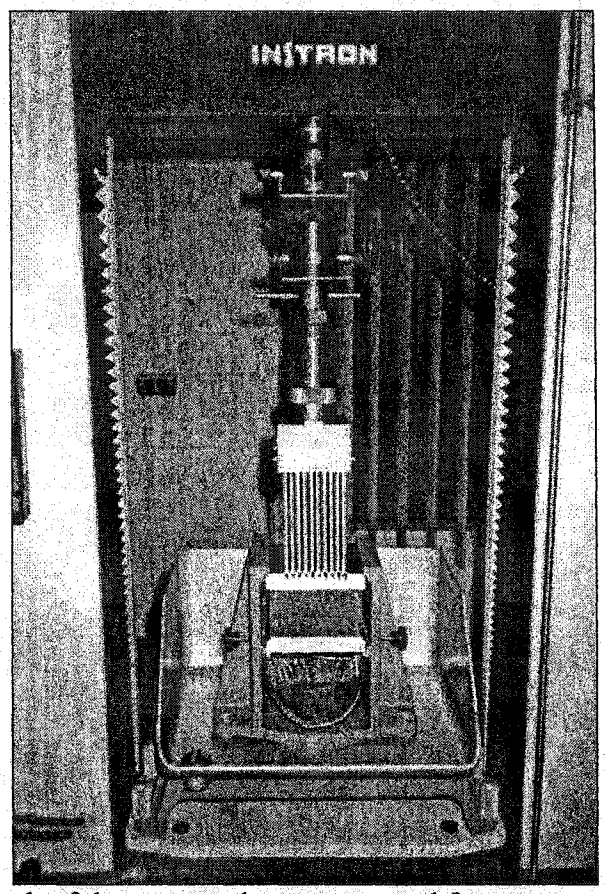

Figure 5.4: Photograph of the cramer shear press used for compression tests on the dried samples.

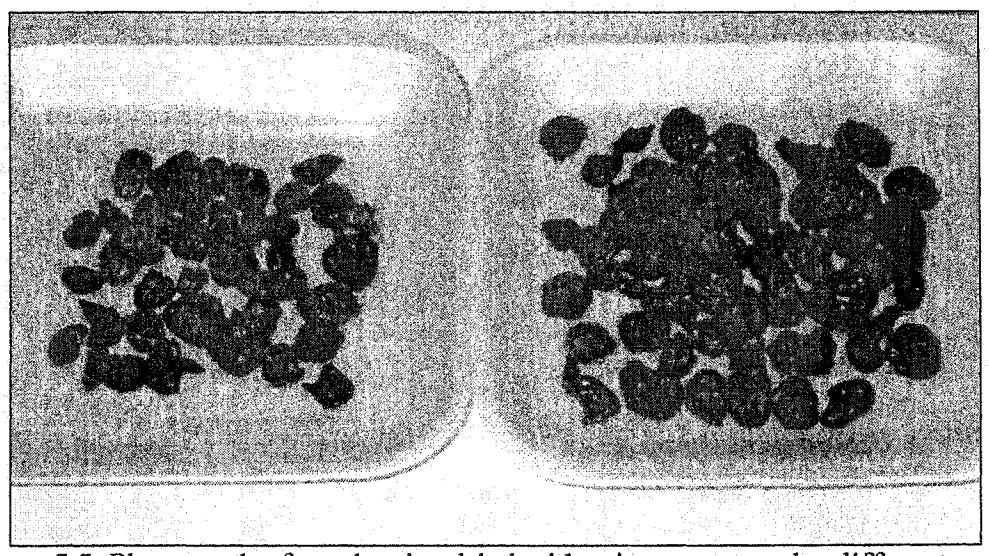

Figure 5.5: Photograph of cranberries dried with microwaves under different power levels (1.25 W/g cycling period A on left, 1.0 W/g cycling period B on right)

Table 5.2 Drying time and sensory evaluation of cranberries dried with microwaves at different power densities and cycling periods.

Power density and cycling period	Drying time (hr)	Overall appearance	Taste
0.75 W/g A	$3.27^{b,c}$	2.5	2.2
0.75 W/g B	4.95^{a}	2.6	2.4
1.00 W/g A	2.51^{d}	3.2	2.8
1.00 W/g B	3.59^{b}	2.9	2.4
1.25 W/g A	2.18^{d}	3.8	3.0
1.25 W/g B	2.93^{c}	3.0	2.4

Duncan groupings: means with the same letters are not significantly different

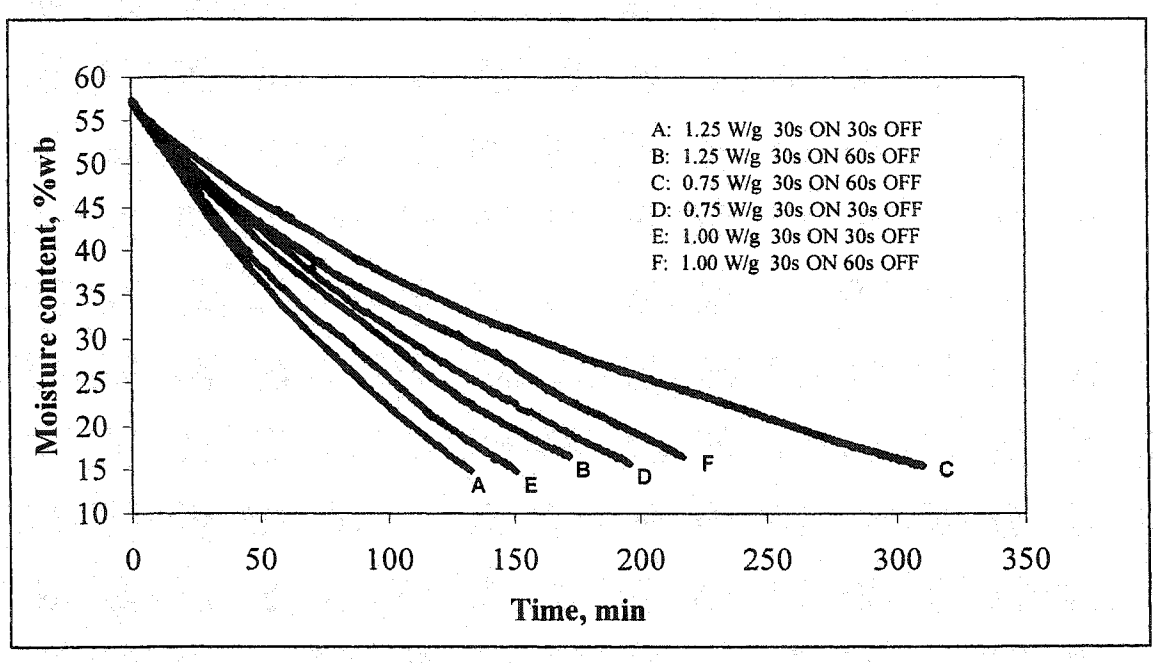

Figure 5.6: Mean drying curve of cranberries dried using microwave at different power densities and cycling period.

A significant difference ($P < 0.05$) in drying time was observed among the six combinations, where the shortest and longest drying times were for power density of 1.25 W/g with cycling period A and for power density of 0.75 W/g with cycling period B, respectively. It is interesting to note that the drying time associated with cycling period A was always significantly lower than that associated with cycling period B for the same

power density. Furthermore, some combinations led to similar drying times with different power levels. For example, a lower power density of 0.75 W/g, with cycling period A, resulted in similar drying times compared to higher power density, such as 1.0 W/g with cycling period B and 1.25 W/g with cycling period B. However, even though the data obtained from sensory evaluation was not statistically valid, a general trend was observed where the overall appearance was less acceptable with an increased power density. This can be due to the fact that a small quantity of fruits tended to burn at a specific location on the sample holder when higher power density was used. This indicates a possible non-uniform distribution of microwaves inside the cavity. When evaluating taste scores, similar results are obtained, with samples that were the most and the least acceptable, based on taste score, were obtained at conditions of power density of 0.75 W/g with cycling period A and power density of 1.25 W/g with cycling period A, respectively. Once again, this can be due to the tendency of some cranberries to burn at higher power densities. It is therefore reasonable to conclude that under the experimental conditions tested in this study, lower power densities with cycling periods such as 30 seconds ON / 30 seconds OFF were more appropriate to produce acceptable products.

5.4.2 Color characteristics

Mean color values of cranberries dried under different microwave conditions were compared to fresh (frozen-thawed) cranberries, which were considered as a standard. The data obtained for lightness (L*), redness (a*) and yellowness (b*), along with the calculated hue angle (h°), Chroma C*, and color difference (ΔE) are shown in Table 5.3. No significant difference ($P < 0.05$) was observed in the values of hue angle and total color difference, but a significant difference ($P < 0.05$) was observed for the Chroma index based on Duncan Groupings.

When looking at the mean color differences for the six different conditions, one would expect the value for power density of 1.0 W/g with cycling period B to be significantly lower than the other values. However, statistical analysis of the values based on Duncan groupings was done and no significant difference was detected. This can be due to the variation within the values, which is not shown when looking at mean values. It was determined, from visual observations, that some cranberries dried under higher power densities, had a tendency to burn, thus presenting a more brown or black

surface color. When measuring color on cranberries within one sample, the fruits were randomly selected. Therefore, cranberries that started to burn may have been picked, thus leading to variation of data within the same sample.

Table 5.3: Effect of power density and cycling period in microwave drying of cranberry on the mean surface color

Power density and cycling period	L*	a*	b*	h°	C*	ΔE
0.75 W/g A	33.7	32.8	16.0	25.6^{a}	36.6^{a}	6.2^{a}
0.75 W/g B	33.5	32.4	14.9	24.3^{a}	$35.7^{a,b}$	6.2^{a}
1.00 W/g A	31.0	27.4	11.9	23.3^{a}	$29.8^{b,c,d}$	5.9^{a}
1.00 W/g B	33.2	32.0	13.8	23.3^{a}	$34.9^{a,b,c}$	2.4^{a}
1.25 W/g A	32.5	25.0	12.5	26.5^{a}	27.9^{d}	6.4^{a}
1.25 W/g B	29.6	26.8	10.8	21.9^{a}	$28.9^{c,d}$	6.6^{a}
Frozen thawed cranberries	34.0	30.9	13.4	23.3^{a}	$33.8^{a,b,c,d}$	-

Duncan groupings: means with the same letters are not significantly different

A significant difference ($P < 0.05$) was observed for the Chroma index within the six combinations; however, no significant difference was observed between the standard (frozen-thawed fruits) and those dried under the six combinations of power density and cycling period. Therefore, it can be stated that under the tested conditions, a possible effect on surface color by different power density and cycling periods was not observed.

5.4.3 Textural characteristics

Toughness and Young's Modulus were used to describe texture of the dried samples. These values are shown in Table 5.4 and were compared with the toughness and Young's Modulus of commercially available dried cranberries. A significant difference ($P < 0.05$) among treatments was found for both Young's modulus and toughness.

Cranberries dried under a power density of 1.25 W/g with cycling period A had values significantly different ($P < 0.05$) than commercial Craisins™ for both toughness and Young's Modulus. Also, cranberries dried under a power density of 1.0 W/g with

cycling period B had a toughness value significantly different ($P < 0.05$) than that of commercial Craisins™. As shown in Table 5.4, all other combinations of power density and cycling period under the conditions tested appeared to have no effect on textural characteristics. It would therefore be appropriate to select a condition that would result in similar textural characteristics than those of the commercial samples. These results, along with those from drying time, sensory evaluation, surface color and energy consumption will result in selection of appropriate conditions for microwave drying of cranberries.

Table 5.4: Effect of power density and cycling period on dried cranberry textural characteristics

Power density and cycling period	Young's Modulus (MPa)	Toughness (MPa)
0.75 W/g A	$11.0^{a,b}$	$0.0203^{a,b}$
0.75 W/g B	$9.7^{a,b}$	0.0170^{b}
1.00 W/g A	$10.9^{a,b}$	$0.0198^{a,b}$
1.00 W/g B	12.1^{a}	$0.0208^{a,b}$
1.25 W/g A	11.6^{a}	0.0240^{a}
1.25 W/g B	$11.4^{a,b}$	$0.0214^{a,b}$
Commercial Craisins™	8.9^{b}	0.0163^{b}

Duncan groupings: means with the same letters are not significantly different

5.4.4 Energy consumption

The analysis of energy consumption in microwave drying is closely related to drying times. In microwave-vacuum drying of osmotically dehydrated cranberries, Yongsawatdigul and Gunasekaran (1996) determined the most favorable value of drying efficiency for microwave power-on and power-off times was 30 and 150 s, respectively. The mean value of the drying efficiency under these conditions was 2.66 MJ/kg, which represents an improvement of about 40-60% over conventional hot-air drying and about 46% over continuous microwave-vacuum drying. Yongsawatdigul and Gunasekaran (1996) used Equation 5.4 in order to calculate the drying efficiency of their process:

$$DE = \left(\frac{t_{on} P (1 - m_f) \, 10^{-6}}{(M_i (m_i - m_f))} \right) \tag{5.4}$$

where DE is the drying efficiency (MJ/kg of water), t_{on} is the total amount of time of microwave power (s), P is the microwave power input (W), M_i is the initial mass of the sample (kg), m_i and m_f are the initial and final moisture content (fraction). This equation considered the energy demand due to the use of microwave, but did not take into consideration the energy demand from the vacuum used in these experiments. Equation 5.4 can, therefore, be used to determine the drying efficiency based on microwave consumption for the experiments in this present study. The energy requirements to heat up and blow the air for the convective part of the drying process are not examined here. The drying efficiency, based on microwave consumption, was determined for each combination of power density and cycling period and results are shown in Table 5.5.

Table 5.5: Mean values of drying efficiency based on microwave consumption for different combinations of power densities and cycling periods.

Power density and cycling period	Total time of microwave power (s)	Microwave power input (W)	Energy consumption (MJ/kg water)
0.75 W/g A	5886	94	$8.9^{a,b}$
0.75 W/g B	5940	94	$9.0^{a,b}$
1.00 W/g A	4518	125	$9.1^{a,b}$
1.00 W/g B	4308	125	8.7^{b}
1.25 W/g A	3924	156	9.9^{a}
1.25 W/g B	3516	156	$8.9^{a,b}$

Duncan groupings: means with the same letters are not significantly different

As shown in Table 5.5, the highest energy demands occured with power densities of 1.0 and 1.25 W/g with cycling period A. In both conditions, the total time of microwave power was large, due to the cycling period where microwaves were generated only half of the total process time. It is interesting to note that a lower power density did not necessarily mean lower energy consumption. For example, the combination of 0.75 W/g with cycling period B resulted in a higher energy demand than conditions of 1.0 W/g

also with cycling period B. This was due to the longer drying time observed with the lower power density, therefore the longer amount of time of microwave power. In fact, the combination of power density of 1.0 W/g with cycling period B was the only condition significantly different ($P < 0.05$) than the highest energy demand at 1.25 W/g with cycling period A. This clearly shows that both drying time and energy demand should be considered when selecting conditions for microwave drying.

5.5 Conclusions

By testing different combinations of power densities and cycling period for microwave drying of cranberries, various conclusions can be drawn. Distinct differences were observed in drying times according to the various conditions applied, where the shortest time was found for 1.25 W/g with cycling of 30 s ON / 30 s OFF. However, other factors, along with drying time, were considered in order to select appropriate conditions for microwave drying of cranberries. Results from the sensory evaluation, although not statistically valid, showed a clear appreciation of cranberries dried at 0.75 W/g with 30 s ON / 30 s OFF, based on both taste and the overall appearance.

Even though a significant difference ($P < 0.05$) was observed in the Chroma index for the surface color evaluation of the dried cranberries, no difference was detected on the total color difference of the fruits due to different power density and cycling periods. However, from visual observations, cranberries dried under higher power densities had a tendency to burn, resulted in a more brown or black surface color, which was unacceptable to the consumer, based on sensory evaluation scores.

It was also determined that cranberries dried under power densities of 1.0 W/g with cycling period B and 1.25 W/g with cycling periods A and B presented significantly different ($P < 0.05$) textural characteristics than commercially available dried cranberries, based on the toughness of the samples. These conditions were therefore less appropriate since the end product should somehow resemble the commercial product, which is well accepted by consumers.

The energy demand through microwave drying under different conditions is another factor to be considered when selecting appropriate drying conditions. The lowest energy demands were observed for the following conditions: 0.75 W/g with cycling

period A, 1.0 W/g with cycling period B and 1.25 W/g with cycling period B. Since these last two conditions did not give favorable results for textural characteristics, the combination of 0.75 W/g with cycling period B was appropriate to dry cranberries in this study.

This combination resulted in a reasonably low drying time, a clear appreciation of both taste and overall appearance from judges, similar textural characteristics compared to commercial product, along with one of the lowest energy demands observed. This combination was therefore the most appropriate one to be used to dry osmotically dehydrated cranberries using microwaves.

5.6 References

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CONNECTING TEXT

Upon determining the appropriate power density and cycling period combination in microwave drying, the next step was to compare the drying behavior of osmotically dehydrated cranberries when subjected to different drying methods. In this work, four methods were investigated: a combination of microwaves and hot-air, convective hot-air drying alone, freeze-drying and vacuum drying. Cranberries were dried down to moisture content around 15% (wet basis) and their quality attributes were evaluated. These included a sensory evaluation, along with the measurement of surface color, water activity, rehydration capacity and textural characteristics.

VI. EFFECT OF FOUR DRYING METHODS ON THE QUALITY OF OSMOTICALLY DEHYDRATED CRANBERRIES

6.1 Introduction

Drying is one of the oldest unit operations and competes with distillation as the most energy-intensive unit operation (Mujumdar, 1992). Drying can be defined as "the process of thermally removing volatile substances (usually moisture) in order to yield a solid product" (Mujumdar and Menon, 1995). Through the years, hundreds of dryers have been reported in the literature for a wide range of products. Various industrial sectors need drying processes, including wood and wood products, pulp and paper, biotechnological products, pharmaceuticals, polymers, and agri-food products.

Today, several types of drying methods are commercially implemented for fruits and vegetables, however, all drying processes can be grouped into three basic types; sun and solar drying, atmospheric drying (including cabinet, tunnel, fluidized bed, spray and microwave heated dryers), and subatmospheric drying (Jayaraman and Das Gupta, 1992). This study deals with two different atmospheric drying methods, microwave and hot-air drying, along with two subatmospheric drying methods, freeze-drying and vacuum drying.

6.1.1 Microwave drying

Over the last decades, it has been recognized that microwave heating can lead to potential economic, engineering and social benefits (Sanga et al., 2000). Radio frequency (RF) and microwaves (MW) are forms of electromagnetic wave energy which are used in industrial applications, such as drying of foodstuffs, wood, papers and textile. Radio frequency and microwave have a penetrating effect on the product, which causes volumetric heating. Materials that are absorbers and transmitters of microwaves are said to be dielectric, and when subjected to microwaves, heat is generated through the materials.

An advantage of using microwave technology is the possibility of combining diverse drying methods with microwaves. For example, the combination of convection hot-air drying with microwaves has been adopted by several food-processing facilities in

order to reduce drying time and improve food quality (Giese, 1992). In their comparison of four drying methods on the quality of lowbush blueberries, Yang and Atallah (1985) determined that the samples dried using a combination of hot-air and microwaves had a higher sodium content than the samples dried under other methods, and also presented a lighter color than freeze-dried and vacuum dried samples. Venkatachalapathy and Raghavan (1998) determined that osmotically dehydrated blueberries, dried by a combination of hot-air and microwaves, resulted in dried samples comparable to freeze-dried samples in a much shorter time.

Along with combining them with hot-air, microwaves can also be combined with freeze-drying or vacuum drying in order to dry food materials. Cohen et al. (1992) reported that the combination of microwaves with freeze-drying significantly increased drying rates of peas and enhanced rehydration capacity of the dried product. Microwave vacuum dryers are in commercial use for production of fruit juice concentrates, tea powder and enzymes (Sanga et al., 2000). Yongsawatdigul and Gunasekaran (1996) studied the combination of microwaves and vacuum in order to dry osmotically dehydrated cranberries. They found the storage stability of the resulting product comparable to that of conventionally-dried cranberries.

6.1.2 Hot-air drying

Fruits and vegetables can be dried by a technique using hot air as the drying medium, which is often found as the simplest and most economical method (Jayaraman and Das Gupta, 1995). In hot air drying, convectional heat transfer is mainly involved since moving heated air is in contact with the material to be dried. In this type of system, four main factors can affect the rate and total time of drying: the physical properties of the food (particle size and geometry), the physical arrangement of the food with air, the physical properties of the air (temperature, humidity, velocity), and the design characteristics of the drying equipment (Jayaraman and Das Gupta, 1995).

The main disadvantages of hot air drying are the non-uniformity obtained in the dried sample (Barbosa-Canovas and Vega-Mercado, 1996), the slower drying rates compared to other drying methods, and the quality of the resulting product, which may be improved by using other drying methods. Tulasidas (1994) reported that there was a quality-related upper temperature limit for hot air drying of grapes of 80°C, beyond

which browning and other quality defects occurred. Research has determined that the taste, color and overall quality of dried berries can be improved by using alternative methods, such as a combination of hot-air and microwaves (Yongsawatdigul and Gunasekaran, 1996; Tulasidas, 1994; Venkatachalapathy and Raghavan, 1998; Venkatachalapathy, 1998).

6.1.3 Freeze-drying

Freeze-drying has been used for a wide variety of products and is today's most commonly used drying method for high-value products (Liapis and Bruttini, 1995). Although it has major disadvantages, such as expensive equipment and the need of special packaging to avoid oxidation and moisture pickup, freeze-drying is justified since the nature of the freeze-dried product is hardly altered (Jayaraman and Das Gupta, 1992). An important feature of freeze-drying is the structural rigidity afforded by the frozen skin of the product (Liapis and Bruttini, 1995). This rigidity can prevent the collapse of the solid matrix, resulting in a freeze-dried product that tends to have a porous and non-shrunken structure with excellent rehydration capacity.

When examining four different drying methods on lowbush blueberries, Yang and Atallah (1985) determined that vitamin C content was higher in freeze-dried berries, compared to samples dried under forced air, vacuum oven, and micro-convection. Furthermore, it was determined that freeze-dried, along with vacuum dried blueberries, had higher soluble solids retention and were darker and redder than forced-air or micro-convection dried berries. Of the four drying methods, freeze-drying was found to produce dried berries with the highest rehydration ratio and lowest bulk density (Yang and Atallah, 1985).

Nsonzi and Ramaswamy (1998) performed a quality evaluation on osmo-convective dried blueberries. The results from this drying method were compared with those of freeze-dried blueberries. The obtained results were similar to those of Yang and Atallah (1985), where rehydration ratio was higher for the freeze-dried samples over osmo-convective dried samples.

The main limitation of using freeze-drying for fruits and vegetables is its high initial investment and operating costs. Atmospheric freeze-drying is one alternative to reduce the cost of the process, where simple equipment, such as conventional fluidized

bed, can be used (Jayaraman and Das Gupta, 1995). It is reported that several foods, including mushrooms and carrots, were dried under atmospheric freeze-drying, achieving improved heat and mass transfer and shorter drying time compared to vacuum drying (Jayaraman and Das Gupta, 1995).

6.1.4 Vacuum drying

In vacuum dryers, the boiling point of water is reduced due to the lower pressure in the retort containing the product. Like freeze-drying, vacuum drying is an expensive drying method due to the equipment involved. However, vacuum drying presents various advantages, mainly by offering a product temperature lower than conventional drying methods and by preventing contact with air, which can reduce oxidation of the product (van't Land, 1991). Vacuum drying has been applied to the dehydration of citrus juices, apple flakes, and various heat-sensitive products in which the ascorbic acid retention is important (Sokhansanj and Jayas, 1995). This method is also being used for the extraction and concentration of essences and flavors (Sokhansanj and Jayas, 1995). Even though the degree of vacuum and the temperature for drying depend on the sensitivity of the product, most vacuum applications use levels of absolute pressure of 7 kPa, at which the boiling point of water is reduced to 39°C (Barbosa-Canovas and Vega-Mercado, 1996).

Since vacuum drying is an expensive technique, it is often used as a secondary dryer. The moisture content of high moisture food can be reduced to 20-25% by a conventional, less expensive method, and then vacuum is applied to bring the moisture down to the desired level (Sokhansanj and Jayas, 1995).

6.2 Objectives

The objectives of this study were to compare the characteristics of osmotically dehydrated cranberries dried under four different methods: combined microwave and hot-air drying, conventional hot-air drying, freeze-drying and vacuum drying, and to perform a quality evaluation of the dried samples.

6.3 Materials and Methods

All tests were performed on cranberries (*Vaccinium macrocarpon*) of the Stevens cultivar, which were harvested using flooding of sandy soils. The fresh fruits were frozen after harvest and were completely thawed by immersion in ambient temperature water for 1 hour just before being used for dehydration. The fruits were initially cut in half and dehydrated through osmosis, by placing the fruits in high fructose corn syrup (76 °Brix) at a 1:1 fruit to sugar ratio, at ambient temperature and for 24 hours (as determined in Chapter 4). The fruits were then rinsed with warm tap water and gently dried with towels. The samples to be freeze-dried were frozen to a temperature around –40°C until they were used for drying. The samples to be dried under the remaining three methods were refrigerated at 2°C after they were osmotically dehydrated. The mean moisture content of the osmotically dehydrated cranberries was 57% (wet basis) before drying. The mean initial moisture content of fresh (thawed) cranberries was 88.0% (wet basis).

6.3.1 Microwave drying

The tests were performed using a custom designed laboratory scale convective and microwave dryer as shown in Figures 5.1 and 5.2. The dryer was equipped with a 750 Watts, 2450 MHz microwave generator. Incident power was set according to the tested power density, which was based on the initial mass of the sample. The tested power densities were 0.75 W/g, 1.0 W/g, and 1.25 W/g. Microwaves were generated for a certain cycling period, which was 30 seconds on, 30 seconds off, and 30 seconds on, 60 seconds off. Reflected power was manually maintained around zero throughout the experiments, by the use of three tuning screws inserted in the top of the wave-guide assembly. Heated air was continually blown on the sample placed as a single layer on the sample holder, by a 0.25 kW blower placed underneath the drying cavity. Three 2 kW-electrical heaters were used to raise the air temperature. The temperature and velocity of the air were maintained constant throughout the tests, and were set at 45°C and 2 m/s, respectively. The mass of the samples (initially 125 g) was monitored during the drying process, as the sample holder was equipped with a strain gage. The temperature of the inlet and outlet air was measured with Type-K thermocouples, and the temperature of the sample was measured through a digital fiber optic thermometer (Nortech Fibronic Inc. Canada) specially used in microwave applications. All temperature, power and mass data

was recorded by a data acquisition system (HP34970A – Data Acquisition / Switch Unit, Hewlett-Packard, USA). A computer program was written in HPVEE to monitor the drying process. The sample was removed when it reached a moisture content of 15% (wet basis) and refrigerated at 4±1°C until quality evaluation was performed, one week later.

6.3.2 Hot-air convective drying

The tests were performed using the same laboratory scale dryer than that used for microwave drying, shown in Figures 5.1 and 5.2. The microwave generator was turned off for all hot-air drying tests and the blower and heaters ensure the movement of the heated air through a single layer of fruits on the sample holder. The experiments were performed at an air temperature (inlet air) of 45°C and a velocity of approximately 2 m/s. All temperature and mass data were recorded as described in section 6.3.1 with the HP data acquisition system. The sample, placed as a single layer of fruits on the sample holder, was removed from the dryer once it reached a moisture content of 15% (wet basis). It was refrigerated at 4±1°C until quality evaluation was performed, one week later.

6.3.3 Freeze-drying

The tests were performed using a laboratory scale freeze-dryer. The freeze-dryer (Unitop 400L, Virtis, USA) shown in Figure 4.1, was equipped with twelve 600mL-bottles, shown in Figure 4.2, linked to the main oven cavity where vacuum was applied. A manual valve connected each bottle to the oven cavity, hence the bottles could be removed individually while in operation in order to monitor the mass of each sample. Another advantage of using these bottles was the possibility to perform drying at room temperature. The mass of the samples (initially 25-g) was measured periodically (every two hours) using a digital balance giving precision to ±0.01g. The sample was removed once it reached a moisture content of 15% (wet basis) and refrigerated at 4±1°C until quality evaluation was performed, one week later. The applied vacuum during the freeze-drying experiments ranged between 0 and 10 mT at any time. The condenser temperature was set at –85°C during all tests and the ice formed on the condenser was removed through the defrost cycle, done following every second experiment. The

vacuum pump operating on the freeze-dryer dropped the pressure from normal atmosphere to 20 mT in approximately 20 minutes.

6.3.4 Vacuum drying

The tests were performed using a laboratory scale vacuum dryer. The dryer was a VWR Scientific model (John Scientific Inc., Canada), shown in Figure 4.3. The vacuum pump was operated with a 1-phase 0.186 kW (0.25 hp), 115 V electric motor. The tests were performed at a plate temperature (inside the vacuum oven) of 70°C and a pressure of approximately 7 kPa (a vacuum of 94.6 kPa). The mass of the samples (initially 25-g) was measured periodically (every two hours) by breaking the vacuum and stopping the experiment for a brief moment. A digital balance was used to measure the mass to a precision of ±0.01g. The sample, placed on an aluminum plate, was removed from the dryer when it reached a moisture content of 15% (wet basis) and refrigerated at 4±1°C until quality evaluation, performed one week later. The vacuum pump operating on the vacuum dryer dropped the pressure from normal atmosphere to 7 kPa in approximately 2 minutes. The moisture released by the produce was captured by drierite (anhydrous calcium sulfate), which was replaced when saturated.

6.3.5 Quality evaluation

In this work, five methods were selected to evaluate the quality of the dried cranberries. A sensory evaluation of the samples was performed, along with the measurement of its surface color, texture, water activity and rehydration capacity.

Sensory evaluation of a produce, though subjective, is an important part of quality evaluation since it represents the same procedure that would be used by a consumer (Rennie et al., 2001). The scale that was used for the sensory evaluation of the dried cranberries is shown in Table 6.1. The main drawback of this method is the subjectivity of the judges involved. Because of the high number of samples evaluated, there was a difficulty in having the same judges for all tests. This would have lead to data applicable for statistical analysis, where the judges would have represented a block in a randomized complete block design. However, because the judges differed from test to test, the data obtained was not valid for statistical analysis, but was still considered important since it

gave an idea of the consumer's reaction to the different samples. The judges were asked to evaluate the overall appearance of the sample, along with its taste.

Table 6.1: Sensory evaluation scale

Score	Description
1	Like extremely
2	Like very much
3	Like
4	Neutral
5	Dislike
6	Dislike very much
7	Dislike extremely

Objective measurements, including water activity, rehydration capacity, surface color and texture, were determined. Water activity of dried foodstuffs is very important since it is an indication of safety and stability with respect to microbial growth, chemical and biochemical reaction rates and physical properties (Aqualab, 1999). The water activity of the dried cranberries was measured using a water activity meter (Model 3 TE Series, Meyer Service & Supply, Ont., Canada). All measurements were performed at 40°C and the water activity meter was calibrated before each series of tests. The sample was manually sliced and placed into the 40 mm diameter sample cup as fast as possible to avoid moisture loss or pickup. The sample used represented a single layer of sliced pieces covering the bottom of the sample cup.

The rehydration capacity of a dried product is also an important factor to consider. It is useful to determine how the dried product will react to the future contact with moisture. For example, dried fruits used in breakfast cereals should have some rehydration capacity in order to absorb moisture from the added milk. In this work, rehydration capacity was determined by placing a 2.5g sample in boiling water for 4

minutes. The sample was then transferred to a 7.5 cm Buchner funnel covered with Whatman no.1 filter paper. Water was drained out by applying a gentle suction until no more drops were observed. The sample was then removed and weighed, and the rehydration ratio was calculated by using the following equation (Venkatachalapathy, 1998)

$$RR = 10\left(\frac{m_{rh}(100 - M_{in})}{m_{dh}(100 - M_{dh})}\right) \quad (6.1)$$

where RR = rehydration ratio
m_{rh} = mass of rehydrated sample (g)
M_{in} = initial moisture content (%wet basis) of the sample before drying
m_{dh} = mass of the dehydrated sample (g)
M_{dh} = moisture content (%wet basis) of the dried sample

The color of any dried product is an important factor to consider, as it is one of the main attributes to evaluate quality. The color of dried cranberries is caused by red anthocyanins and yellow flavonoids (Yongsawatdigul and Gunasekaran, 1996). The surface color of the samples was measured by using a chroma meter (Model CR-300X, Minolta camera Co. Ltd., Japan) equipped with a measuring area of 5 mm diameter. The reading was done on the external side of the cut cranberries and the mean of three readings at the same location was taken. Five different fruits from the same sample were randomly tested. The instrument was initially calibrated on a Minolta standard-white plate (L = 98.28 a* = -0.05 and b* = 2.32). Each reading provided a value for three coordinates, L^*, a^*, b^*, providing information on lightness directly (McGuire, 1992). The lightness coefficient, L^*, ranged from 0 (black) to 100 (white), the a^* coordinates indicated red-purple color (positive value) or bluish-green color (negative value), and the b^* coordinate indicated a yellow color (positive value) or a blue color (negative value) (McGuire, 1992). Mean color values of cranberries dried under different treatments were compared to those of fresh (frozen-thawed) cranberries, which were considered as a standard. The commercially available dried cranberries were not used as a standard for color because of the unknown processing conditions. Furthermore, different cultivars of cranberries and harvesting times can lead to variations in color. The data obtained were in terms of lightness (L*), redness (a*) and yellowness (b*), but was converted to hue angle

(h^o), and Chroma C*, an index somewhat analogous to color saturation or intensity (McGuire, 1992). Color difference (ΔE) was also calculated in order to evaluate the change in color between the fresh (frozen-thawed) and the dried cranberries. The following equations were therefore needed for the analysis (McGuire, 1992; Yongsawatdigul and Gunasekaran, 1996):

$$H^o = \tan^{-1}(b^*/a^*) \quad (6.2)$$

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2} \quad (6.3)$$

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (6.4)$$

where $\Delta L^* = L^*_{sample} - L^*_{standard}$

$\Delta a^* = a^*_{sample} - a^*_{standard}$

$\Delta b^* = b^*_{sample} - b^*_{standard}$

The textural characteristics of the dried samples were determined by using the Instron Universal Testing Machine (Series IX Automated Materials Testing System 1.16), shown in Figure 5.3. Compression tests, using a Kramer shear press shown in Figure 5.4, were performed on 15-g samples (for the osmotically dehydrated samples) and 4g-samples (for the controls). These masses were used in order to have a single layer of dried fruits in the 66mm by 66mm Kramer shear press cavity. A 50kN load cell was used and the crosshead speed for all tests was 160 mm/min. Three samples were used, for each treatment condition (i.e. drying method), and their mean was used. Different parameters were obtained, including Young's Modulus, and the toughness of the tested samples.

6.3.6 Experimental design

All experiments were conducted in triplicate and the data were subjected to analysis of variance (ANOVA). Differences were identified as significant or non-significant based on the Student-Newman-Keuls test and Duncan's multiple range tests for each variable (i.e. drying methods). A significance level of 0.05 was used in all cases.

6.4 Results and Discussions

6.4.1 Drying characteristics

Osmotically dehydrated samples were microwave dried, hot-air dried, freeze-dried and vacuum dried to a final moisture content of 15% (wet basis) in 3.5, 12.6, 5.7 and 4.6 hrs, respectively. All these times were found to be significantly different ($P < 0.05$), based on Duncan groupings. Figures 6.1 through 6.4 present the drying curve for each situation, where the mean of the three replicates was plotted. From these graphs, it can be observed that the typical constant and falling rate periods seem to be present for microwave and hot-air drying, but not for the other drying methods. Lewicki and Lenart (1992) observed no constant rate period in the drying of osmotically dehydrated apples and explained this phenomenon by the fact that the water content of the investigated material following osmotic dehydration falls below the critical water content. Other authors, such as Barbanti et al. (1994), observed that there was no constant drying rate period during air-drying kinetics of fruits following osmotic dehydration. When looking at Figures 6.1 to 6.4, a longer time is observed for hot-air drying, which resulted in the lowest drying rate.

Table 6.2: Effect of four drying methods on sensory evaluation, water activity and rehydration ratio

Drying method	Overall appearance	Taste	Water activity	Rehydration ratio
Microwave and hot-air drying	2.6	2.4	0.676^{a}	1.70^{c}
Conventional hot-air drying	1.7	2.5	0.648^{a}	$1.75^{b,c}$
Freeze-drying	2.4	2.1	0.664^{a}	2.01^{a}
Vacuum drying	2.4	2.3	0.602^{a}	1.83^{b}

Duncan groupings: means with the same letters are not significantly different

6.4.2 Sensory evaluation

Even though the data from the sensory evaluation was not statistically valid, it still shows the appreciation of the judges for all samples, based on both overall appearance and taste. Conventional hot-air drying seems to have a slight advantage over the other methods based on overall appearance of the dried samples. This is probably due

to the uniformity of the sample, which was as significant with the other samples. For example, cranberries dried with microwaves produced a few darker fruits, and a few fruits dried under vacuum were less aesthetic probably due to excessive bleeding of the fruits during drying. Data obtained based on the taste of the samples seems to present no difference among the different drying methods.

6.4.3 Water activity

The water activity of all dried samples was measured around 40°C and was found to be lower than 0.7, which is often referred to as the limit for intermediate moisture foods (Raoult-Wack et al., 1992). In fact, foods having a_w between 0.4 and 0.65 are considered as dried products, whereas those having a water activity between 0.65 and 0.75 represent the intermediate moisture foods (Raoult-Wack et al., 1992). When looking at Table 6.2, no significant difference ($P < 0.05$) is observed for the four drying methods. This was expected, since a_w is closely related to the moisture content of a product, and here all samples were dried to the same moisture content. The important feature to consider is that all values of a_w are below 0.7, which indicates that the growth of molds, bacteria and yeast is not promoted, and enzymatic reactions are not likely to occur (Barbosa-Canovas and Vega-Mercado, 1996). In this work, the measurement of a_w was considered for determining the stability of the samples, not for measuring differences between treatments.

6.4.4 Rehydration capacity

As observed in Table 6.2, the rehydration capacity of freeze-dried cranberries was significantly greater ($P < 0.05$) than that of the fruits dried under other methods, as expected. In fact, freeze-drying has been shown to produce samples with greater rehydration capacity than other drying methods, where the internal structure of the fruit remains quite undisturbed. This is due to the fact that there is structural rigidity afforded by the frozen skin of the product, which can prevent the collapse of the solid matrix remaining after drying (Liapis and Bruttini, 1995). Therefore, freeze-dried products tended to have a porous and nonshrunken structure with excellent rehydration capacity.

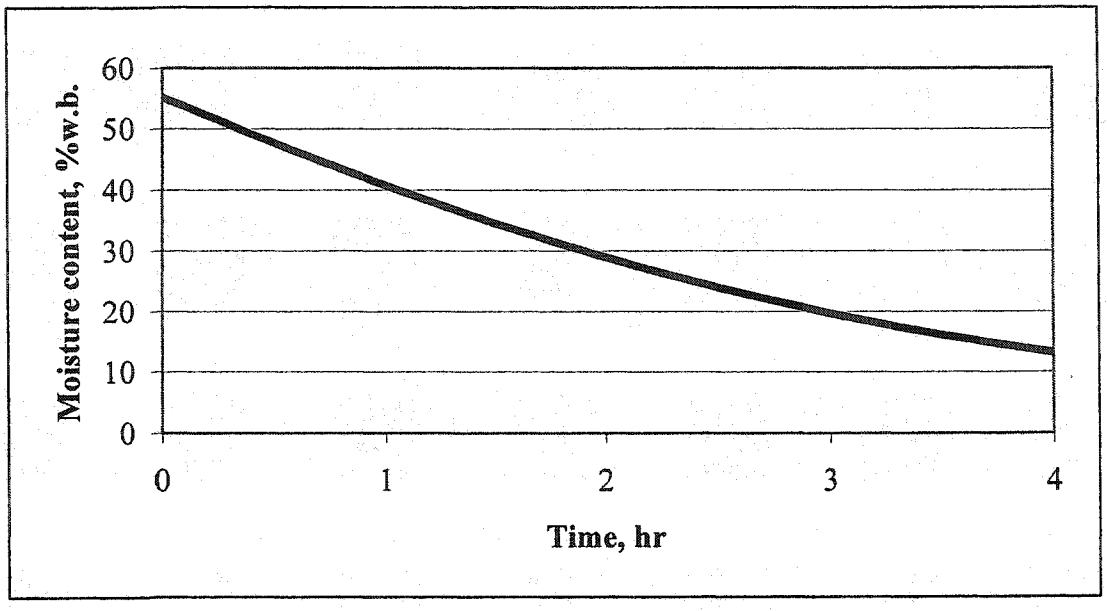

Figure 6.1: Mean drying curve of osmotically dehydrated cranberries being microwave dried (power density of 0.75W/g, power-on and power-off times of 30 s).

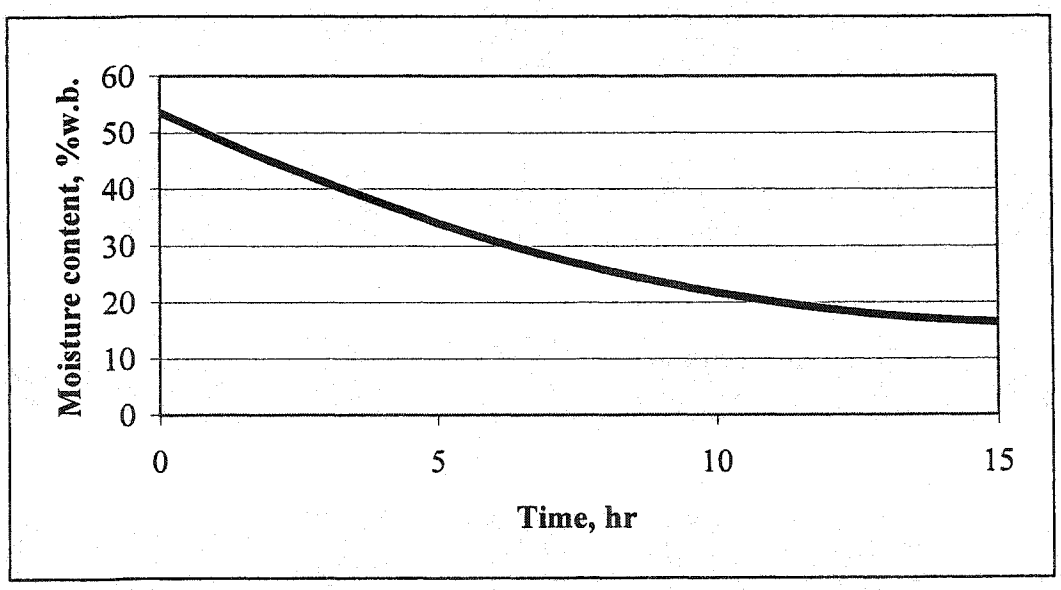

Figure 6.2: Mean drying curve of osmotically dehydrated cranberries being hot-air dried.

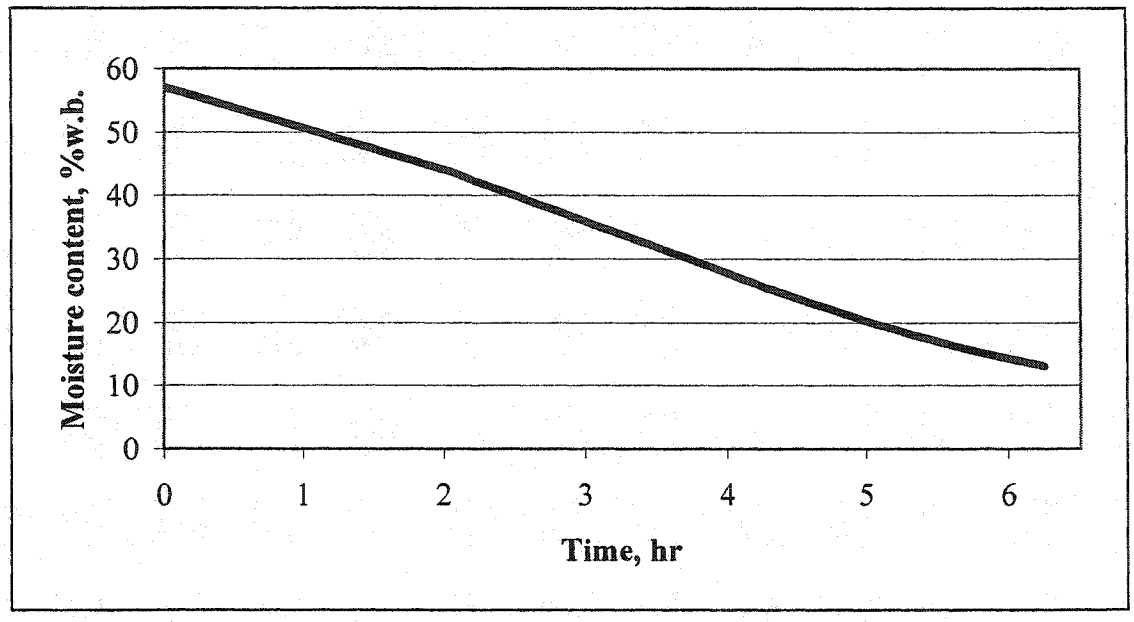

Figure 6.3: Mean drying curve of osmotically dehydrated cranberries being freeze-dried.

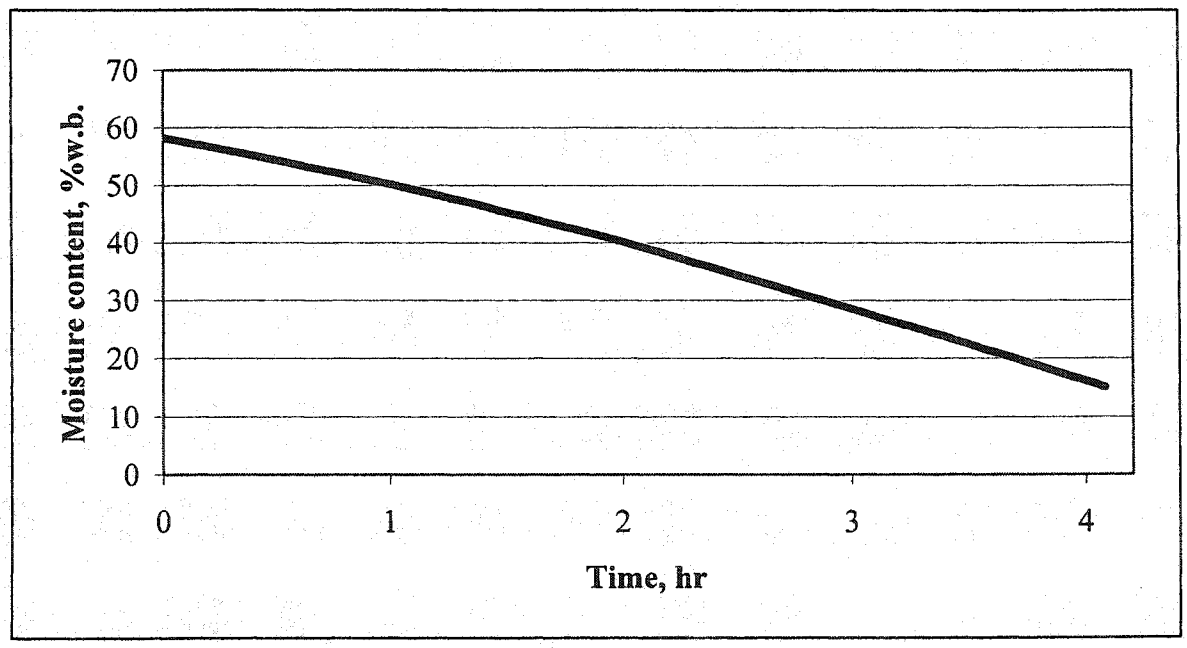

Figure 6.4: Mean drying curve of osmotically dehydrated cranberries being vacuum dried.

Also, vacuum drying produced samples with the second best rehydration capacity, along with convective drying. However, samples conventionally dried had a rehydration capacity that was not significantly different ($P < 0.05$) from the lowest value, observed with the microwave samples. Similar results were observed by Yang and Atallah (1985) when drying blueberries. In fact, the authors determined that blueberries dried using a combination of microwaves and convection had the lowest rehydration capacity compared to fruits dried under freeze-drying, vacuum drying and convection alone. Three methods of rehydration were tested (by boiling, vacuum and soaking) and similar results were obtained in all tests. It is probable that the lower rehydration capacity was due to the heat damage of the fruits. In fact, the highest internal temperature of the fruits was observed during microwave drying, and Figure 6.5 shows a typical trend for the internal temperature of a cranberry being dried under hot-air and microwave and hot-air alone.

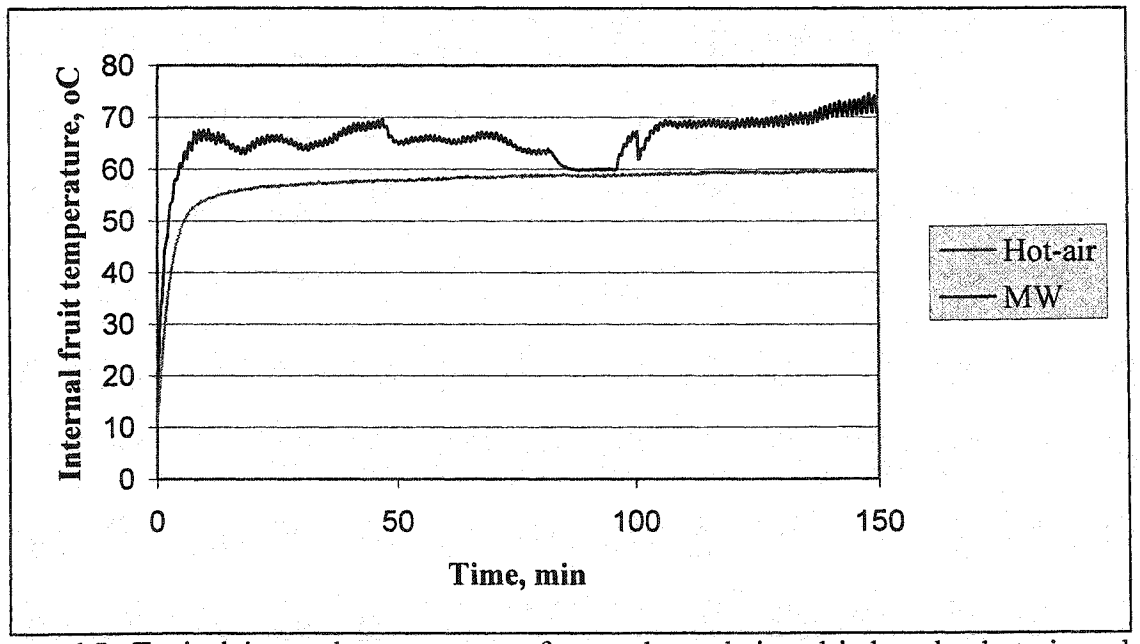

Figure 6.5: Typical internal temperature of a cranberry being dried under hot-air and microwaves and hot-air alone.

6.4.5 Color characteristics

Mean color values of cranberries, dried under different treatments, were compared to those of fresh (frozen-thawed) cranberries, which were used as a standard. The data obtained of lightness (L*), redness (a*) and yellowness (b*), along with the calculated

hue angle (h^o), Chroma C*, and color difference (ΔE) are shown in Table 6.3. No significant difference ($P < 0.05$) was observed in the values of hue angle, Chroma index and total color difference. It would be expected that cranberries subjected to higher temperatures would have lower values of redness, due to the degradation of anthocyanin pigments, which are closely related to redness of fruits (Forni et al., 1993). Anthocyanins are reported as not being chemically stable and their exposure to heat treatments can enhance their oxidation, thus resulting in degradation of color (Forni et al., 1993). However, no such difference is observed with cranberries subjected to higher temperature in microwave and hot-air drying, and those freeze-dried and vacuum dried. Also, by looking at total color difference ΔE from the four drying methods, one would expect significant differences between cranberries dried under microwave/hot-air compared to the other three methods. However, no such difference ($P < 0.05$) was detected based on Duncan groupings. This is probably due to variation within the values, which was not shown when looking at mean values.

Table 6.3: Effect of four drying methods on cranberry mean surface color

	L*	a*	b*	h^o	C*	ΔE
Microwave/hot-air drying	31.5	29.2	12.8	23.5^a	31.9^a	7.2^a
Conventional hot-air drying	31.9	33.6	14.4	23.2^a	36.5^a	4.5^a
Freeze-dried	32.6	34.0	14.0	22.3^a	36.8^a	4.3^a
Vacuum dried	30.6	31.3	13.1	22.6^a	33.9^a	4.4^a
Frozen-thawed cranberries	34.0	30.9	13.4	23.3^a	33.8^a	-

Duncan groupings: means with the same letters are not significantly different

6.4.6 Textural characteristics

Toughness and Young's Modulus were used to describe the texture of the dried samples. These values are shown in Table 6.4 and were compared with the toughness and Young's Modulus of commercially available dried cranberries. Significant difference ($P < 0.05$) among treatments was not observed for Young's modulus, whereas some significant difference was observed for toughness values. The toughness value

closest to that of the commercially available product is seen with cranberries dried with microwaves. Freeze-dried cranberries had the lowest toughness compared to the other samples, and both vacuum dried and hot-air dried fruits had values of toughness higher than freeze-dried samples, and lower than microwave-dried samples. Possible causes of higher toughness include exposure to high temperature, along with the presence of certain pretreatments such as osmotic dehydration (Yongsawatdigul and Gunasekaran, 1996).

Table 6.4: Effect of four drying methods on cranberry textural characteristics

	Young's Modulus (MPa)	Toughness (MPa)
Microwave/hot-air drying	9.9^{a}	0.0176^{a}
Conventional hot-air drying	7.3^{a}	$0.0120^{a,b}$
Freeze-dried	7.8^{a}	0.0099^{b}
Vacuum dried	9.2^{a}	$0.0128^{a,b}$
Commercial Craisins™	8.9^{a}	0.0163^{a}

Duncan groupings: means with the same letters are not significantly different

6.5 Conclusions

Two different atmospheric drying methods, along with two subatmospheric drying methods were investigated on osmotically dehydrated cranberries. A significant difference ($P < 0.05$) was observed in drying times, where the shortest was found by using a combination of microwaves and hot-air. The longest drying time was observed for hot-air drying alone, and reached a mean value of 12.6 hours to dry cranberries down to 15 % (w.b.). The sensory evaluation performed by judges determined that all four drying methods led to product with acceptable taste and overall appearance, and the sample dried using hot-air presented higher uniformity in appearance. All values of a_w were found to be lower than 0.7, which indicates microbiological stability of the end product. Important differences were observed in the rehydration capacity of the dried cranberries, with freeze-dried cranberries having a rehydration capacity greater than cranberries dried under other conditions, and cranberries dried using microwaves had a

significantly lower rehydration capacity ($P < 0.05$). No significant difference ($P < 0.05$) was observed in surface color and Young's Modulus among the four drying methods. However, significant differences ($P < 0.05$) were observed in toughness of the samples, where those dried using microwaves had the value closest to that of commercial dried cranberries. Freeze-dried cranberries had the lowest value of toughness, and would therefore be less appreciated by consumers.

Overall, results from this work indicate that four drying methods can be applied to dry osmotically dehydrated cranberries. However, specific characteristics show that some methods may be more appropriate than others for this specific product. For example, the toughness characteristics of the dried fruits indicated that the use of microwaves to dry cranberries resulted in a product with similar texture compared to the commercial Craisins™. Also, the lowest drying time, when using microwaves, suggests that this method could bring convenience, both in terms of time and energy efficiency. However, the rehydration characteristics of cranberries dried with microwaves were lower and could be improved by lowering the maximum internal temperature of the fruits being dried.

Future studies should include more tests using microwaves, since this alternative seems appropriate to dry small fruits such as cranberries. A method to maintain the internal temperature of the fruits as low as possible during microwaving should be examined, and an applied vacuum could achieve this objective.

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VII. General Discussions and Conclusions

One goal of food processing is to convert perishable commodities into stable products, in order to extend their storage life and hence reduce postharvest losses. One processing technology, drying, has been found to be successful in transforming certain commodities into a whole new form. Dried berries, such as cranberries, are being used for a wide variety of processed products and various drying techniques can be used to produce high quality products. Thus, experiments were carried out to determine the changes in quality in cranberries dried using various methods.

Different pretreatments were tested prior to drying, such as skin pretreatments and osmotic dehydration, in order to enhance drying rates and quality of the product. Skin pretreatments included chemical and mechanical pretreatments, and osmotic dehydration was performed subsequently, in order to reduce the moisture content of the fruits. The chemical pretreatment, which consisted of dipping the fruits in ethyl oleate and sodium hydroxide, was not found successful for cranberries. A mechanical pretreatment, consisting of cutting each fruit in half, was found successful and was used as a skin pretreatment for cranberries. Different parameters involved in osmotic dehydration were tested, such as the nature of osmotic agent, the mass ratio of fruits versus osmotic agent, and the dehydration time. Granular sugar and high fructose corn syrup were tested at fruit to sugar ratios ranging from 1:1 to 4:1. All tests were conducted at room temperature, and no movement was induced in the fruit-sugar mixture during the dehydration. Also, four different dehydration periods were tested, 12, 24, 36, and 48 hours. High fructose corn syrup at a 1:1 fruit to sugar mass ratio was selected and a dehydration time of 24 hours led to significant moisture content decrease and sugar uptake.

Osmotically dehydrated fruits were dried and compared to untreated and dried samples in order to determine the effects of osmotic dehydration on the dried characteristics of the berries. Drying times and rehydration capacity of the fruits were significantly ($P < 0.05$) reduced when performing osmotic dehydration prior to drying. However, the addition of sugar was an essential factor for consumer acceptance of the dried cranberries, which are quite tart in nature.

Various drying techniques can be used for fruits and vegetables, depending on the nature of the product and the desired end quality. Drying techniques can be grouped as atmospheric or subatmospheric methods. In this work, experiments were carried out and tested two atmospheric methods, convective hot-air drying and microwave drying, along with two subatmospheric methods, freeze-drying and vacuum drying. The effect of different parameters involved in microwave drying, such as power density and cycling period, were determined. Overall, six combinations of power density and cycling period were tested, and factors such as drying time, sensory evaluation, surface color, texture and drying efficiency were evaluated. From the experimental tests performed in this work, it was determined that higher power densities, even with shorter microwave power periods, tended to burn the cranberries. Furthermore, different power density and cycling periods did not have an effect on total color difference of the fruits, but did have a significant effect on textural characteristics such as toughness and Young's Modulus. A significant difference ($P < 0.05$) was also observed in energy demands for each combination of power density and cycling period. It was determined that a lower power density does not necessarily mean lower energy consumption. This was due to the longer drying time observed with the lower power density, therefore the longer amount of time of applied microwave power.

Overall, the appropriateness of four drying methods, along with their effect on diverse parameters were determined. In fact, a quality evaluation was performed on the dried samples, which included a sensory evaluation done by untrained judges (taste and overall appearance of the product were graded), surface color determination, textural characteristics measurements, water activity and rehydration capacity determination. A significant difference ($P < 0.05$) was observed in drying times, where the shortest was found by using a combination of microwaves and hot-air, and the longest drying time was observed for hot-air drying alone. The sensory evaluation determined that all four drying methods resulted in a product with acceptable taste and overall appearance, and the sample dried using hot-air presented higher uniformity in appearance. All values of a_w were found to be lower than 0.7, which indicates microbiological stability of the end product. An important difference was observed in the rehydration capacity of the dried cranberries, where freeze-dried cranberries presented a rehydration capacity greater than

cranberries dried under other conditions, and cranberries dried using microwaves had a significantly lower rehydration capacity. No significant difference was observed in surface color and Young's Modulus among the four drying methods. However, a significant difference ($P < 0.05$) was observed in toughness of the samples, where those dried using microwaves had the value closest to that of commercial dried cranberries. Freeze-dried cranberries had the lowest value of toughness.

Overall, results from this work indicate that cranberries should be pretreated prior to drying, and that different drying methods can be applied. However, specific characteristics show that some methods might be more appropriate for this specific product. The use of microwaves seems an alternative to dry small fruits, such as cranberries.

Future work in this area should include more small-fruit drying using microwaves and combinations with some other means, such as vacuum, should be examined in order to keep the internal temperature of the fruits as low as possible. A wide variety of fruits could be dried along with cranberries, and drying behavior of different products could be determined. Further work should also include a study on appropriate packaging to be used for the final product. The characteristics and quality of the dried berries should be maintained by selecting the correct packaging.

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