Osmotic Dehydration of Zucchini and Cherry

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Supervisor

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ABSTRACT

OSMOTIC DEHYDRATION OF ZUCCHINI AND CHERRY

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M. Sc. in Food Engineering

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In this study, osmotic dehydration process on zucchini (*Cucurbita pepo*), and cherry (*Malpighia punicifolia*) was investigated.

The effect of osmotic dehydration and osmotic dehydration with ultrasound effect in different salt (NaCl) concentrations (5, 15, and 25 %) and temperatures (15, 25, and 35°C) for different lengths on zucchini was evaluated. Responses of water loss (WL), solid gain (SG) and weight reduction (WR) were evaluated. Water loss was linearly affected by salt concentration and immersion time. The influence of temperature was found to be highly insignificant ($p<0.05$). Response Surface Methodology (RSM) was used to study the effect of temperature, concentration and time factors which influence the responses. First and second degree polynomial models were fitted to data. Ultrasound affected mass transport during osmotic dehydration increasing both water losses and solute gains.

Cherry was osmotically dehydrated in various sucrose concentrations (40, 55, and 70 %). Responses of water loss (WL), solid gain (SG) and weight reduction (WR) were evaluated. First and second degree polynomial models were fitted to data for studying the effect of concentration and time. Osmotic treatment of cheryy prior to air drying was also studied.The drying curves obtained from drying experiments were used for the determination of water effective diffusion coefficients.

Keywords: osmotic dehydration, air drying, cherry, zucchini, water loss, solid gain and weight reduction.

ÖZET

KABAK VE KİRAZIN OZMOTİK OLARAK KURUTULMASI

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Bu çalışmada, ozmotik kurutmanın etkisi kabak (*Cucurbita pepo*), ve kiraz (*Malpighia punicifolia*) üzerinde araştırıldı. Ozmotik kurutmanın etkisi ve ozmotik kurutma ultrasonik ile birlikte farklı tuz (NaCI) konsantrasyonlarında (5, 15, 25 %) ve farklı sıcaklıklarda (15°C, 25°C ve 35°C) zaman aralıkların da kabak için uygulandı. Su kaybı, katı kazanımı ve ağırlık azalması değerleri çalışıldı. Su kaybını tuz konsantrasyonu ve zaman doğrusal olarak etkiledi. Tepki Yüzey Metodu (RSM) ile konsantrasyon, zaman ve sıcaklık faktör olarak seçilmiş ve değişkenler üzerindeki etkisi incelenmiştir.Birinci ve ikinci dereceden polinomik model datalara uygulanmıştır. Ultrasond ozmotik kurutma boyunca kütle transferini etkileyip hem su kaybı hem de katı madde kazançlarını artırmıştır.

Kiraz belli şeker konsantrasyonunda (40, 55, 70%) ozmotik olarak kurutulmuştur. Su kaybı, katı madde kazancı ve ağırlık azalışı değerleri çalışılmıştır. Birinci ve ikinci dereceden polinomik model datalara konsantrasyon ve zamanın etkisini araştırmak için uygulanmıştır. Kirazda hava kurutma öncesi ozmotik kurutma işlemi de çalışıldı. Kurutma deneylerinden elde edilen kurutma eğrisi kullanılarak suyun difüzyon katsayısı belirlenmiştir.

Anahtar Kelimeler: Ozmotik kurutma, hava kurutma, kiraz, kabak, su kaybı, katı madde kazancı ve ağırlık azalışı

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LIST OF ABREVIATIONS

AOAC	Association of Official Analytical Chemists
ANOVA	Analysis of variance
DF	Diffusivity coefficient
HIPEF	High electric field pulse pre-treatment
R	Drying Rate, kg water/kg dry solids.min.
SG	Solid gain
W	Moisture of sample at any time (%)
WL	Water loss
WR	Weight reduction
W_1	Moisture of sample at the beginning (%)
Ws	Amount of salt in the sample at any time (g)
Wso	Amount of salt in the sample at the beginning
W_0	Weight of sample before osmotic dehydration (g)
m/s	Unit of air flow
rpm	Revolution per minute
w.b.	Wet basis
w/v	Weight volume ratio

CHAPTER I

INTRODUCTION

1.1. Definition of Dehydration

1.1.1. History

The drying of fruits and vegetables was practiced long before Biblical times by Chinese, Hindus, Persians, Greeks, and Egyptians. Dates, figs, apricots and raisins were sun dried by those early inhabitants of the Middle and Near East. Sun drying is still used for many fruits and vegetables (Salunkhe et al., 1991).

The first known record of drying involved vegetables and appeared in the 18th century (Van Arsdel and Copley, 1963). Development of the drying industry was closely related to war scenarios around the world. British troops in Crimea (1854-1856) received dried vegetables from their homeland, Canadian dried vegetables were shipped to South Africa during the Boer War (1899-1902) and around 4500 tons of dehydrated vegetables were shipped from the US during World War I. By 1919, among the products processed in the US were green beans, cabbage, carrots, celery, potatoes, spinach, sweet corn, turnips, and soup mixtures (Van Arsdel and Copley, 1963).

1.1.2. Significance

Modern technology has greatly increased the yields of fruits and vegetables. One fourth of the highly perishable produce harvested is, however, never consumed due to spoilage during its storage, transportation, and processing.

Proper processing and preservation of harvested produce minimize post-harvest losses and thus help offset shortages in supply. Preservation of fruits and vegetables by dehydration is highly effective and practicable.

The storage stability of dehydrated fruits and vegetables is affected by many factors: temperature, humidity, light, packaging method, microorganisms, trace elements, etc. The dehydrated product should be protected as much as possible from these adverse conditions so that its quality can be maintained.

1.2. Drying Methods

Drying technology has evolved from the simple use of solar energy to current technology that includes, among others, kiln drying, tray drying, tunnel drying, spray drying, drum drying, freeze drying, osmotic dehydration, extrusion, fluidization The development of dehydration technology can be divided in four groups or generations.

1.2.1. First Generation

Cabinet or bed type dryer (i.e., kiln, tray, truck tray, rotary flow conveyor, tunnel) falls into this generation. This type of dryer involves hot air flowing over the product to remove water from the surface. Dryers in this category are mostly suitable for the solid material such as grains, sliced fruits and vegetables or crunched products.

The basic configuration of a dryer comprises a feeder, a heater, and a collector and final arrangement of these components is characteristic for each dryer type. Figure 1.1. presents a basic scheme for a cabinet air dryer.

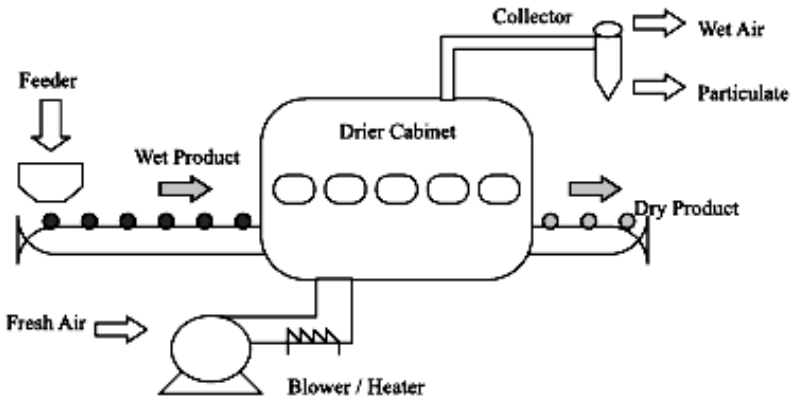


Figure 1.1. Configuration of a cabinet air dryer (Barbosa-Canovas and Vega-Mercado, 1996).

The operation is semi continuous, in that fresh produce is added at one of the tunnel and the dried products removed from the other end at predetermined intervals. The material flow can be in the same direction as the heated air (concurrent flow) or in the opposite direction (counter flow). The throughput of the dryer depends upon number of trays, the size of the tunnel and the air temperature and flow rates, among many other factors. Drying with tunnel and cabinet dryers of all types is a slow process and requires lower operating temperatures to prevent scorching (Hui et al., 2004).

1.2.2. Second Generation

Second-generation dryers are more dedicated to the dehydration of slurries and purees. Among these are the spray dryers and drum dryers indented for dehydrated powders and flakes.

Spray drying is often used in food industry to dry liquid foods of relatively low viscosity, e.g., liquid milk, coffee or tea extract vegetables juices, etc. To save energy, some liquid foods are concentrated in multi effect evaporators before being spray dried. A disadvantage with this process is the size of equipment required to achieve the drying.

Drum drying is the one of the most energy efficient drying methods and is particularly effective for drying high viscous liquid or pureed foods, such as baby foods, pureed vegetable, mashed potatoes, and cooked starch.

1.2.3. Third Generation

Freeze dehydration and osmotic dehydration fall into this generation of drying technology. While freeze dehydration was developed to overcome structural damages and minimize losses of flavors and aroma compounds (Karel, 1975; Dalgleish, 1990) osmotic dehydration (Raoult-Wack et al., 1989) is mainly indented for processing fruits and vegetables by immersion in a hypertonic solution (i.e., sugar, salt, glycerol). The freeze-drying process consists mainly of two steps: (1) the product is frozen, and (2) the product is dried by direct sublimation of the ice under reduced pressure (Rey, 1975).

1.2.4. Fourth Generation

Dehydration technology, which involves high- vacuum, fluidization, and the use of microwaves, radio frequency (RF), refraction window, and the hurdle approach, represents the latest advance in this area of food processing.

Microwave drying uses the electromagnetic radiation in the microwave frequency range (300-3,000MHz) as a form of energy to dry the food products.

Radio frequency (RF) is being used for precooking, sterilization, tempering, and baking processes in the food industry. Similar to microwaves, RF uses electromagnetic energy to heat products with exceptional results in terms of time cycle and efficiency. Unlike conventional conduction, convection, and radiant methods that are depending on the heat transfer capability of the product, dielectric heating occurs instantly inside the product. Heating is more effective since the process does not depend on a temperature gradient (Hui et al., 2004).

1.3. Osmotic Dehydration

1.3.1. Definition of Osmotic Dehydration

Osmotic dehydration is an unit operation used for practical removal of water from plant tissues by immersion in a hypertonic (osmotic) solution. Water removal is based on the natural and non-destructive phenomenon of osmosis across cell membranes. The driving force for the diffusion of water from the tissue into solution is provided by the higher osmotic pressure of the hypertonic solution. The diffusion of water is accompanied by the simultaneous counter diffusion of solute from the osmotic solution into the tissue. Since the cell membrane responsible for osmotic transport is not perfectly selective, solute present in the cells (organic acids, reducing sugars, minerals, flavors and pigment compounds) can also be leached into the osmotic solution (Dixon and Jen, 1977; Lerici et al., 1985; Giangiacomo et al., 1987), which affects the orgonoleptic and nutritional characteristics of the product. The rate of diffusion of water from any material made up of such tissues depends upon factors such as temperature and concentration of the osmotic solution, the size and geometry of the material, the solution-to-material mass ratio and, to a certain level, agitation of the solution (Raoult-Wack et al., 1991; Torreggiani, 1993; Raoult-Wack, 1994; Rastogi and Raghavarao, 1994, 2004; Rastogi et al., 2000).

1.3.2. Advantages of Osmotic Dehydration

Due to energy and quality related advantages, the technique of osmotic dehydration is gaining popularity as a complementary processing step in the chain of integrated food processing. Generally, osmotic dehydration is inherently slow and there is need to find ways of increasing mass transfer rate without adversely affecting quality. Various methods, such as the application of high hydrostatic pressure, high electrical field pulses, gamma irradiation, ultrasound, vacuum and centrifugal force have been attempted.

Osmotic dehydration used as a pre-treatment to many processes to improve nutritional, sensorial and functional properties of food without changing its integrity (Torreggiani, 1993). It generally precedes processes such as freezing (Ponting, 1966), freeze drying (Hawkes and Flink, 1978), vacuum drying (Dixon and Jen, 1977) or air drying (Nanjundaswamy et al., 1978) . It also increases the sugar to acid ratio and improves the texture and stability of pigments during the dehydration as well as storage (Raoult-Wack, 1994). It is effective even at ambient temperatures, so heat damage to texture, color and flavor can be minimized (Torreggiani, 1993).

The osmotic process may provide the possibility of modifying the functional propertied of food materials, improving the overall quality of final product and giving potential energy savings (Shi et al., 2000). The other major application is to reduce the water activity of many food materials so that microbial growth will be inhibited. Since most foods contain large amounts of water, they are also cost intensive to ship, pack and store (Rao, 1977).

Osmotic dehydration is acknowledged to be an energy-efficient method of partial dehydration, since there is no need for a phase change (Bolin et al., 1983). In order to make osmotic dehydration more attractive in economic terms, the osmotic solution needs to be reconcentrated by some means, either by evaporation or by adding fresh osmotic reagent. It can be an efficient complementary, if not an alternative, processing step to thermal dehydration in the overall chain of integrated food processing. (Ponting et al., 1966).

1.3.3. Process of Osmotic Dehydration

The concentration of food products by means of product immersion in a hypertonic solution (i.e., sugar, salt, sorbitol or glycerol) is known as osmotic dehydration (Raoult-Wack et al., 1989), water removal in this process can be aided with use of vacuum (Fito, 1994; Fito and Pastor, 1994). Osmotic dehydration systems consist mainly of a storage tank where the osmotic solution is prepared, followed by a pump to control the flow rate at the processing tank. The product is placed in the processing tank where the osmotic solution is pumped in a constant rate. The configuration of a typical osmotic dehydration is presented (Figure 1.2) as discussed by Raoult-Wack et al., 1989. Industrial application of osmotic dehydration is schematically shown in Figure 1.3.

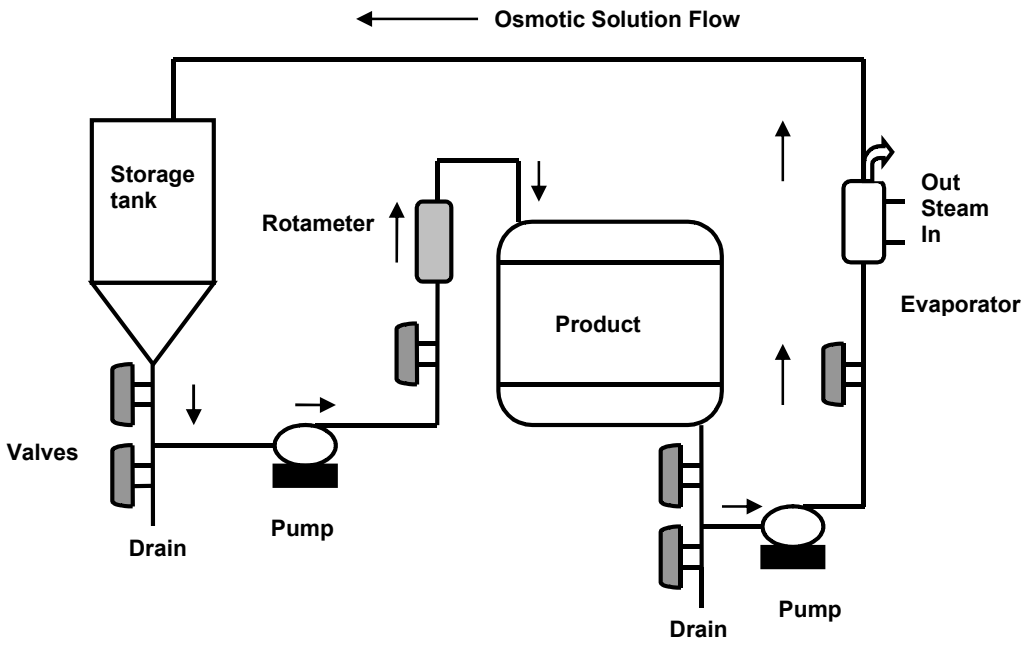


Figure 1.2. Osmotic dehydration system (Barbosa et al., 1996).

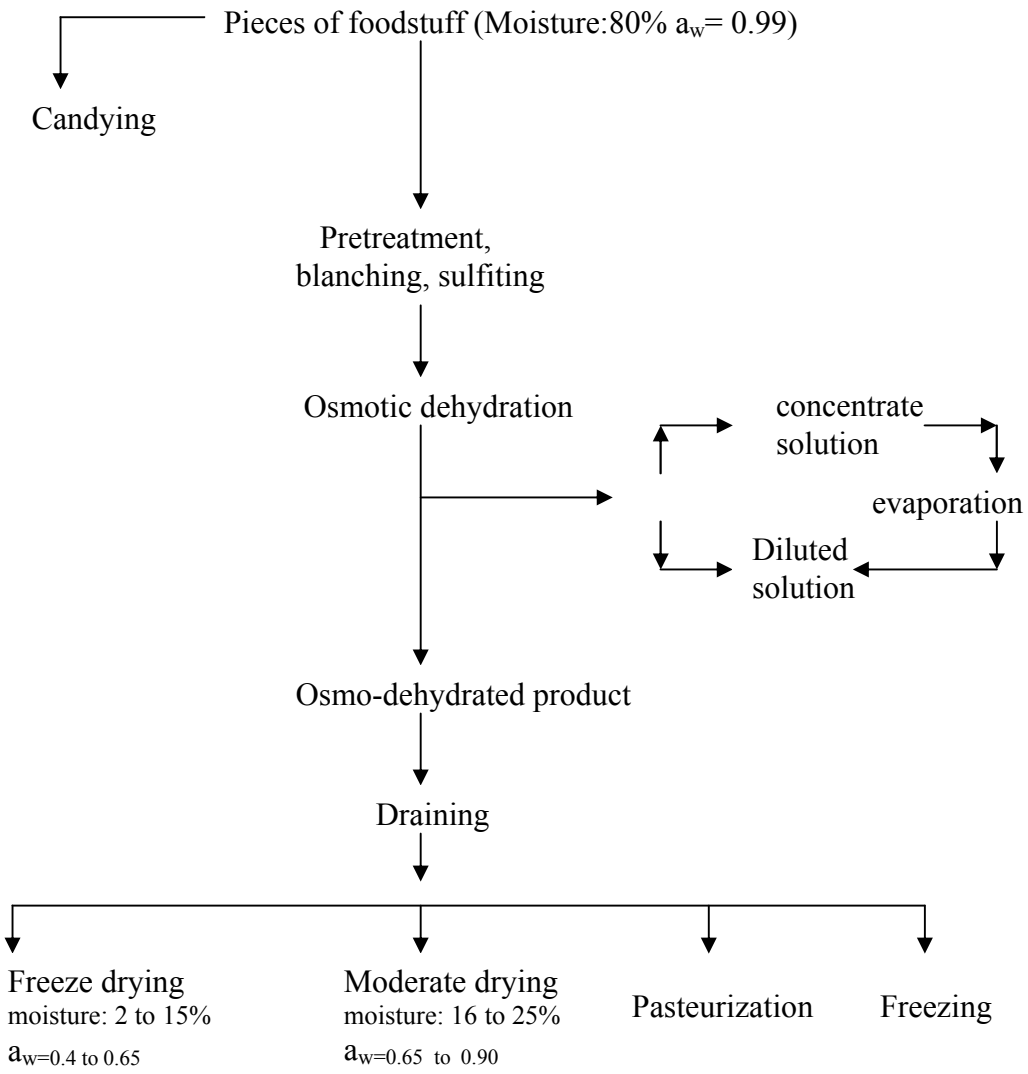


Figure 1.3. Industrial application of osmotic dehydration (Raoult-Wack et al., 1989).

By combining osmotic drying with vacuum drying, a high-quality intermediate-moisture food can be produced. A modified osmotic dehydration process was developed to air dry food particles to 20-50% of their original weight (i.e., process stopped before heat damage caused significant quality deterioration), and then mix them with recalculated solute for further concentration of solids via infusion. By using this method, foods can be rendered shelf life stable with the minimum waste.

A potential problem with osmotic drying is large amount of residual fluid that must be disposed of after the process is complete. This fluid can be recycled, or further processed into such products as puree, juice, jelly, jam and fruit leathers, or used as a flavoring agent (Hui et al., 2004).

1.4. Mass Transfer during Osmotic Dehydration

Mass transfer during osmotic treatment occurs through semi permeable cell membranes of biological materials, which offers the dominant resistance to the mass transfer. The state of the cell membrane can change from partial to total permeability and this can lead to significant change in the tissue architecture. During the osmotic removal of water from foods, the dehydration front moves from the food surface that is in contact with the osmotic solution to the centre and the associated osmotic stress results in cell disintegration. The most likely cause of cell damage can be attributed to the reduction in size caused by water loss during osmotic treatment, resulting in the loss of contact between the outer cell membrane and the cell wall (Rastogi et al., 2000).

Two resistances oppose mass transfer during osmotic dehydration of horticultural products, an internal and an external. The fluid dynamics of solid-fluid interface governs the external resistance, whereas the internal one is influenced by the cell tissue structure and the interaction between the different mass fluxes. Under usual treatment conditions the external resistance is negligible compared to the internal one.

During the osmotic dehydration, three types of mass transfer in counter-current flux can occur-water flux from the product to the solution, solute transference from the solution to the product, and flux of natural solutes (organic, mineral sugars, acid, vitamins, etc.,) from the fruit to the solution (Raoult-Wack, 1994). Leakage of the natural solutes from the plant tissue occurs because the cell membranes of the plant tissue responsible for osmotic transport, is not perfectly selective but this flow is negligible, although it may be important for the organoleptic and nutritional properties of the product (Heng et al., 1990; Mizrahi et al., 2001).

Rate and dewatering degree of the material and changes in its chemical composition depends upon a number of different factors such as: the kind of osmotic substance

used temperature and concentration of the osmotic solution, dehydration time, the size and geometry of material, the solution-to-material mass ratio, agitation and etc. (Qi and Sharma, 1998).

Osmotic dehydration removes water from the fruits and vegetables up to a certain level, which is still high for food preservation, so this process must be followed by an other process in order to lower even more the fruit water content (Spiazzi and Mascheroni, 1997; Yao and Maguer, 1996).

A number of investigators used Fick's unsteady state law of diffusion to estimate the water or solute diffusivity, simulating the experiments with boundary conditions to overcome the assumptions involved in Fick's law. Assumptions include constant concentrations of external solution and negligible surface resistance compared with the internal diffusion coefficient. The assumption of constant solution concentration can be satisfied in laboratory scale.

While solute transfer is assumed to be of diffusion type, the fact that water loss is greater than solid gain is attributed to an osmotic transport phenomenon across the semi permeable cellular membranes. Thus, the process is termed ' osmotic dehydration ' though perhaps the most appropriate term would be ' dehydration driven by concentration differences' or 'dehydration and impregnation by immersion'.

1.5. Equipment Used For the Osmotic Dehydration

In terms of the principles of food- solution contacting osmotic process falls into several categories:

(1) the osmotic solution is passed to external of the food, or the flow of a film solution around food agitation or immersion . This can be examined in four categories

(a) Immersion of food in osmotic solution without agitation
(b) Immersion of food in osmotic solution with continuous agitation
(c) Immersion of food in osmotic solution with intermittent agitation
(d) flowing of osmotic solution onto food

(2) Placing of osmotic solution inside the food with injection

(3) Flowing of osmotic solution onto food with mechanized spraying

(4) Flowing of osmotic solution with pressure

1.5.1. Food Immersion in Solution without Agitation

Immersion in a static bath is the simplest and most obvious way of contacting food with a solution. It has often been used in the past and is still frequently used today. This ancestral technique is applied to fruit and vegetable processing and to the brining (Voskresensky, 1965) and marinating (McLay, 1972) of meat and fish. In these principles, movement of the solution relative to the food is slight, usually nil. As the temperature cannot be controlled by solution circulation, the tanks replaced in a chamber regulated to the required temperature (Mc Lay, 1972).

1.5.2. Without Solution Renewal

Candying and brining devices essentially consist of tanks of solution in which the food is immersed; often in wide-mesh baskets (Figure 1.4.). Apart from the immersion and removal phase, there is no movement of the solution relative to the food. The aim of such processes is impregnation, so they are long (10 h to 8 days) with slow transfer kinetics (Marouzé et al., 2001).

1.5.3. With Solution Renewal

Semi-candying processes use a series of several tanks containing increasingly concentrated solutions in which the pieces of food are successively immersed (Figure1.5)

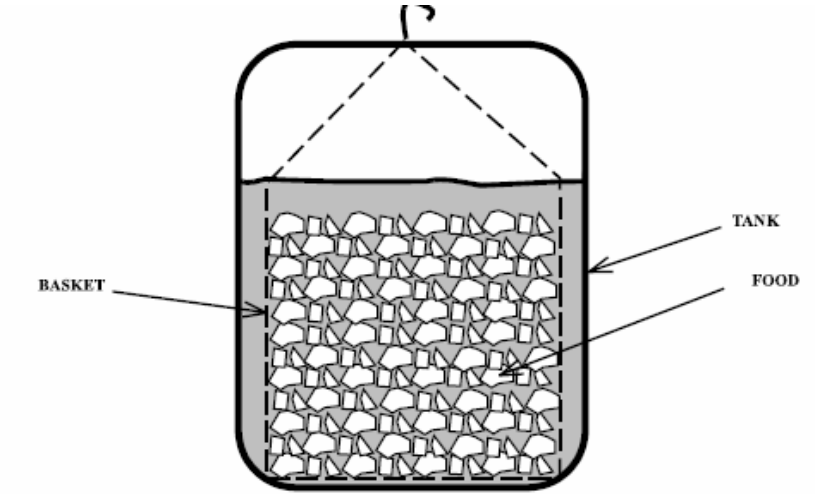


Figure 1.4. Products immersed in solution without agitation or solution renewal (Marouzé et al., 2001).

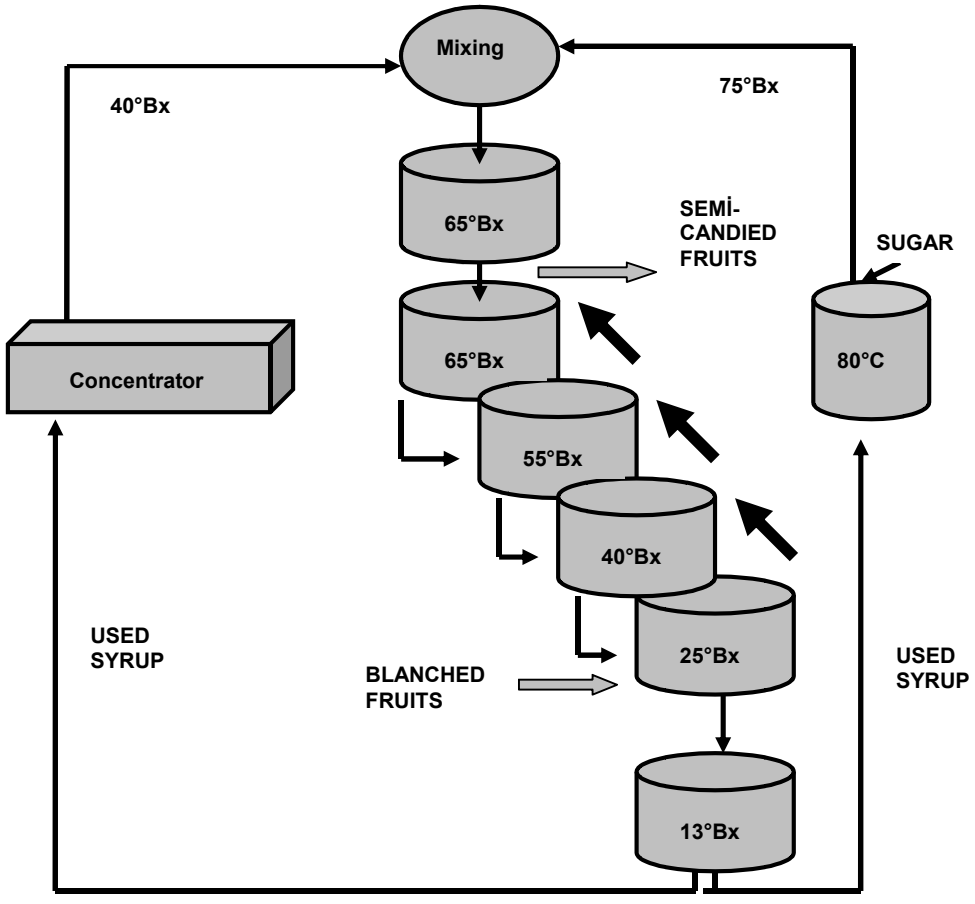


Figure 1.5. Products immersed in solution without agitation but with solution renewal (Marouzé et al., 2001).

Maintenance of the initial concentrations is obtained by slow circulation of the solution from tank to tank in the opposite direction to that of food transfer. Displacement of the solution relative to the food is virtually nil, so there is no agitation other than that carried out periodically either on transfer of the food from one tank to the next (Marouzé et al., 2001).

1.5.4. With Slow Movement of Food in the Tank of Solution

Food immersed in an elongated tank is displaced by mechanical means. It is transported by the horizontal displacement of baskets containing the food or by means of a conveyor (Figure 1.6.). The latter can force immersion if the food is lighter than the solution, or to movement it from settling on the bottom of the tank. Agitation at the centre of the mass is slight or even nil, even where solution is added to the tank from time to time (Deumier et al., 1996).

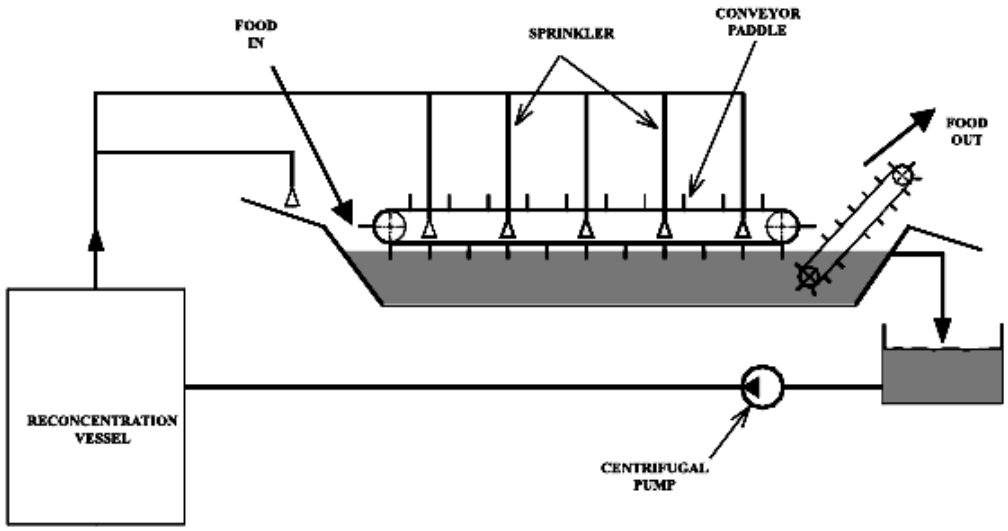


Figure 1.6. Principle of slow movement of food in the solution (Marouzé et al., 2001).

1.6. Immersion with Continuous Agitation

1.6.1. Mechanical Mixing

The contactor is horizontal cylindrical tank equipment internally and axially with a helical tube with blades at regular intervals that give an axial counter flow of food (Marouzé et al., 2001). The contactor mixes the food in the solution under vacuum (Figure 1.7.). Temperature control is achieved through the circulation of steam inside the tube.

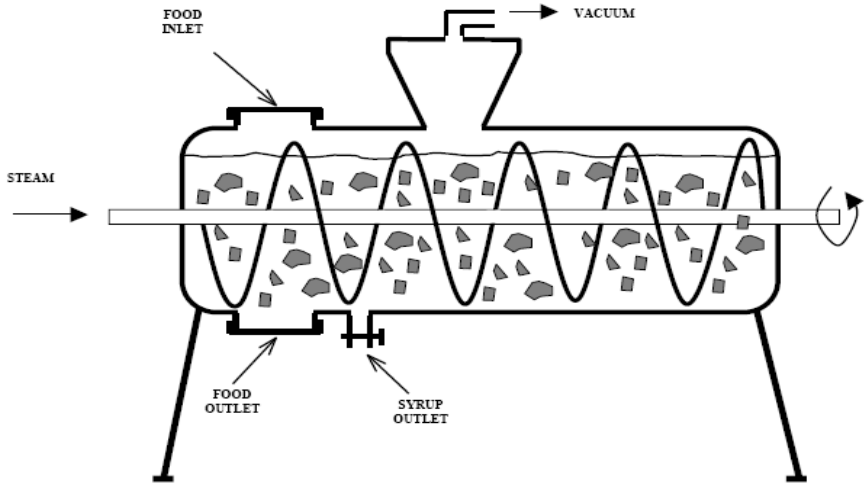


Figure 1.7. Principle of mechanical agitation of the food in the solution (Marouzé et al., 2001).

1.6.2. Fixed Percolated Bed in Batch Processing

The principles presented below operate with the solution circulating through the food mass. An arrangement external to the contactor proper is used to circulate the solution via a circuit consisting of a pump and accessories, giving solution temperature, concentration and filtration control.

With the fixed percolated bed principle used in batch processing, the food is placed either in basket or on horizontal trays in a vertical cylindrical tank (Figure 1.8).

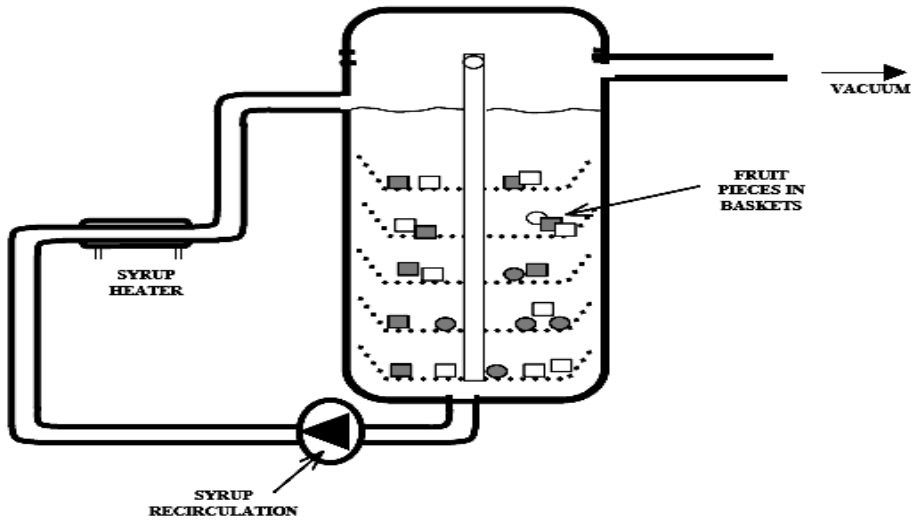


Figure 1.8. Principle of fixed percolated bed in batch processing (Marouzé et al., 1994).

High solution flow rates are required, and the homogeneous treatment of the food depends on the distribution of solution flow, the porosity of the food mass and on the whether or not preferential paths are created for the passage of the solution into the food mass (Marouzé et al., 1994).

1.6.3. Percolated Bed with Slow Counter-Current Displacement of the Food

The nucleus of the device is a vertical cylindrical tank in which the solution circulated downwards (Figure 1.9.).

Fresh food is delivered through the tank bottom via a hydraulic feed and formed a compact bed. The speed of food displacement (<<1m/s) is well below that of the solution at the end of treatment. The food arriving at the top of the tank is extracted by a bucket conveyor that allowed the solution to drip off (Pavasovic et al., 1986).

1.6.4. Percolated Bed with Slow Co-current Displacement of the Food

The device consisted of a vertical tower with the fresh food and the solution entering at the top (Figure 1.10.). It is a co-current device with a low speed of food displacement (several hours to pass through the tower) and a high solution speed (20 times faster than the speed of food displacement).

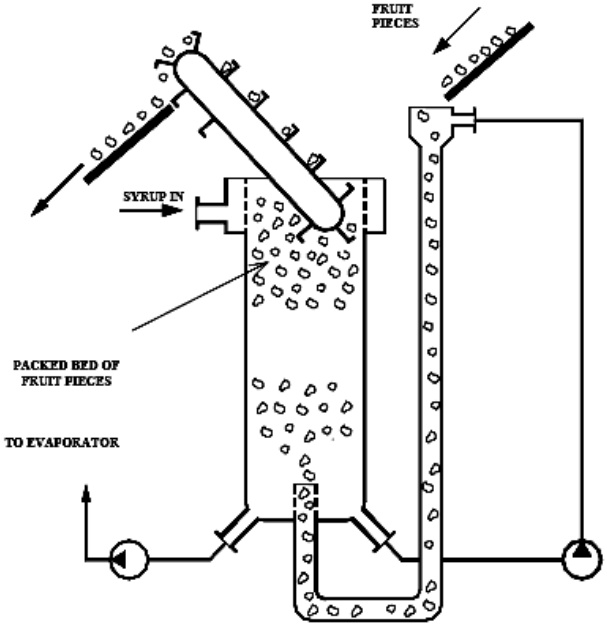


Figure 1.9. Principle of percolated bed with slow counter-current displacement of the food (Pavasovic et al., 1986).

The sprinkler device at the top of the tower give good initial impregnation of the food before it is propelled downwards. The base of the tower is conical and contained a device that mixed the food by re-injecting part of the solution and a treated food outlet by hydraulic transport.

Compared to the previous principle, the food outlet appeared to be better controlled and avoided crushing, but the other difficulties remained (Brimelow and Brittain, 1976).

1.7. Inverse Fluidization

The food is placed in a vertical column and subject to an intense flow of solution; giving rise to inverse fluidization, i.e., the driving force is in the opposite direction. Fluidization causes the food bed to expand, giving very good solution circulation around the pieces and optimizing convective transfer (Raoult-Wack, 1991).

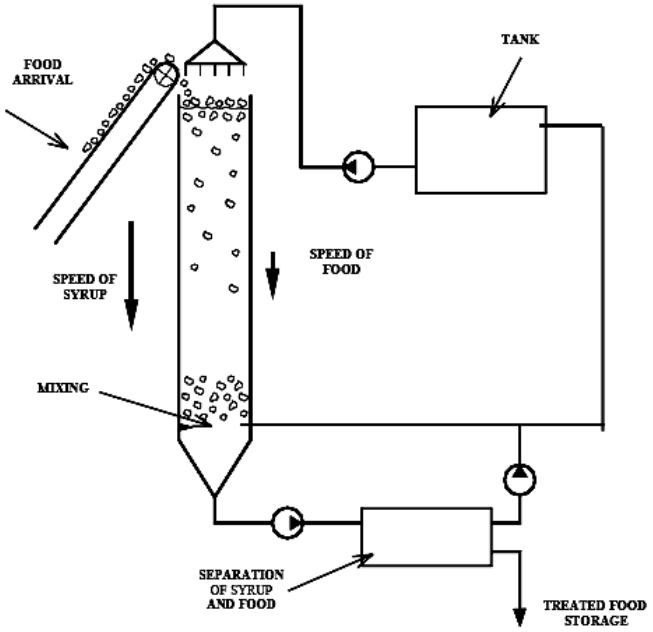


Figure 1.10. Principle of percolated bed with slow co-current displacement of the food (Brimelow and Brittain, 1976).

1.7.1. Immersion with Intermittent Agitation

The principles presented for with continuous agitation are often used in candying, semi-candying or brining. Movement of the solution relative to the food is slight except with the last two principles (hydraulic mixing and combined mechanical-hydraulic mixing) presented, which were developed to facilitate mass transfer and hence dehydration by more vigorous agitation; but they are difficult to implement. More vigorous agitation is essential if the aim is to favor dehydration (rather than impregnation) but continuous agitation is unnecessary. Hence the idea of intermittent agitation, with short sequences of vigorous agitation followed by longer ones of slight agitation or even none at all. These could be used for fruit pieces and the following ones primarily for meat products (Raoult-Wack, 1991).

1.7.2. Hydraulic Mixing

Food pieces are forcibly immersed by a wide-mesh horizontal grid placed just below the surface (Figure 1.11.). A vertical jet of solution projected through the grid and

onto part of its surface propels the pieces placed in its trajectory towards the bottom of the tank.

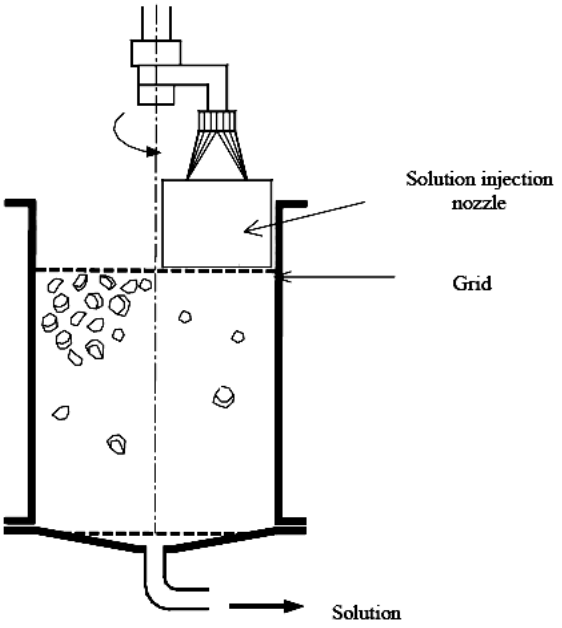


Figure 1.11. Principle of hydraulic agitation of the food (Marouzé et al., 1992a).

To allow the bed of pieces to expand, a free volume of food is necessary at the bottom of the tank, and this sets an upper limit for the solution mass/food mass ratio. Moreover, the flow of solution is powerful when it strikes the food mass held under the grid, so the principle cannot be used with fragile or elongated pieces of food (Marouzé, et al., 1992a)

1.7.3. Combined Mechanical-hydraulic Mixing

With this principle (Figure 1.12.), the food is forced downwards by a mechanical device and released at the bottom of the contactor. Its free rise in the solution under effect of the Archimedes' force provides sufficient agitation to renew the solution around the food and to activate mass transfer. A circulation system external to the contactor allows an appropriate solution temperature and concentration to be maintained but it is no direct use for agitation (Marouzé et al., 1992b).

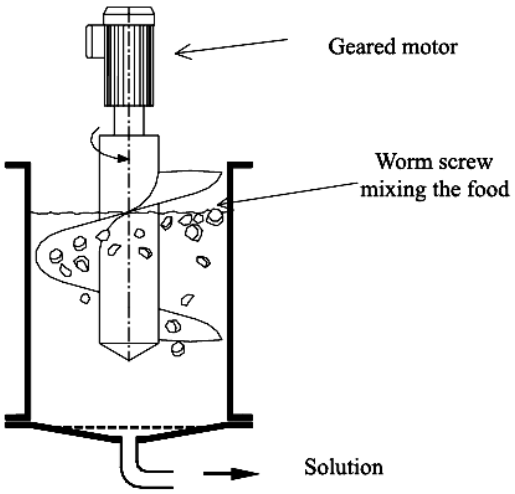


Figure 1.12. Principle of combined mechanical/hydraulic agitation of the food in batch processing (Marouzé et al., 1992b).

1.7.4. Immersion with Combined Food Solution Displacement

The principles are used in batch processing meat or fish pieces (Figure 1.13.). Fillets are laid flat on trays arranged in layers and fixed to a cradle. The tray –frame assembly is immersed in a tank with internal dimensions matching the external dimensions of the trays. The treatment cycle consists of a rapid descent of the trays, a pause, and then their slow rise.

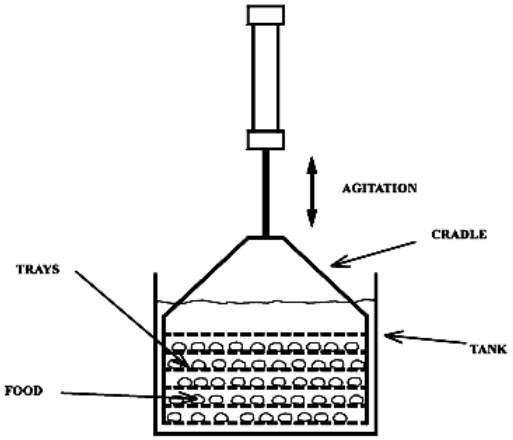


Figure1.13. Principle of immersion with combined food/ solution displacement (Deumier et al., 1997).

The rapid downward movement of the trays causes solution movement relative to the food. The greater the load on the trays, the faster the relative movement of the

solution. The rise is slow to prevent the pieces held under the trays by the Archimedes' force becoming detached and being displaced horizontally. The travel is such that the pieces are kept immersed at all times (Deumier et al., 1997).

1.8. Flow of a Thin Layer of Solution around the Food

The principles involving immersion require a high solution mass/food mass ratio if renewal of the solution on all product surface is necessary, as the food mass has to expand (to separate the pieces and to allow the passage of the solution). By establishing a thin layer of solution all around the product with a flow of solution, the "creating relative movement" function can be achieved without the large volumes of solution required for immersion.

1.8.1. Single- Layer Drenching

The solution is recovered from beneath the belt and recycled. The principle is ideally suited to continuous processing but mass transfer is low on the surfaces that are not directly sprayed, especially if the pieces remain stuck together (Figure 1.14). The technique has been applied to the brining of cheese. (Shiler and Okinchits, 1978; Krayer 1986; Bines and Holmes, 1994).

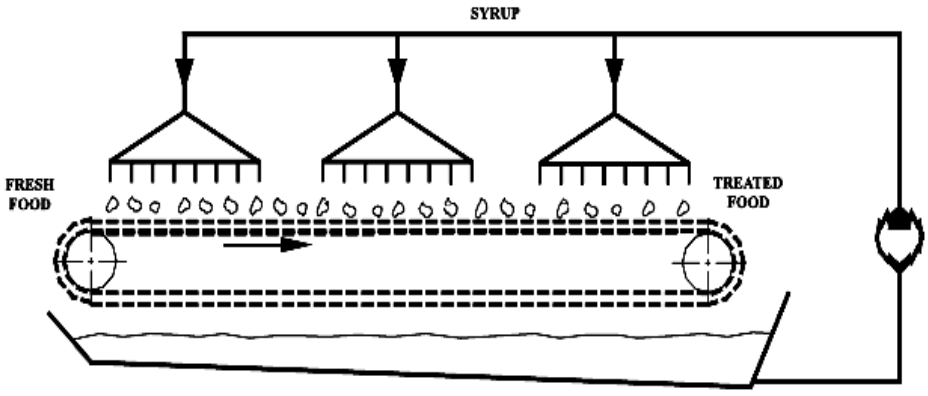


Figure 1.14. Principle of single-layer drenching with conveyor (Qi, 1989)

1.8.2. Recurrent- action Multi-level Drenching

It is particularly used meat and fish products (Figure 1.15).

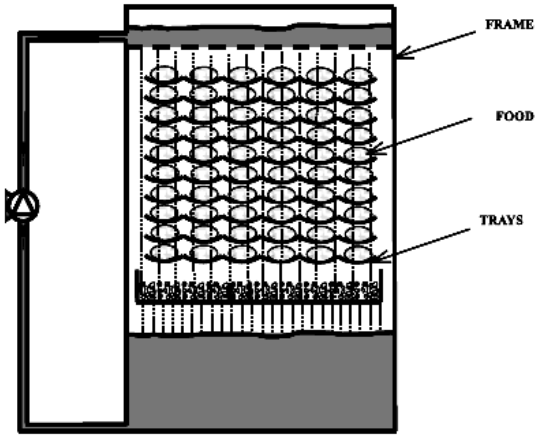


Figure 1.15. Principle of multi-level drenching with conveyor (Marouzé et al., 1997).

For example, fish fillets are arranged in the troughs of corrugated trays. The trays are stacked and continuously drenched with solution. The flow of solution was channeled under pieces along the axis of the corrugations, so the pieces on all trays are drenched, and therefore treated, identically. The process is easy to implement in both batch and continuous processing. It also considerably reduces the volume of effective solution, reduces equipment size and optimizes mass transfer (Marouzé et al., 1997).

1.8.3. Massaging/tumbling

This is usually used fo massaging pieces of meat, more particularly hams (Theno et al., 1978), and to facilitate salt absorption, are cylindrical or truncated cone shaped tanks that slowly rotate on a horizontal axis (Frentz and Zert, 1990). Mechanical action on the fiber caused by the pieces being against one other accelerated solute transfer and makes it possible to process them to full depth.

The process can be started without solution by introducing a mixture of salt and curing ingredients into the tank. During treatment, the pieces of meat exude water, creating brine that flows around them when the tank is set in motion.

1.9. Injection of Solution into the Food

Pressurized injection of solution is a very well developed technique for salting meat and fish (Schmidt, 1986; Claus et al., 1994). The solution, previously saturated with salt, is injected through needles implanted in the flesh. Where meat is concerned, arterial injection is often used (Pearson and Tauber, 1984). It improves the performance (speed of impregnation, yield) of the salting processes (Mandigo et al., 1977; Handel and Mally, 1991; Klaassen, 1993), but can cause sanitary problems because the flesh is in contact with the needles, a possible vector of contamination.

1.10. Solid Solute on the Food

Dry processing, mainly used for salting meat and fish, is still widely used, particularly in small-scale processing. It consists of contacting the food with salt crystals. The technique requires few resources but salt consumption can be high. The application of dry salt can be automated. Mechanized spraying has been proposed. This can be done under pressure (salt cannot, mechanical introduction) when salting cheeses (Muzzarelli, 1984) and fish (Ismail & Wooton, 1992), thus minimizing salt consumption and enabling the food to be salted quickly.

1.11. Selection of Solute of Osmotic Dehydration

The choice of solute and concentration of osmotic solution depends on several factors such as its effect on the organoleptic quality, final products' taste, its capacity to lower the water activity, solute solubility, permeability to the cell's membrane, preservative effect and its cost. Properties of some solutes for osmotic dehydration are shown in Table 1.1. Sucrose has been found to be one of the best osmotic agents because of its effectiveness, convenience, and desirable flavor. It is an effective inhibitor of polyphenol oxidaze, prevents loss of volatile flavors, and is impermeable to most cell membranes. Its diffusivity is much lower than that of water, which results in little solid uptake in the tissue. However, its sweetness limits its application to vegetables.

Table 1.1. Properties of some solutes used for osmotic dehydration.

Type of solute	molar mass(g/mol)	Density (g/cm^3)	Melting point (ºC)	Solubility in water (g/100ml, 35 °C)
NaCI	58.5	2.16	801	25.4
Sucrose	342.29	1.587	186	211.5
Glucose	180.16	1.54	150	91

(adapted from Green, D.W. and Perry, R.H., 2007)

Sodium chloride is an excellent osmotic agent because of its higher capacity to reduce water activity, resulting in a higher driving force during the water removal process. The salt driving force is much higher than for sucrose at the same concentration level. In some cases such as freeze-dried carrots, salt incorporation has shown a markedly improved effect during rehydration. Salt has been found satisfactory in the concentration range of 10 to 15%. However, its use is limited in the case of fruit dehydration. In some cases, a combination of sugar and salt has shown maximum result in terms of higher water loss, low solute gain, and good product flavor (Sharma et al., 2000).

1.12. Parameters Affecting the Osmotic Dehydration

The parameters influencing mass transfer are concentration and temperature of the osmotic solution, agitation, solid-to-osmotic solution ratio, solid structure (such as porosity), shape and size (which determines surface area and resistance for mass transfer in the form of thickness) and nature and molecular weight of the osmotic solute and pressure (high pressure, ambient or vacuum).

The selection of process parameters also depends on the application. For instance, candying needs high solid gain, which is favored by the low molecular weight of the osmotic solute and low concentration of the solution. On the other hand, dehydration requires high water loss, which is favored by a high molecular weight solute. Thus it is necessary to strike the right balance between these process parameters so that the relative rates of the two main mass transfers suit the application at hand. The shape and size of the food being osmotically dehydrated varies from application to

application. The common shapes are slab, cylinder, cube and sphere (Sharma et al., 2000).

1.12.1. Temperature and Concentration

The effect of the concentration and temperature of the osmotic solution has been studied in considerable details and it has been shown that the rate of osmotic dehydration generally increases with an increase in both parameters.

Kaymak-Ertekin and Sultanoğlu (2000) investigated the osmotic dehydration mechanism of apple slices in different concentrations of sucrose, dextrose and sucrose + dextrose mixed solutions and also at different temperature. As the concentration and temperature are increased, water loss was also increased considerably.

Chenlo et al., (2007) examined effect of solutions of glucose of different concentrations (40, 50 and 56.5 % w/w) and at three different temperatures (25, 35 and 45ºC) on the weight reduction, water loss and solid gain on for chestnut. They found that all the results obtained allow concluding that the osmotic dehydration depends strongly on glucose concentration and temperature of osmotic media. At higher values for both variables, the water loss and solid gain are more intensive.

1.12.2. Solid to Solution Ratio

At low solid to solution ratio, as the dehydration progresses, the osmotic solution becomes increasingly dilute and the driving force further release of water drops. It is therefore necessary to have a solid-to- solution mass ratio of around 1:20 in order to ensure a more or less uniform driving force. It was reported that the increase in fruit-to-sugar syrup ratio (from 1:1 to 1:4.5) resulted in increased weight loss during osmotic dehydration of banana (Bongirwar and Srinivasan, 1977).

Khoyi and Hesari (2006) investigated to find the best sucrose concentration, temperature and sample ratio for osmotic dehydration of apricot. The followings observed; increasing temperature increased water loss and solid gain because of two

reasons: increasing diffusion coefficients and decreasing viscosity of sucrose solution. So the best temperature and concentration were found to be 50ºC and 60%, respectively. Increasing the volume of solution for a fixed amount of sample resulted in more water loss but increasing the volume means more costs arising from more materials to be used and greater volume to operate with the results showed that 10:1 solution ratio is the best choice.

1.12.3. Solid Size

If the solid size is greater, dehydration will occur more slowly because the length of the diffusion path is longer. The molecular size of the osmotic solute has a significant effect. The smaller the solute size, the larger the depth and the extent of solute penetration. Increased solute concentration results in increased water loss and solute gain up to a certain level.

Hence, smaller pieces dehydrate more rapidly. The shape of the solid material is another important factor. In order to evaluate the effect of size and shape on mass transfer during osmotic dehydration, apples were cut into stick, slice, cube and ring shapes and then subjected these pieces to osmotic dehydration. The weight loss and solid gain increased in proportion to the ratio of the surface area to the characteristic length (Lerici et al., 1985).

1.12.4. Agitation

The rate of dehydration also increases as the level of agitation is increased up to a certain extent. Agitation is indeed one of the key factors and an adequate level of agitation ensures reduction or elimination of liquid-side mass transfer resistance and constant driving force.

Mavroudis et al., (1998) investigated the effects of agitation on the osmotic dehydration. Free convection was the mechanism used by the solution in pore penetration, although lack of understanding of this phenomenon at the cell level prevented conclusions from being drawn. Water loss was higher in the turbulent flow region than in the laminar flow region. Thus the existence of external mass

transfer limitations was confirmed at least for the present experimental conditions. Agitation strongly affected water removal.

1.13. Methods Used for Increasing the Mass Transfer During Osmotic Dehydration

Since the rate of mass transfer during osmotic dehydration is generally low, a number of techniques have been attempted to improve it. These techniques include subjecting the food to ultra high hydrostatic pressure (Rastogi and Niranjan, 1998), high intensity electrical field pulses (Rastogi et al., 1999) or gamma irradiation (Rastogi et al., 2000; Rastogi and Raghavarao, 2004) prior to osmotic dehydration and applying ultrasound (Simal et al., 1998), partial vacuum (Fito, 1994; Rastogi and Raghavarao, 1996) or centrifugal force (Azuara et al., 1996) during or prior to osmotic treatment.

1.13.1. Application of High Hydrostatic Pressure

The application of high pressure changes the cell wall structure and tissue architecture, making the cells more permeable (Farr, 1990; Dornenburg and Knorr, 1993; Eshtiaghi et al., 1994; Rastogi et al.,1994). In the case of pineapple this led to an increase in mass transfer rates (Rastogi and Niranjan, 1998). The diffusion coefficients were found to increase fourfold for water and twofold for sugar in the pressure range varying between 100 and 700MPa. Compression and decompression taking place during the high pressure pre-treatment itself cause the removal of a significant amount of water in the case of pineapple and this is attributed to cell wall breakage (Rastogi and Niranjan, 1998).

1.13.2. Application of High Electric Field Pulse Pre-treatment

High intensity pulsed electrical field (HIPEF) treatment resulted in an increase in the permeability of plant cells (Geulen et al., 1994; Knorr et al., 1994; Knorr and Angersbach, 1998 ; Rastogi et al., 1999) due to induced cell damage, which resulted in tissue softening. This in turn resulted in the loss of turgor pressure leading to a reduction in compressive strength or product softening, which in turn led to increased mass transfer rates during osmotic dehydration. High intensity electrical field pulse (0.22-1.60 kV/cm) pre-treatment was shown for the first time to accelerate osmotic

dehydration. HIPEF shows increased cell membrane permeabilitization with increasing field strength and pulse numbers, which facilitated water loss during osmotic dehydration. The application of HIPEF resulted in the development of brown color. However, sample brightness was reported to increase with increase in dehydration time and it decreased with increasing pulse number. The vitamin C content of dried samples also reduced at higher field strengths and longer osmotic dehydration duration (Taiwo et al., 2003).

1.13.3. Application of Ultrasound during Osmotic Dehydration

In a solid medium, sound waves cause a series of rapid and successive compressions and rarefactions, with rates depending on the frequency. This mechanism is of great relevance to the drying and dewatering of foods. The mechanical and physical effects of sounds can be used to enhance many processes where diffusion takes place (Florous and Liang, 1994). Acoustic streaming will favorably affect the thickness of the boundary layer which exists between stirred fluid and solid. Cavitations, a phenomenon caused by sanitation, results in the formation of bubbles in the liquid, which can explosively collapse and generate localized pressure fluctuations. This effect increases diffusion during osmotic processes and accelerates degassing of the tissue (Florous and Liang, 1994). Diffusion across the boundary between the suspended solid and liquid is substantially accelerated in an ultrasound field. Pressure and frequency are the two main factors to take into consideration. No increase in diffusion rates was reported when intensity was maximal due to violent cavitations that produces extreme turbulence or vapor locks at the interface. Solute diffusion rates increase with higher acoustic intensities once the threshold value is crossed (Lenart and Auslander, 1980).

Ultrasonic osmotic dehydration can be carried out at a lower solution temperature to obtain higher water loss and solid gain rates while preserving the natural flavor, color and heat-sensitive nutritive components.

Ultrasound is more significant at low temperature which reduces the probability of food degradation (Mason, 1998). In addition, ultrasound permits the removal of moisture content from solids without producing a liquid phase change (Lopez-

Gallego, 1996). Drying heat-sensitive food materials by power ultrasound is one example of the potential use of ultrasound in the food industry. When a high-intensity ultrasonic wave is directed coupled to the material to be dried, it travels through the solid medium causing a rapid series of alternative compressions and expansions, in a similar way to sponge when it is squeezed and released repeatedly. The forces involved by this mechanical mechanism can be higher than surface tension which maintains the moisture inside the capillaries of the material creating microscopic channels which may take the moisture removal easier. In addition ultrasound produces cavitations which may be beneficial for the removal of moisture strongly attached (Tarleton, 1998). Sarabia et al. studied application of high-power ultrasound for drying vegetables. They examined with an experimental work in which the result obtained with different kind of vegetables (apple, carrots, mushroom, etc.) under the application of ultrasonic vibration. From the investigation presented in that work on the application of high- power ultrasound for drying different kind of vegetables materials (apple, carrot and mushroom) the following conclusions were stated: The application of a high-power ultrasonic vibration in direct contact with samples in both, without and with static pressure has confirmed to be a very effective procedure for vegetable dehydration. A direct coupled vibration accelerates forced-air drying process notably. Both procedures may be useful for vegetable dehydration as a method for preserving foods without affecting their main characteristics.

The improvement obtained by applying high-intensity air-borne ultrasound for vegetable dehydration is less than with direct contact. This fact can be due to the low penetration ultrasonic energy in the vegetable material produced by mismatch between the acoustic impedance of media, the air and the vegetable.

1.13.3.1. Ultrasound as a Processing Aid for Drying

The use of the ultrasonic energy in drying is very promising because it can act without affecting the main characteristics and quality of the products. In particular, power ultrasound is an especially attractive means of drying heat-sensitive foods because they can be dried more rapidly and at a lower temperature than in the conventional hot-air driers.

Osmotic dehydration is widely used for partial removal of water from food materials by immersion in a hypertonic solution. However, one of the main difficulties when applying this technique is the usually slow kinetics of the process. A classical way to increase the rates of mass transfer is the application of a mechanical agitation system; another possibility is the use of power ultrasound.

Simal et al., (1998) reported the application of ultrasound with cubes of apples in a hypertonic solution of sucrose (70°Brix) at four different temperatures (40, 50, 60 and 70 °C) and showed that the rates of mass transfer increase with the use of ultrasound at 40 kHz. They found an increases of water loss (14-17 percent) and a sugar gain rate (23 percent at 40°C; 11 percent at 70°C) when ultrasound was applied. Therefore, osmotic dehydration can be carried out at a lower solution temperature to obtain higher water loss and solute gain rates, while preserving the heat-sensitive nutritive components, flavors and color.

1.13.4. Application of Gamma-Irradiation in Osmotic Dehydration

Gamma-irradiation pre-treatment has been reported to change the interior tissue structure (Wang and Chao, 2002) thereby increasing the permeability of plant cells and mass transfer during osmotic dehydration.

1.13.5. Application of Vacuum during Osmotic Dehydration

The vacuum applied only affects the rate at which equilibrium is achieved and not the equilibrium moisture content. The overall mass transfer under vacuum was higher than at atmospheric conditions due to increased interfacial area resulting from increased pore filling by osmotic solution and increased capillary action (Rastogi and Raghavarao, 1996). In some fruits, such as apple, the presence of intercellular voids is characteristic of the parenchyma tissue. The pore volume represents about 20 percent of the total volume of the apple. These pores are occupied by gas that can be removed by the application of low pressure as in vacuum osmotic dehydration. The reduction in pressure causes the expansion and escape of gas occluded in the pores. When the pressure is restored, the pores can be occupied by osmotic solution,

increasing the available mass transfer surface area (Fito, 1994; Fito and Pasteur, 1994).

1.14. Applications of Osmotic Dehydration

1.14.1. Osmotic Dehydration and Air Drying

Dehydration operations are important activities of food processing industries. The basic objective in drying food products is removal of water in the solids up to a certain level.

The quality changes of dried fruits and vegetables are dependent largely on the drying times and temperature of process. The lower operation temperature causes less thermal damage to the products. It is costly process and is only suitable for high value products. In hot air drying, the drying rates are higher in the beginning of the process when the air stream easily evaporates moisture from the sample. The moisture content decrease exponentially with the drying time and drying take place in falling rate period. The high temperature and long drying time often cause heat damage and adversely affect texture, color, flavor and nutritional value of products.

Unfortunately, classical convective drying in tray dryer is hardly acceptable because of excessive drying time due to relatively low drying rates. On other hand, evaporation of water cannot be accelerated by raising drying air temperature because fruits and vegetables are highly heat sensitive. A solution to this problem could come from pretreatment by osmotic dehydration which not only reduces energy consumption but also offers sugar infused cherry a new market product with enhanced textural, structural and sensory properties.

Osmotic treatment as a preparation step to further processing of plant and animal material allows improving the overall quality of food products by modifying the composition and the structure of the material.

Osmotic dehydration removes water from the fruit and vegetable up to a certain level which is still high for food preservation so this process must be followed by another process in order to lower even more the fruit and vegetables water content. A tray dryer can be used to remove the remaining water from the fruit and vegetables by consumption but also offers sugar infused cherry a new market product with

enhanced textural, structural and sensory properties. In fact, infusion of sweeteners or other ingredients into fruit and vegetable to modify their properties and facilitate processing is a new trend in food technology (Lewicki, 1998).

The economic interest in osmotic treatments focuses on reduced energy consumption for water removal without phase change, as compared to convection drying, and the possible reduction of the refrigeration load by partial concentration prior to freezing of fruit or vegetables. The beneficial effect of an osmotic treatment on dried carrot slices has been proved (Spiee and Behsnilian, 1998). The drying time of carrot slices was reduced and the retention of physiological active compounds enhanced. Reduced processing times at higher temperature could also reduce processing costs.

With the correct choice of solutes, and controlled and equilibrated ratio of water removal and impregnation, it is possible to enhance natural flavor and color retention in fruit products, hence to avoid additives such as antioxidants; softer textures in partially dehydrated products can be obtained; food ingredients can be designed for particular uses.
Spiess and Behsnilian (2006) studied the impact of the solution applied for the treatment on the composition of the processed substrates (dewatering, uptake of osmotic agent). The process was carried out at moderate temperatures (25-45ºC) and as substrate apples, carrots and potatoes were used. It was observed that the dewatering effect is enhanced by increasing the solute concentration, the solute uptake however is limited because of a parallel increase of the viscosity of the solution which has to be considered as a restricting factor for the mass transfer by substrate. Furthermore, the beneficial effects of an osmotic treatment as a pre-treatment to convective warm air drying was confirmed for dried carrot slices. For osmotic treatment, food tissues are immersed in aqueous solutions of sufficiently high concentration at moderate temperature. Osmotic treatments have been studied in combination with air-vacuum, freezing, sun-drying, pasteurizing, canning, frying, addition of preservatives and acidification and coating by edible surface layers.

Osmotic dehydration as a pre-treatment to an air drying process can be used to improve nutritional, sensorial and functional properties of food without changing the integrity of the foods (Nanjundaswamy et al., 1978; Torreggiani and Bertolo, 2001). Osmotic dehydration increases the sugar to acid ratio and improves the texture and

stability of pigments during dehydration and storage of foods (Raoult-Wack, 1994). It is effective around ambient temperatures, so heat damage to texture; color and flavor can be minimized.

The combined use of microwave and convective drying has been reported to enhance the drying rate as well as to improve the final product quality. Osmotic dehydration pre-treatment resulted in reduced drying rate and effective moisture diffusivity and increased cell wall thickness in apple pieces, increased firmness of rehydrated apple pieces and reduced rehydration capacity. The quality of the final the product was reported to improve by osmotic dehydration prior to drying (Proton et al., 2001).

Fernandes et al., (2005) was studied osmotic dehydration of bananas followed by air-drying and they found that the results show the advantage of using high sucrose concentrations for the osmotic solution, and the use of the osmotic treatment to reduce the total processing time of fruit drying.
Mandola et al., (2005) examined the influence of different pre-treatments on apple air drying and their physical characteristics during drying. Samples osmosed in high sugar concentration had better physical characteristics than those treated at lower concentrations. Among them, osmosed sample in glucose had even better characteristics and additionally had a higher drying rate. The only disadvantage of this sample was the firmness increase during drying.

Fabiano et al., (2006) studied the process of papaya of osmotic dehydration followed by air drying. An optimization was done using the model in order to search for the best operation condition that would be reducing the total processing time. The results showed the advantage of using high sucrose concentrations for the osmotic solution and the use of osmotic treatment to reduce total processing time of fruit drying. Total processing time can be optimized in order to reduce the drying process to a minimum, which can reduce costs and increase the overall productivity.

Shukla and Sring (2006) dried cauliflower, mushroom and green pea with osmo-convective drying. They examined the effect of osmo-convective on texture and color of vegetables. During the osmosis, the product gains solid and looses the water. Due to solid gains, the texture is not disturbed. Moisture loss during convective

drying at 60ºC was 52-8 % in 5 hours; 53-7% in 9 hours and 63-8% in 7 hours respectively. Solid gain during osmotic dehydration was about 15 % in all three vegetables. Texture and color of osmo-convective dried vegetables were improved.

Fruit drying is a well-known preservation method, mainly because water removal and water activity lowering reduce the risk of microbial development. Moreover, dried fruit can be stored and transported at a relatively low cost. However, water removal using high temperatures and long drying times may cause serious decreases in the nutritive and sensorial values. The flavor, the color and nutrients of dried are mainly damaged (Lenart, 1996).

Drying is an energy intensive operation, and a greater understanding of the drying process is important if drying efficiency is to be increased while maintaining product quality. The main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum throughput, and to optimize this factor consistently. Often good quality of a biological product implies that the dried product undergoes several physical, chemical or biological changes to yield a product of desired specifications. Drying is an energy intensive operation that easily accounts for up to 15% of all industrial energy usage, often with relatively low thermal efficiency in the range of 25-50%. Thus, to reduce energy consumption per unit of product moisture, it is necessary to improve the energy efficiency of the drying equipment reducing the processing time (Chua et al., 2001). Osmotic dehydration removes water partially from fruits or vegetables immersed in a hypertonic solution. A driving force for water removal is set up because of a difference in osmotic pressure between the food and its surrounding solution. The complex cellular structure of food acts as a semi-permeable membrane. During osmotic processing, water flows from the product into the osmotic solution, whereas osmotic solute is transferred from the solution into the product. The rate of diffusion of water from any material made up of such tissue depends upon factors such as temperature and concentration of the osmotic solution, the size and geometry of material, the solution to material mass ratio, and the level of agitation of the solution (Corzo and Gomes, 2004; Fito, 1994; Pokharkar et al., 1997). Osmotic dehydration removes water from the fruit up to a certain level, which is still high for food preservation, so this process must be followed by another process in order to lower

even more the fruit water content. An air dryer can be used to remove the remaining water from the fruit, by putting it in contact with a hot air stream flowing continuously (Spiazzi and Mascheroni, 1997; Yao and Maguer, 1996).

1.14.2. Osmotic Dehydration and Freezing

The use of osmotic dehydration for partial concentration of food as a pre-freezing treatment (osmo-dehydrofreezing) has been shown to decrease enzymatic browning (Conway et al., 1983) and to reduce structural collapse and drip during thawing (Forni et al., 1990). During freezing/thawing of plant cells, it is thought that membranes, particularly the plasma membrane, play a key role in the changes that occur within the tissue; the plasma membrane is considered the primary site of freezing injury. Osmotic removal of water results in a reduction in subsequent ice formation.

Osmo-dehydrofreezing (osmotic dehydration followed by air drying and freezing) has been proposed as a suitable for different applications Incorporation of different sugars (maltose, sucrose or sorbitol) into the product affected their low-temperature phase transitions and the percentage distribution of sugars. Maltose have the greatest protective effect on color stability during frozen storage. (Forni et al., 1997).

1.14.3. Osmotic Dehydration and Frying

Osmotic dehydration before frying partially dehydrates materials through the elimination of a large portion of the water present in the food. The effects of osmotic dehydration on oil absorption, moisture loss phenomena and changes in color as well as structure of French fries during subsequent deep fat frying were studied (Krokida et al., 2001). The osmotic pre-treatment reduced moisture loss and oil uptake during frying. Darkening of color occurred during osmotic drying, which produced more intense coloration in the fried products.

1.14.4. Osmotic Dehydration and Jam Manufacture

Jams are made from fruit and sugar mixed in proportions so that the final product contains a minimum fruit content of 30 percent and strength of minimum 45°B. Traditional manufacturing methods require concentration by heat treatment, which causes quality change that adversely affects sensory and nutritional properties, the latter being related mainly to ascorbic acid losses. An alternative to thermal concentration is to incorporate previously dehydrated fruit, avoiding thermal damage. Osmotic dehydration with sugar solutions has been described as a suitable method for concentration of fruits (Shi et al., 1996).

1.15. Limitations of Osmotic Dehydration

There are still some limitations in scaling up osmotic dehydration technology. The high viscosity of the osmotic solution and low density difference between the solid and solution are the main drawbacks. An increase in viscosity increases resistance to mass transfer as the diffusion coefficient is inversely proportional to the system viscosity (Wilke and Chang, 1955). The labile nature of foods will also not permit an increase in agitation levels beyond a point to overcome this viscosity effect. The low density difference makes the product float, requiring an additional mechanical means to keep it immersed in the solution.

The major constraint for the industrial adoption of osmotic dehydration is the cost of osmotic solution that necessitates a proper means for its recycling. During osmotic dehydration, the solution become diluted and acquires flavor as well as color the extent of which depends upon the food. The osmotic solution has to be concentrated in order to recycle which can be achieved through concentration by evaporation and/or by the addition of solute. The processing steps involved in recycling of spent osmotic solution still remain proprietary in the form of patents.

1.16. The Aims of the Present Study

Osmotic dehydration is a gentle method to remove water from fruits or vegetables, and is considered as intermediate step or as a pretreatment technology in food preservation. Dried-cherry has been generating a lot of interest in recent years among both consumer and producers due to its high antioxidant content. Various varieties of

zucchini is usually sun-dried and consumed during winter times in particularly, South and Eastern part of Turkey. The objective of this thesis was to study the effect of temperature, concentration of solution, mixing and ultrasound use on the extent of osmotic dehydration of zucchini, and cherry; to investigate the mechanism of mass transfer during the osmotic dehydration, and to examine whether osmotic dehydration can be used as a pretreatment before air drying or not

CHAPTER II

MATERIALS AND METHODS

2.1. Materials

Zucchini (*Cucurbita pepo*), which has a moisture content of 94 % (w.b.) was obtained from a local market in Gaziantep.
Cherry (*Malpighia punicifolia*), which has a moisture content of 82 % (w.b.) was obtained from a local market in Gaziantep.
Salt (NaCI) and sucrose (sucrose) obtained from a local market in Gaziantep.

2.2. Methods

2.2.1. Preparation of Samples

The osmotic solution used in each experiment for zucchini runs was prepared by mixing salt (NaCI) with the sufficient amount of distilled water to obtain 5, 15, 25 % (w/v) salt solutions. Zucchini was cut into 1cm^3 pieces with a knife. Cherry was separated into two pieces with a knife and seed of cherry was removed. The osmotic solutions used in each experiment for cherry run were as follows; 40, 55, and 70 % (w/v) sucrose solutions were prepared by mixing sucrose with the sufficient amount of distilled water.

2.2.1.1. Moisture Determination

Moisture was determined in a drying oven (W.C. HERAEUS HANAU; RT 500 (Hanau, Germany) at 105°C for 24 hours until constant weight obtained (AOAC, 1990).

2.2.1.2.Color Determination

Color change was followed with Hunter Lab Colorimeter (Colorflex /A60-1010-615 Model Calorimeter, Reston, VA) in terms of L, a, b values as measures of lightness, redness and yellowness, respectively. The equipment was calibrated with a white tile

standard (L=93.01, a=-1.10, b=1.29). For each sample, three measurements were taken and averaged.

The results were expressed as total color difference (ΔE) between the reference (fresh sample) and samples (exposed to osmotic dehydration) to the equation (1)

$$\Delta E = \sqrt{(L_{sample} - L_{fresh})^2 + (a_{sample} - a_{fresh})^2 + (b_{sample} - b_{fresh})^2} \quad (1)$$

2.2.1.3 Vitamin C Determination

Vitamin C content of cherry was determined after drying of osmotically dehydrated cherry in tray dryer and fresh cherry by the AOAC's official titrimetric method (AOAC, 1990). This method is summarised below.

Preparation of acid solution: 2g metaphosphoric acid was dissolved with distilled water at 60 °C. Then it was cooled to room temperature. Eight mL glacial acetic acid was added and volume was completed to 100 mL. This solution was kept in refrigerator. Preparation of dye solution: 250 mg 2,6-dichloroindophenol sodium salt salt was dissolved in 500 mL distilled water at 60 °C and cooled to room temperature. Preparation of standard ascorbic acid solution : 100 mg ascorbic acid was dissolved in 10 mL acid solution and made up to volume 100 mL. Standardization of dye solution: 10 mL ascorbic acid solution was placed in a flask and 10 mL acid solution was added. Then, this solution was titrated with dye solution until pink color observed. Vitamin C determination: 10 g sample was taken and 10 mL acid solution was added. Later, this solution was titrated with dye solution until pink color observed.

Calculation : Dye titer x titration (mL) 100/10= mg ascorbic acid/ 100g sample.

2.2.2. Osmotic Dehydration of Zucchini

Table 2.1. shows the experimental conditions for osmotic dehydration of zucchini. Sample-solution ratio was determined as 1/10 in order to prevent dilution of solution. This situation causes a decrease in the driving force for mass transfer.

Table 2.1. Experimental conditions for osmotic dehydration of zucchini.

Temperature of solution (ºC)	Concentration of salt (NaCI) solution (w/v)	Initial weight of sample in a beaker (g)
15	5, 15, 25	80
25	5, 15, 25	80
35	5, 15, 25	80

Solution was agitated with a magnetic stirrer. This provided uniform distribution of temperature and an increase the contact of samples and solution. Thus, mass transfer increased. The osmotic process was conducted in a thermostatically controlled oven to keep the temperature constant throughout the experiment. Samples were exposed to osmotic dehydration for 4 hours in 250 mL beakers. Samples were taken at 30, 60, 180 and 240 minutes to follow the changes in moisture loss, salt (NaCI) content and color. Triplicate samples were taken. The samples were gently wiped with filter paper to remove excess salt solution and taken for further analyses. Color of fresh and osmotically dehydrated sample pieces of zucchini was measured by measuring L, a, b and YI values (section 2.2.1.2). Moisture was determined in a drying oven (Section 2.2.1.1)

The experimental design was evaluated using Design Expert Software (Version 6.01.0, State-Ease, Inc Minneapolis, MN). The full factorial design was used. The features of design are well explained in section 2.4. Experimental conditions for zucchini osmotic dehydration are shown in Table 2.2.

2.2.2.1. Salt Determination

Amount of salt was determined by Mohr Method (Skoog and West, 1976).Ten grams of sample was taken and cut into pieces. Hot distilled water was poured onto sample and mixed vigorously. Later the sample was filtered with a filter paper. Solution obtained from filtration was completed to100 mL. 10 mL solution from this solution was taken and placed into a 250 ml beaker. 2-3 drops potassium chromate was added and later this solution was titrated with 0.1N $AgNO_3$ until color changed from yellow to red.

Table 2.2. Experimental conditions of osmotic dehydration of zucchini.

Run	Temperature(°C)	Salt(w/v)	Time(min.)
1	15	5	30
2	25	5	30
3	35	5	30
4	15	15	30
5	25	15	30
6	35	15	30
7	15	25	30
8	25	25	30
9	35	25	30
10	15	5	60
11	25	5	60
12	35	5	60
13	15	15	60
14	25	15	60
15	35	15	60
16	15	25	60
17	25	25	60
18	35	25	60
19	15	5	180
20	25	5	180
21	35	5	180
22	15	15	180
23	25	15	180
24	35	15	180
25	15	25	180
26	25	25	180
27	35	25	180
28	15	5	240
29	25	5	240
30	35	5	240
31	15	15	240
32	25	15	240
33	35	15	240
34	15	25	240
35	25	25	240
36	35	25	240

2.2.3. Osmotic Dehydration of Zucchini in the Ultrasonic Bath

The osmotic dehydration was carried out in a beaker fitted inside ultrasound bath. (Model B-2200 E4 Blason, Power output 60W, Frequency 47 Hz, Danbury, CT). Even though, the ultrasound bath was a thermostatically controlled, the temperature of the water in the ultrasound bath was also controlled by passing cold tap water through a plastic hose. Several runs conducted to adjust the flow rate of water to keep the water in the bath at constant temperature.

Therefore, the temperature in the bath was kept constant temperature of 25±2°C. This was good enough because earlier runs indicated that temperature did not affect osmotic dehydration significantly. Samples were exposed to dehydration for 3 hours. The experimental design was evaluated using Design Expert Software (Version 6.01.0, State-Ease, Inc Minneapolis, MN). Fractional factorial design was used and variables and levels were given by the above software. The features of composite design are explained in section 2.4. Experimental conditions for zucchini osmotic dehydration are shown in Table 2.3. Moisture was determined in a drying oven (section 2.2.1.1). Color change was followed by measuring L, a, b values (section 2.2.1.2).

2.2.4. Osmotic Parameter Calculations for Zucchini

Weight reduction (WR), solid gain (SG, as salt increase) and water loss (WL) were determined by using the gravimetric method using below equations (2, 3, and 4).

2.2.5. Osmotic Dehydration of Cherry

The osmotic dehydration was carried out in a shaker (Selectra, Unitronic-Orbital 6032011; 1500 watt; Barcelona, Spain) fitted inside a thermostatically controlled chamber, 250 mL Erlenmeyer flasks filled with osmotic solution in which samples (about 25 g) were placed and exposed to osmotic dehydration for 6 hours in this shaker bath. The experimental design was evaluated using Design Expert Software (Version 6.01.0, State-Ease, Inc Minneapolis, MN). Fractional factorial design was used and variables and levels were given by the above software. Experimental conditions for osmotic dehydration of cherry are shown in Table 2.4. In this study, a temperature of 25ºC was being selected.

Preliminary studies indicated that temperature range (15-35ºC) did not affect osmo-dehydration process significantly. In addition, use of high temperature, such as 50 to 60ºC did not provide us for energy savings and was not suitable the texture of cherry.

Agitation of sucrose solution with magnetic agitation was not suitable for cherry because of structural disturbances. Use of shaker bath solved the problem. The speed of the shaker was chosen as 70 rpm beyond this speed disturbed the structure of fruits.

Table 2.3.Experimental conditions of zucchini with ultrasound.

Run	Temperature(ºC)	Concentration(w/v)	Time(min.)
1	15	5	30
2	15	5	105
3	15	5	30
4	15	15	105
5	15	25	30
6	15	25	105
7	25	5	105
8	25	5	180
9	25	15	30
10	25	15	105
11	25	15	105
12	25	15	105
13	25	15	105
14	25	15	105
15	25	15	180
16	35	5	30
17	35	5	105
18	35	15	30
19	35	25	30
20	35	25	105

$$WR=WL+SG \tag{2}$$

where

WR=weight reduction (kg matter / kg initial weight of the sample)

SG= solid gain (kg salt/kg initial weight of the sample)

WL= water loss (kg water/ kg initial weight of the sample)

$$SG=\frac{Ws-Wso}{Wo}*100 \tag{3}$$

$$WL=\frac{W_1-W}{100} \tag{4}$$

where

Ws: amount of salt in the sample at any time (g)

Wso: amount of salt in the sample at the beginning (g)

W_0: weight of sample before osmotic dehydration (g)

W_1: moisture of sample at the beginning (kg water/kg sample)

W: moisture of sample at any time (kg water/kg sample)

Table 2.4. Experimental conditions of osmotic dehydration of cherry.

Run	Sucrose(w/v)	Time(min.)
1	40	30
2	55	30
3	70	30
4	40	60
5	55	60
6	70	60
7	40	90
8	55	90
9	70	90
10	40	120
11	55	120
12	70	120
13	40	180
14	55	180
15	70	180
16	40	240
17	55	240
18	70	240
19	40	300
20	55	300
21	70	300

Samples were taken at 30, 60, 90, 120, 180, 240 and 300 minutes to follow the changes in moisture loss, and color change. Moisture was determined in a drying oven (Section 2.2.1.1). Color change was followed by measuring L, a, b and YI values (section 2.2.1.2). Each assay was made in duplicates and the mean values were used.

In addition, weight reduction was determined different than that of zucchini. About 25 g of cherry was placed in a Erlenmeyer flask and then 250 mL of sucrose solution was added into Erlenmeyer flask. At predetermined time intervals, sample was taken and this data was used for calculation of weight reduction using below equations (5-7).

2.2.6. Calculation of Osmotic Parameters for Cherry

Weight reduction (WR), solid gain (SG) and water loss (WL) were determined by using the gravimetric method according to the following equations:

$$SG=WR-WL \quad (5)$$

Where

WR=weight reduction (kg matter / kg initial weight of the sample)

SG= solid gain (kg sucrose/kg initial weight of the sample)

WL= water loss (kg water/ kg initial weight of the sample)

$$WR = \frac{Wf - Wo}{Wo} * 100 \quad (6)$$

$$WL = \frac{Wa - W}{100} \quad (7)$$

Where

W*f*: weight of the sample after osmotic dehydration (g)

W_0: weight of sample before osmotic dehydration (g)

Wa: moisture of sample at the beginning (%)

W: moisture of sample at any time (%)

2.3. Drying in the Tray Dryer after Osmotic Dehydration

2.3.1. Tray Dryer

A tray dryer (Armfield VOP 8-Tray Drier, England) was used for drying purposes (Figure 2.1.). Air is drawn into air duct through a mesh guard by a motor driven axial flow fan impeller whose speed can be controlled by a regulator. The air passed over an electrically heated element controlled by a power regulator to provide a variation in air temperature to a maximum of about 80ºC at low velocities. The air passes into the central section of the duct, where four trays are carried on a support frame and air is then discharged to atmosphere of the end of the duct.

Figure 2.1. Tray dryer which used for drying of cherry

2.3.2. Drying of Zucchini in the Tray Dryer after Osmotic Dehydration

The zucchini samples were sliced in 1 cm thick slabs. Then 1 cm^3 cubes were obtained from these slices. Zucchini cubes were osmotically pretreated. Approximately 25 grams of zucchini cubes were put into 5, 15 and 25% (w/v) salt solutions. The ratio of zucchini to solution ratio was 1:10. Osmotic treatment was carried out for duration of four hours at 25ºC. After treatment, sample was dipped into distilled water for 2-3 seconds to prevent crystallization of salt on the surfaces. Samples were then blotted with a filter paper. Dipping the samples in water provided better drying since salt could slow down the drying process. Samples to be dried were put in a tray dryer. These slices were dried by passing the heated air over drying trays. Drying parameters are shown in Table 2.5. Moisture content of samples was determined by AOAC method (see section 2.2.1.1), (AOAC, 1990). Different drying parameters were primarily studied (Table 2.5.). Among them, dry bulb temperature of 36ºC and air flow of (1.24 m/s) for four hours were applied for drying purposes. Wet and dry bulb temperatures of air were measured using a psychometric (HD 50 Kimo, France). Air velocity was measured by a vane anemometer.

Table 2.5. Drying conditions of zucchini in the tray dryer.

Air flow (m/s)	Air temperature (ºC)	Initial moisture (%)	Final moisture (%)	Time (minute)
0.816	70	94	65	150
1.21	48	94	66 53	150 210
1.24	36	94	75 66	150 210
0.6	48	94	69 58 52	150 210 240

The condition (36 °C dry basis temperature and 1.24 m/s air velocity) was chosen for drying because temperature of drying was very low and thus heat effects were minimized. Low temperature for drying of fruit and vegetables is very important for preserving color and nutritional value of final product. The weight of sample on the tray was measured by a balance periodically. Drying was continued until the constant weight of the sample reached. Zucchini samples without osmotic dehydration were also dried in the tray dryer in order to compare the processes.

2.3.3. Drying of Cherry in the Tray Dryer after Osmotic Dehydration

The cherry samples were sliced into two pieces. Seed of cherry was removed. Cherry pieces (halves) were firstly pretreated osmotically. These pieces were dried by passing the heated air by a tray drier described in section 2.3.1. Drying parameters are shown in Table 2.6. Approximately 25 grams of cherry pieces were put into 40, 55 and 70 % (w/v) sucrose solutions and agitated. The ratio of cherry to solution ratio was 1:10. Osmotic treatment was carried out for duration of four hours at 25ºC. After treatment, samples were dipped into distilled water for 2-3 seconds to prevent crystallization of sucrose on the surfaces. Samples were then blotted with a filter paper. Moisture content of samples was determined by AOAC method (see section

2.2.1.1), (AOAC, 1990) . Different drying parameters were initially studied (Table 2.6.). Among them, dry bulb temperature of 50ºC and air flow of (1.40 m/s) for four hours were applied for the drying purpose. These parameters were chosen because it was expected that low temperature provided better quality values after drying.

Table 2.6. Drying conditions for cherry in tray drying.

RUN	Sucrose concentration(w/v)	Temperature (ºC)	Air flow(m/s)	Drying time(min.)
I	40	50	1,40	570
II	55	50	1,40	510
III	70	50	1,40	480
IV	fresh cherry*	50	1,40	930

* fresh cherry which was not exposed to any osmotic dehydration process

2.4. Experimental Design

Experimental design is important for maximizing the information gained from each experiment and for evaluating statistically the significance of different factor. General factorial design was employed for cherry and zucchini runs. Factorial designs are the most efficient for these types of experiments. The effect of a factor is defined to be the change in level of factor. This is frequently called a main effect, because it refers to the primary factors of interest in the experiment. Statistical evaluation of result for cherry and zucchini were performed using general factorial design. Since the levels of the factors were not same. General factorial design permits using the factors in different levels. The osmotic dehydration process was assumed to be affected by three independent variables: osmotic dehydration time, temperature and solution (sugar or salt) concentration. The three factors (time, temperature and concentration), levels for zucchini and cherry are given in Table 2.7. and Table 2.8., respectively

Table 2.7. Variables and their levels employed for osmotic dehydration of zucchini.

ZUCCHINI		
Code	**Variable Name**	**Levels**
A	Temperature (ºC)	15, 25, 35
B	Salt concentration (w/v)	5, 15, 25
C	Time (min.)	30, 60, 180,240
ZUCCHINI WITH ULTRASOUND		
Code	**Variable Name**	**Levels**
A	Temperature (ºC)	15, 25, 35
B	Salt concentration (w/v)	5, 15, 25
C	Time (min.)	30, 105, 180

Table 2.8. Variables and their levels employed for osmotic dehydration of cherry.

CHERRY		
Code	**Variable Name**	**Level**
A	Sucrose concentration(w/v)	40, 55, 70
B	Time (min.)	30, 60, 90, 120, 180, 240,300

2.4.1. **Statistical Analysis**

General factorial design feature of Design-Expert version 6.01.0 (Stat- Ease, Inc Minneapolis, MN) was used to observe the effects of the process variables over the water loss, weight reduction, solute gain in the osmotic treatment.

The experimental data obtained from the design were analyzed by the response surface regression procedure using following second-order polynomial equation to describe the response variables.

$$Y_i = b_o + \sum b_i x_i + + \sum b_{ii} X^2_i + + \sum b_{ij} x_i x_j \quad (8)$$

where Y_i was the predicted response x_i, x_j were independent variables, b_o was the offset term, b_i was the linear coefficient, b_{ii} was the quadratic coefficient and b_{ij} was the interaction coefficient.

The statistical software package, Design-Expert 6.01.0 (Stat- Ease, Inc Minneapolis, MN) was used for regression analysis of the experimental data. Analysis of variance (ANOVA) was used to estimate the statically parameters. The second order polynomial equation was employed to fit experimental data. The significance of the model equation and model terms were evaluated by F-test. The evaluation of the fitting was checked by the coefficient of determination (R^2), F and the p-values (error probabilities). Response surfaces were generated using a final model considering only the influence of significant factors of above equation at confidence level of 95%.

CHAPTER III

RESULT AND DISCUSSION

3.1. Osmotic Dehydration of Zucchini with Agitation

3.1.1. Water Loss during Osmotic Dehydration of Zucchini with Stirring

Response surface methodology was used for quantative investigation of water and solids transfer during osmotic dehydration of zucchini with agitation effect. Linear and quadratic regression equations describing the effects of temperature, NaCI concentration and time on the water loss, solid gain and weight reduction were developed and regression equation coefficients are given in Table 3.1. and all other statistical parameters are shown in appendices (Tables A1, A2 and A3). The results given in Table 3.1 show that water loss is linearly affected by salt concentration and immersion time. The influence of temperature was found to be highly insignificant ($p>0.05$). The significance of each coefficient was statistically determined. The larger F values and small p-values are thought to be significant. The coefficients given in Table 3.1 are significant at 95% level. The effect of temperature and salt concentration on water loss is also shown in Figure 3.1. The water loss increases with increasing salt concentration. The water loss did not change by increasing temperature. However, it was reported that water loss was increased with temperature (Contreras and Smyral, 1981). High temperatures cause swelling and plasticizing membrane and in that way membrane becomes more permeable to water coming out of the product and in the same time higher temperatures lower viscosity of osmotic medium which result in better water transfer characteristics on the product surface. In this study, temperature did not affect water loss significantly. This is probably due to non-porous structure of zucchini and low temperature ranges (15-35ºC).

The model equation and model terms are significant for water loss (Table A3 in appendices). Because F value for the model was significant ($p<0.05$). The fit of the quadratic model was significant for the water loss. Because R^2 (0.97) for the

quadratic equation was high, also differences between predicted and adjusted R-squared were small.

Table 3.1. Regression equation coefficients for water loss (WL), solid gain (SG) and weight reduction (WR) during osmotic dehydration of zucchini.

Coefficients	WL(kg/kg)	SG(kg/kg)	WR(kg/kg)
b_o	-0.940*	-1.07*	-0.71*
Linear			
b_A	0.039	0.074	0.053
b_B	0.35*	-0.35	0.350*
b_C	0.064*	0.038	0.053*
Quadratic			
b_{AA}	6.433E-003	-0.11	-0.042
b_{BB}	-0.13*	-0.17	-0.15*
b_{CC}	0.036	-0.046	-0.041
Interaction			
b_{AB}	-1.915E-003	-0.015	-6.505E-003
b_{AC}	1.61E-003	-0.024	-8.729E-003
b_{BC}	0.017	9.955E-003	0.015

A- Temperature; B- Salt concentration C- Time

* corresponding parameter has a significant effect on the response.

The response surface plot is presented in Figure 3.1 shows that WL increased as osmotic solution concentration increased. All water loss values are positive; these indicate that there was not a water gain caused by the impregnation of the osmotic solution in the zucchini. Figure 3.1 also shows that there is no effect of temperature and its intermediate with osmotic solution concentration on the water loss of zucchini. No linear and quadratic effect of temperature and its interaction with osmotic solution concentration on the water loss observed.

The regression analysis of the experimental design demonstrated that the linear model terms (A, and C) and quadratic model terms (B^2 and C^2) were significant ($p<0.05$). However, the linear model term A, the quadratic model A^2 and interactive model terms (AB, AC and BC) were found to be insignificant ($p>0.05$).

Water loss is fitted well by polynomial equation (eqn 11) showing that the polynomial equation is versatile, and can be used for predicting water loss formulation .

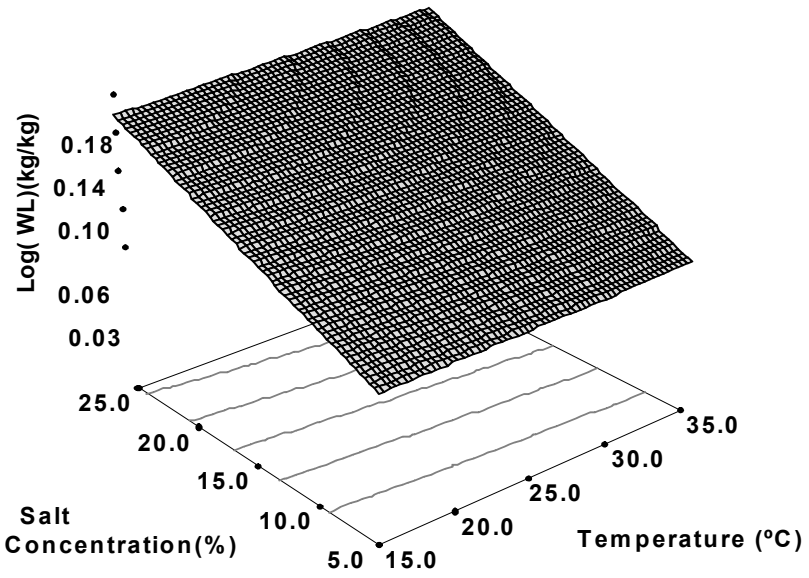


Figure 3.1. Water loss during osmotic dehydration of zucchini as a function of temperature and concentration of salt

A: temperature B: Salt concentration C: time

AB: interaction between temperature and concentration

AC: interaction between temperature and time

BC: interaction between time and concentration

Applying multiple regression analysis, the result was fitted to following equation.

.

$$\mathbf{Log^{*}(WL) = -094 + 0.35B + 0.064C - 0.13B^{2}} \quad (9)$$

Similar multiple regression analyses for osmotic dehydration of guava were done by Panadésa et al., 2006. Water loss, solid gain and weight loss were modeled by polynomial equations.

Equation 9 can be interpreted like this. The estimated coefficient of B is quite high in relation to the other factors studies, thus showing that salt concentarion has a large

effect on water loss. Water loss values decrease with time, but this increase is progressive in time, as a consequence of its negative quadratic effect.

3.1.2 Weight Reduction during Osmotic Dehydration of Zucchini with Stirring

Assuming all coefficients (temperature, concentration and time), several regression models developed and their regression equation coefficients are given in Table 3.1. and other statistical parameters are shown in appendices (Tables A4, A5, and A6). The results given in Table 3.1. show that weight reduction is linearly affected by salt concentration and immersion time. The influence of temperature was found to be highly insignificant ($p>0.05$). The significance of each coefficient was statistically determined. The larger F values and small p-values are thought to be significant. The coefficients given in Table 3.1. are significant at 95% level. The effect of temperature and salt concentration on weight reduction is given in Figure 3.2. Weight reduction was affected significantly by the salt concentration and was slightly affected by temperature as shown in Figure 3.2.

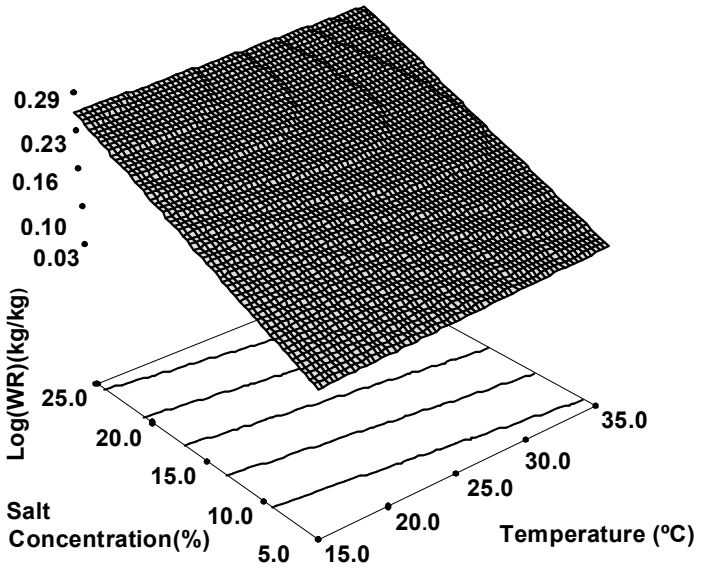


Figure 3.2. Weight reduction during osmotic dehydration of zucchini as a function of temperature and concentration of salt

The fit of the quadratic model was significant for the weight reduction. Because R^2 (0.98) for the quadratic equation was high, also differences between predicted and adjusted R-squared were small. These data are showed in Tables B1; B2 and B3 in appendices.

The regression analysis of the experimental design demonstrated that the linear model terms (A, B, and C) and quadratic model terms (B^2 and C^2) were significant ($p<0.05$). However, the quadratic model A^2 and interactive model terms (AB, AC and BC) were found to be insignificant ($p>0.05$). Weight reduction is fitted well by polynomial equation (Equation 10) showing that the polynomial equation is versatile and can be used for predicting weight reduction formulation.

$$\mathbf{Log^*(WR) = -0.71 + 0.35B + 0.053C - 0.15B^2} \quad (10)$$

3.1.3 Solid Gain during Osmotic Dehydration of Zucchini with Stirring

Assuming all coefficients (temperature, concentration and time), several regression models also developed and their regression equation coefficients are given in Table 3.1. The other statistical parameters are shown in appendices (Tables A7, A8 and A9). The results given in Table 3.1 show that solid gain is linearly affected by salt concentration and immersion time. The influence of temperature was found to be highly insignificant ($p>0.05$). The significance of each coefficient was statistically determined. The larger F values and small p-values are thought to be significant. The coefficients given in Table 3.1. are significant at 95% level. The effect of temperature and salt concentration on water loss is given in Figure 3.3. Salt concentration is the factor that mostly affects the studied responses (WR, WL and SG), with high salt concentrations leading to high water loss and solid gain. In an osmotic dehydration process the higher water loss the better was the dehydration process.

However, high solid gain affects the fruits and vegetables quality and sensory characteristics. When high levels of solids are incorporated into fruit during the osmotic dehydration significant sensory alterations can occur and the final product may present a taste that is very different from the fresh fruit. The solid gain also increases with increasing salt concentration

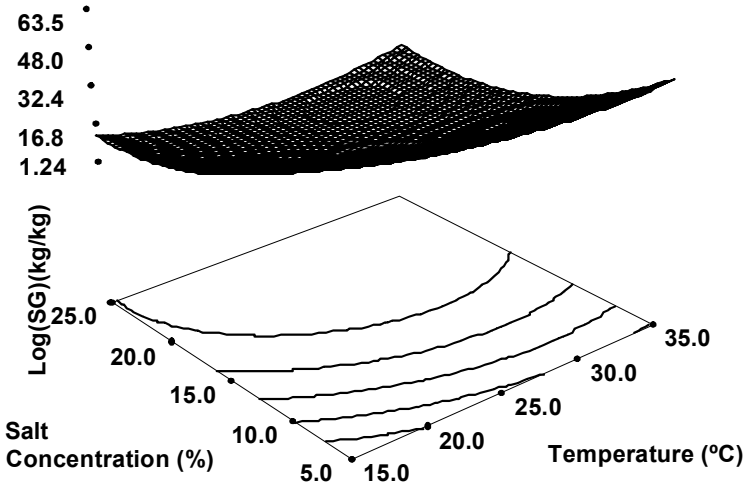


Figure 3.3. Solid gain during osmotic dehydration of zucchini as a function of temperature and concentration of salt

The regression analysis of the experimental design demonstrated that the linear model terms (B, and C) and quadratic model terms (B^2 and C^2) were significant ($p<0.05$). However, the linear model term A, the quadratic model A^2 and interactive model terms (AB, AC and BC) were found to be insignificant ($p>0.05$). Applying multiple regression analysis, the result was fitted to a second-order polynomial equation (equation 11). Because R^2 (0.93) for the quadratic equation was high, also differences between predicted and adjusted R-squared were small.

$$\textbf{Log (SG)= -1.07 + 0.35B -0.17B}^{\textbf{2}} \qquad (11)$$

As it can be seen in Figure 3.3. and model equation at low concentration, B, values, SG increases with concentration, but the quadratic effect provokes a decrease in the process rate at higher concentration values.

3.1.4. Interaction between Time, Temperature and Concentration during Osmotic Dehydration of Zucchini with Stirring

Interaction of salt concentration and immersion time was more significant at 95% level than other interactions (it has a low p-value). There was no significant interaction between temperature and concentration; also between time and temperature.

There was a positive interaction between salt concentration and time. One factor plot graph (general name of interaction graph) could be used to show relationships between water loss and concentration; water loss and temperature; water loss and time. An example of one of the factor plot graph is shown in appendix Figure D4. We can say that water loss was increased with increasing salt concentration and time. However, water loss was not increased with increased temperature. But there was a positive interaction between salt concentration and time. Salt concentration was the main effect on water loss and weight reduction. ANOVA Table (Table A9 in appendices) shows that temperature was not an important factor (It has high p-value). There was no interaction between temperature and concentration. Salt concentration was the main effect on solid gain.

3.2. Water Loss during Osmotic Dehydration of Zucchini with Ultrasonic Effect.

The beneficial effects of ultrasound drive from its mechanical effects on the process by increasing the penetration of the solvent into the product and enhancing the mass transfer process. Cavitations phenomenon produced by sonication consists in the formation of bubbles in the liquid which can explosively collapse and generate localized pressure. In a solid medium, the sound waves cause a series of rapid and successive compression with rates depending on their frequency. This mechanism is of great relevance to drying and dewatering. The mechanical and physical effects of sound can be used to enhance many processes where diffusion takes place (Floros and Liang, 1994).

Simal et al., (1998) studied osmotic dehydration of 1 cm^3 apple cubes in 70°Brix sucrose solution using ultrasound treatment was carried out at 40, 50, 60 and 70°C.

It was observed that ultrasound affected mass transport during osmotic dehydration increasing both the water losses and solute gain. Ultrasonic osmotic dehydration technology uses lower solution temperature to obtain higher water loss and solute gain rates, while preserving the natural flavor, color and heat sensitive nutritive components.

Solution concentration and treatment time are shown to influence the weight reduction. Assuming all coefficients (concentration, time and temperature) several regression models developed and their regression coefficients are given Table 3.2, and other statistical parameters are shown in appendices. The results given in Table 3.2. show that water loss was linearly affected by salt concentration and immersion time. The influence of temperature was found to be highly insignificant ($p<0.05$). The significance of each coefficient was statistically determined. The coefficients given in Table 3.2. are significant at 95% level. The effect of temperature and salt concentration on water loss is also shown in Figure 3.4.

Table 3.2. Regression equation coefficients for water loss (WL), solid gain (SG) and weight reduction (WR) during osmotic dehydration of zucchini with ultrasound.

Coefficients	WL(kg/kg)	SG(kg/kg)	WR(kg/kg)
b_o	-2.47*	-2.89*	-1.92*
Linear			
b_A	-0.096	-0.06	-0.083
b_B	0.55*	0.37*	0.47*
b_C	0.32*	0.22	0.31*
Quadratic			
b_{AA}	0.200	-0.19	2.576E-003
b_{BB}	-0.690*	-0.64*	-0.77*
b_{CC}	0.013	0.36	0.29
Interaction			
b_{AB}	0.017	-0.17	-0.053
b_{AC}	0.032	0.12	0.15
b_{BC}	0.043	0.13	0.068

A- Temperature; B- Salt concentration C- Time

* corresponding parameter has a significant effect on WL, SG, and WR.

Linear model terms were significant for all responses. Because the F value for the model was significant ($p<0.05$). The fit of the linear model was significant for the

water loss. Because R^2(0.88) for the quadratic equation was high, also difference between predicted and adjusted –R squared was small.

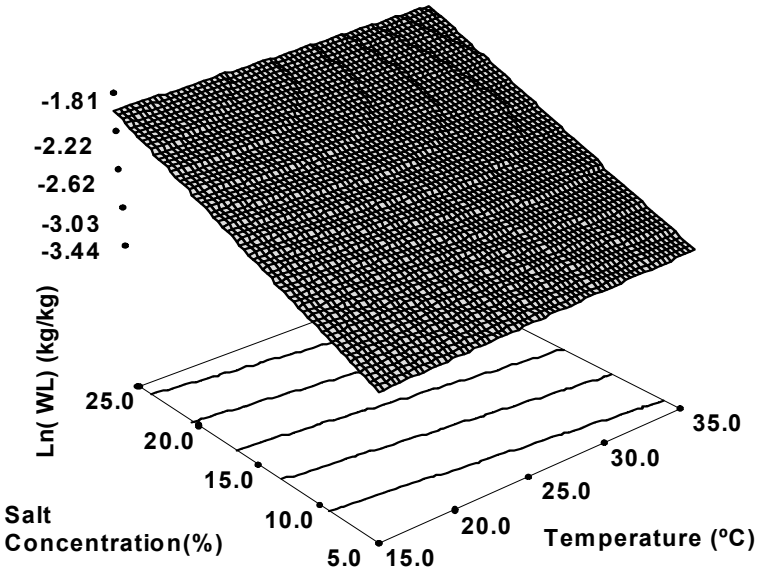


Figure 3.4. Water loss during osmotic dehydration of zucchini with ultrasound as a function of temperature and concentration of salt

The regression analysis of the experimental design demonstrated that model terms (A, B and C) and applying multiple regression analysis the following equation was obtained (equation 12).

$$\mathbf{Log^*(WL) = -2.47 + 0.55B + 0.32C - 069B^2} \qquad \mathbf{(12)}$$

3.2.1. Solid Gain during Osmotic Dehydration of Zucchini with Ultrasonic Effect

Solution concentration and treatment time are shown to influence the solid gain. Assuming all coefficients (concentration, time and temperature), several regression models developed and their regression coefficients are given Table 3.2. The other statistical parameters are shown in appendices (Tables C4, C5, and C6). The results given in Table 3.2. show that solid gain was linearly affected by salt concentration

and immersion time. The influence of temperature was found to be highly insignificant ($p>0.05$). The significance of each coefficient was statistically determined. The coefficients given in Table 3.2. are significant at 95% level. The effect of temperature and salt concentration on solid gain is given in the response graph as Figure 3.5.

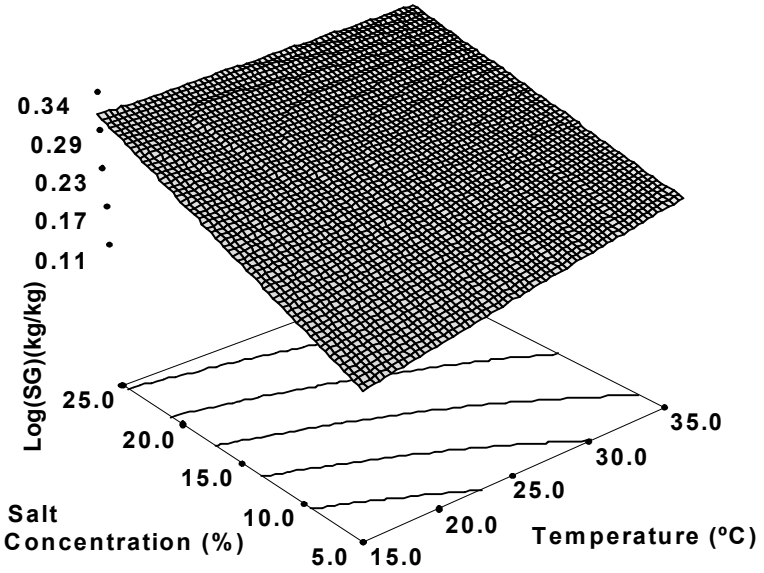


Figure 3.5. Solid gain during osmotic dehydration of zucchini with ultrasound as a function of temperature and concentration of salt

The regression analysis resulted with the following equation (equation 13).

$$\mathbf{Log(SG) = -2.89 + 0.37B - 0.64B^2} \qquad \mathbf{(13)}$$

Solid gain values increases with time. As time becomes higher, solid gain increases, this effect is enhancedby the increase of time by the interaction between time and concentration and the interaction between temperature and concentration.

3.2.2. Weight Reduction during Osmotic Dehydration of Zucchini with Ultrasonic Bath

Assuming all coefficients (concentration, time and temperature) several regression models developed and their regression coefficients are given Table 3.2.

The other statistical parameters are shown in appendices. The effect of temperature and salt concentration on weight reduction is given in Figure 3.6. The results given in Table 3.2. and Figure 3.6 show that weight reduction was linearly affected by salt concentration and immersion time. The influence of temperature was found to be highly insignificant ($p>0.05$). The significance of each coefficient was statistically determined. The coefficients given in Table 3.2. are significant at 95% level.

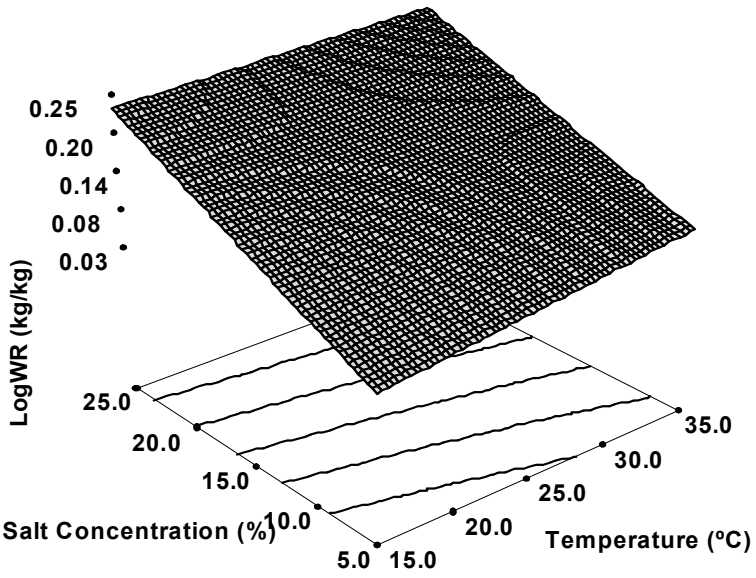


Figure 3.6. Weight reduction during osmotic dehydration of zucchini with ultrasound as a function of temperature and concentration of salt

The fit of the below model was versatile for the weight reduction. Because R^2(0.88) for the equation (equation 14) was high, also difference between predicted and adjusted –R squared was small.

$$\mathbf{Log\ (WR\ ) = -1.92 + 0.47B + 0.31C - 0.77B^2} \quad (14)$$

3.2.3. Interaction between Time, Temperature and Concentration during Osmotic Dehydration of Zucchini with Ultrasonic Bath.

Interaction of salt concentration and immersion time was more significant than other interactions.

Salt concentration was the main effect on solid gain and weight reduction according to graph. Statistical analyses by ANOVA (Tables C3, C4, C5, and C6 in appendices) showed that the temperature was not an important factor (It has high p-value). There was a positive interaction between salt concentrations and time. Water loss was increased with increased salt concentration and time. But water loss was not increased with increased temperature.

3.2.4. Comparison between Experimental Results Obtained with Ultrasound Effect and Agitation

Water losses and solute gain rates were faster when ultrasound was used with the osmotic dehydration. The most important difference was found in solute gain. Water loss in the ultrasound was faster than water loss in the agitation. Amount of water extracted during osmotic dehydration of zucchini with ultrasound during three hours was the same for osmotic dehydration with agitation during four hours. Table 3.3 shows the water content values of zucchini with agitation and ultrasound effect by osmotic dehydration.For example, water content of zucchini after three hours osmotic dehydration with ultrasound (15% salt solution at 15ºC) was 80.06% while water content of zucchini after three hours osmotic dehydration with agitation (15% salt solution at 15ºC) was 83.07% (see Table 3.3).

Table 3.3. Comparison of water content values for experimental results obtained with ultrasound and agitation.

Time (min.)	Water content of zucchini in 5 % salt solution		Water content of zucchini in 25% salt solution	
30	93 (Agitation)	92.53 (Ultrasound)	87.71 (Agitation)	85.38 (Ultrasound)
180	92.13 (Agitation)	90.78 (Ultrasound)	80.06 (Agitation)	77.52 (Ultrasound)

Similar results were observed by Mavroudis et al., (1998) who studied the effect of agitation and of structural differences on osmotic dehydration. Osmotic dehydration was performed in an agitated vessel at 20ºC with a 50% sucrose solution as the osmotic medium. The water loss was higher in the turbulent flow region than in laminar flow. The solid increase did not show significant differences between laminar and turbulent flow regions. The data showed that free convection was the mechanism by which the solution penetrated the pores, although lack of understanding of the phenomena involved at cell prevents a definite conclusion.

Ultrasonic osmotic dehydration technology uses lower solution temperatures to obtain higher water loss and solid gain rates while preserving the natural flavors, color and heat-sensitive nutritive components.

3.3. Osmotic Dehydration of Cherry

Temperature for osmotic dehydration of cherry was not used as an experimental parameter because used temperature range in the osmotic dehydration was very narrow and temperatures above 50 was not suitable for osmotic dehydration because of structural/textural disturbances.

Ramallo et al., (2004) studied osmotic dehydration of pineapple slices in sucrose solution (60% w/w) at three temperatures (30, 40 and 50ºC) water loss, sucrose gain and the variation in concentration of other natural fruit sugars (glucose and fructose). Their results indicated that the solute uptake was function of the water content in the fruit, being this ratio independent of temperature during the first 600 minutes of dehydration within the range of tested temperatures. In our study, we observed the same result for zucchini and therefore temperature was not chosen as a process parameter for cherry.

3.3.1. Water Loss of Cherry during Osmotic Dehydration of Cherry

Assuming all coefficients (concentration and time), several regression models developed and their regression equation coefficients are given in Table 3.4. The other statistical parameters are shown in appendices (Tables B4, B5, and B6). The results given in Table 3.4. show that water loss is linearly affected by sucrose concentration and immersion time. The significance of each coefficient was statistically determined The coefficients given in Table 3.4. are significant at 95% level. The effect of immersion time and sucrose concentration on water loss is given in Figure 3.7. The solution concentration showed a significant effect on water loss. In this study, it was observed that increased concentration increased water loss, solid gain and weight reduction for cherry.

Table 3.4. Regression equation coefficients for water loss (WL), solid gain (SG) and weight reduction (WR) during osmotic dehydration of cherry with shaker bath.

Coefficients	WL(kg/kg)	SG(kg/kg)	WR(kg/kg)
b_o	0.016*	0.098*	0.120*
Linear			
b_B	0.055*	-0.018*	0.036*
b_B	0.018*	0.030*	0.046*
Quadratic			
b_{BB}	0.046*	-0.051*	-9.093E-003*
b_{CC}	1.151E-003	-0.011	-4.45E-003
Interaction			
b_{BC}	0.025*	-0.016*	9.274E-003*

B: Sucrose concentration C: Immersion time

* corresponding parameter has a significant effect on WL, SG, and WR.

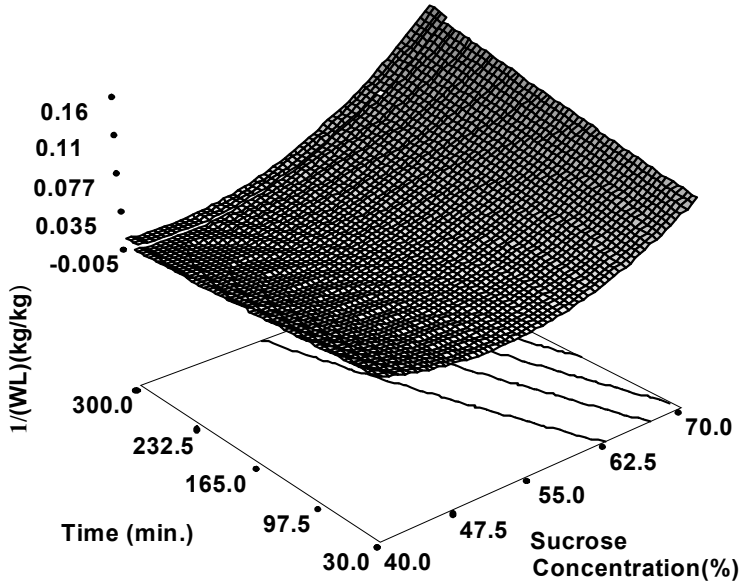


Figure 3.7. Water loss during osmotic dehydration of cherry as function of time and concentration of sucrose.

The regression analysis of the experimental design demonstrated that the linear model terms (B, and C) and quadratic model terms (B^2) and interactive model terms (BC) were significant ($p<0.05$). However, the quadratic model C^2 was found to be insignificant ($p>0.05$). Applying multiple regression analysis, the result was fitted to a second-order polynomial equation (equation 15). This equation could be used for predicting water loss formulation.

$$\mathbf{1/(WL)= 0.016 + 0.055B + 0.018C + 0.046B^2 + 0.025BC} \quad (15)$$

3.3.2. Weight Reduction of Cherry during Osmotic Dehydration of Cherry

Solution concentration and treatment time are shown to influence the weight reduction. Assuming all coefficients, several regression models developed. Regression coefficients are given Table 3.4

Regression equation coefficients are given in Table 3.4.. and other statistical parameters are shown in appendices (Tables B1, B2 and B3). The results given in

Table 3.4. show that weight reduction is linearly affected by sucrose concentration and immersion time. The significance of each coefficient was statistically determined. The coefficients given in Table 3.4. are significant at 95% level.

The effect of immersion time and sucrose concentration on the solid gain (WR) was given in Figure 3.8. The (WR) was increased rapidly with immersion time and sucrose concentration.

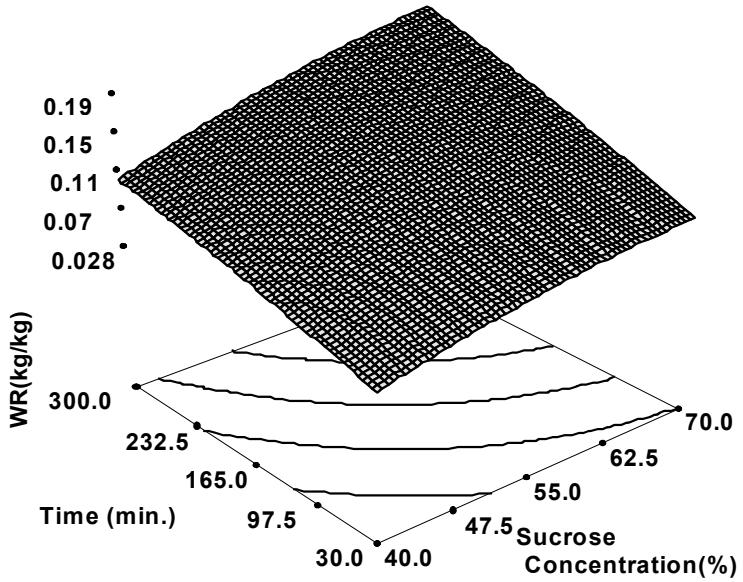


Figure 3.8. Weight reduction during osmotic dehydration of cherry as a function of time and concentration of sucrose.

Regression equation coefficients are given in appendix (Table B1). Relatively high values of R^2 obtained for weight reduction, indicated good fit of experimental data.

The regression analysis of the experimental design demonstrated that the linear model terms (B, and C) and quadratic model terms (B^2) and interactive model terms (BC) were significant ($p<0.05$). However, the quadratic model C^2 was found to be insignificant ($p>0.05$). Applying multiple regression analysis, the result was fitted to a second-order polynomial equation. Weight reduction is fitted well by polynomial equation showing that the polynomial equation is versatile , and can be used for predicting solid gain formulation .

$$WR=0.12+0.036B+0.046C-9.093E\text{-}003B^2+9.274E\text{-}003BC \quad (16)$$

3.3.3. Solid Gain of Cherry during Osmotic Dehydration of Cherry.

Solution concentration and treatment time are shown to influence the solid gain. Assuming all coefficients (concentration, time and temperature) several regression models developed and their regression coefficients are given Table 3.4. The other statistical parameters are shown in appendices (Tables B7, B8 and B9). The results given in Table 3.4 show that solid gain is linearly affected by sucrose concentration and immersion time. The significance of each coefficient was statistically determined. The coefficients given in Table 3.4. are significant at 95% level. The effect of temperature and sucrose concentration on solid gain is given in Figure 3.9.

The same result for solid gain of cherry was obtained. Immersion time and sucrose concentration was the main effect on the mass transfer mechanism for cherry.

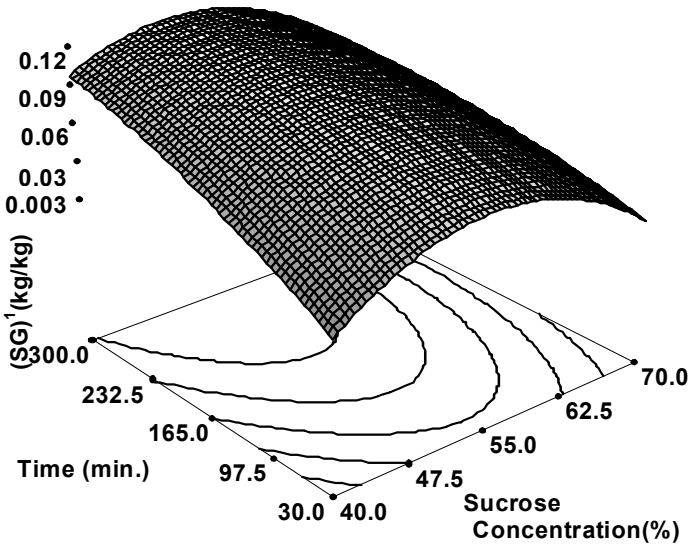


Figure 3.9. Solid gain during osmotic dehydration of cherry as a function of time and concentration of sucrose.

Solid gain is fitted well by polynomial equation. The fit of the quadratic model is significant for the solid gain. Because R^2 (0.95) for the quadratic equation was high, also difference between predicted and adjusted –R squared was small.

Therefore, the below polynomial equation (equation 17) is versatile, and can be used for predicting solid gain formulation.

$$\mathbf{(SG) = 0.098 - 0.018B + 0.03C - 0.051B^2 - 0.016BC} \quad (17)$$

3.3.4. Interaction between Process Parameters of Osmotic Dehydration of Cherry.

Interaction of sucrose concentration and immersion time was significant (it has lower p-values). There was a positive interaction between sucrose concentration and time. Sucrose concentration was the main effect on water loss and weight reduction and solid gain. Statistical analyses by ANOVA (Table B7 in appendices) showed that sucrose concentration was main effect (It has high a p-value, see appendix Table D7). There was a positive interaction between sucrose concentrations and time. As a result, water loss increased with increased sucrose concentration and time.

3.4. Effect of Osmotic Dehydration on Color of the Sample

The color of food plays an important role in how consumer perceives a product; therefore it is important to be able to asses color. Therefore, the variation of color in each pretreatment of zucchini and cherry were studied.

Color parameters changed with different conditions for both cherry and zucchini as seen in Figures 3.10 to 3.12.

The L, a, and b values of cherry sample dried in 40 % sucrose solutions as a function of time is shown in Figure 3.10.

Generally, the total color values of cherry samples did not change significantly with osmotic dehydration time. Temperature did not affect the measured color values with time significantly (not shown).

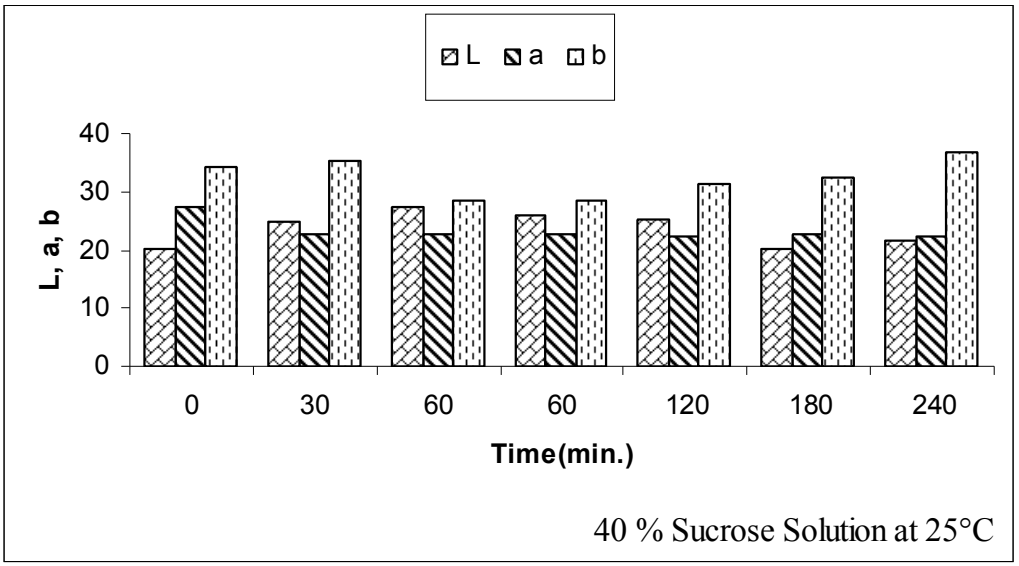


Figure 3.10. Color change of cherry during osmotic dehydration in 40% sucrose concentration

The brightness index (L) was more or less the same with increasing osmotic dehydration time (Figure 3.10). Statistical analysis of data exhibited no significant difference ($p > 0.05$) in (L) values over the osmotic drying period. Redness index (a) and yellowness index (b) of cherry showed smooth fluctuations. Redness index (a) slightly decreased over osmotic drying period. Redness index is usually related to Maillard reactions.

Falade et al., (2007) studied mass transfer during osmotic dehydration of watermelon and color changes of fresh, osmosed and osmo-oven dried watermelon. Darkening and loss of redness, as indicated by a-value, accompanied the osmotic dehydration and subsequent oven drying of watermelon.

Figure 3.11 shows that total color difference values (ΔE) of cherry with different sucrose concentrations at 25 °C. The total color change of the samples samples depends on the change in brightness, yellowness and redness. The effect of sucrose concentration on the total color difference values of cherry was not seen upto 70% sucrose solution. The use of higher sucrose solution (70%) decreased the difference in total color difference value.

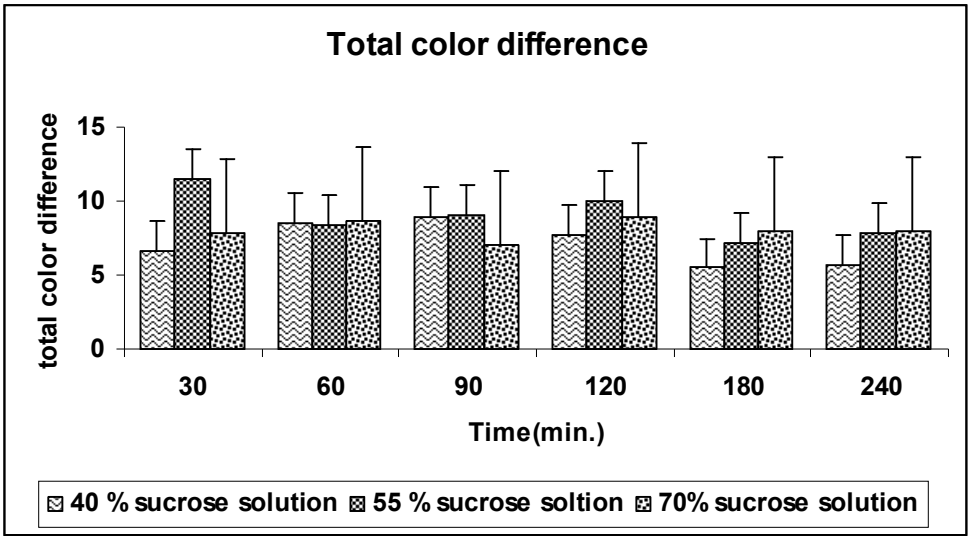
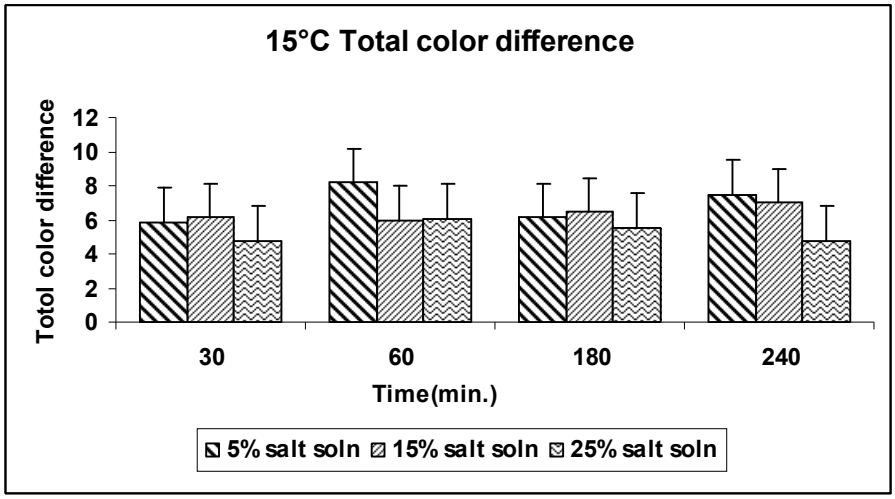


Figure 3.11. Total color difference of cherry vs time during osmotic dehydration

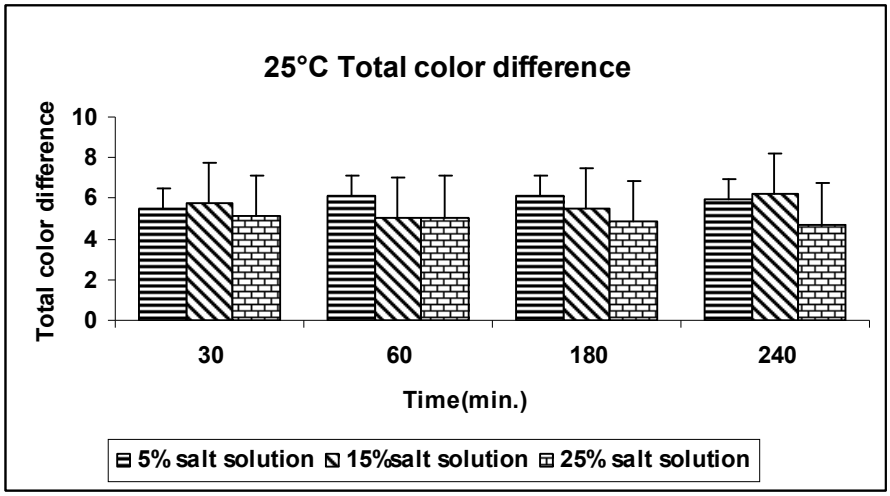
Figure 3.12 shows that total color difference values (ΔE) vs time of zucchini with salt concentration and temperature. First of all, total color difference values (ΔE) were not changed significantly with osmotic dehydration time at all temperatures studied. Temperature did also not affect this significantly. Total color difference with increasing salt concentration indicated no trend at all temperatures. Osmotic dehydration at low temperature (15 °C) did not affect the total color difference significantly.

3.4.1.Effect of Osmotic Dehydration on Vitamin C

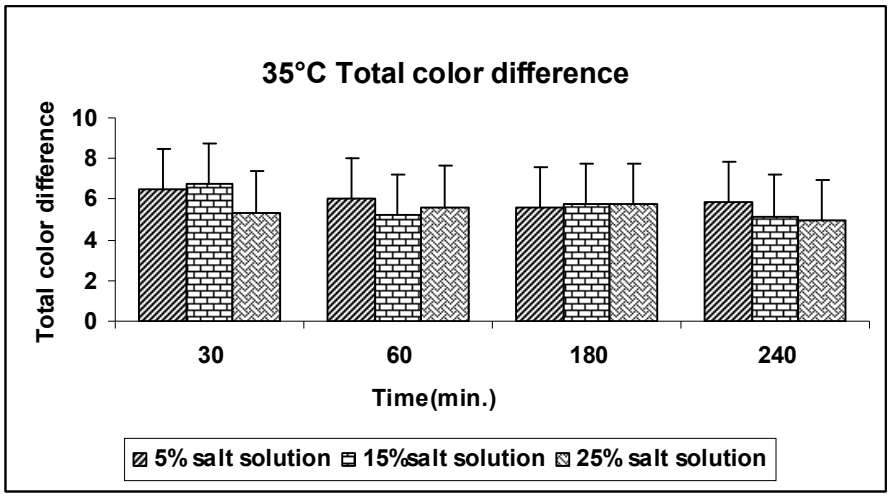
Table 3.5 shows that osmotic dehydration pretreatment preserve the vitamin C content of cherry after air drying process.. As a result air drying retained vitamin C to approximately 27.80, 42.50, 34.40, and 37.70% of initial concentration for fresh cherry, osmotically dehydrated cherries in 40%, 55% and 70% sucrose solutions, respectively. It was observed that the vitamin C content retention increased with increase in solute uptake which might be due to solute barrier layer that was formed at the periphery of the samples thus hindering the outflow of the vitamin into the soaking solution as reported (Heng et al.,1990).



(a)



(b)



(c)

Figure 3.12. Total color difference of zucchini vs time at different temperatures

The percentage reduction after osmotic dehydration for vitamin C for bell peppers at varied temperatures (25–55 ^{o}C) ranged from 20% to 4% (Ade-Omowaye et al.. 2002). No air-drying after osmotic treatment was conducted in above work. The percentage reduction after osmotic dehydration for vitamin C for cherries at varied sucrose concentrations (40 to 75%) was approximately 50%.

Table 3.5.Vitamin C content of fresh, osmotically dehydrated in 40%, 55% and 70% sucrose solutions before and after tray drying.

	Vitamin C (mg/gr)	Vitamin C after tray drying (mg/gr)	% retained by the drying process	% retained from initial value
Fresh cherry	0.6420	0.1785	27.80	27.80
40 % sucrose solution	0.3760	0.2730	72.60	42.50
55 % sucrose solution	0.3210	0.2210	68.85	34.40
70 % sucrose solution	0.2885	0.2380	82.50	37.70

3.5. Osmotic Dehydration as a Pretreatment before Air Drying

The current increase of interest in osmotic treatments arises primarily from the need for quality improvement and from economic factors. Quality improvement is related not only to the water removal with minimal thermal stress but also the impregnated solutes and the modification of the structure (Torreggiani and Bertolo, 2001).

Osmotic dehydration is most reported pre-treatment used prior to air-drying. In this part, drying behavior of osmotically-pretreated cherry is discussed. Zucchini samples could not be able to air dried after osmotic treatment. Because a salt layer occured on the surface of zucchini after three hours of dehydration. This layer prevented drying. Therefore, zucchini air drying was not run. To study the air drying of cherry, drying kinetics of the control sample consists of fresh cherry halves was compared with

osmotically dehydrated cherry halves. Figure 3.13 shows the drying curves of osmotically treated and non-treated cherries.

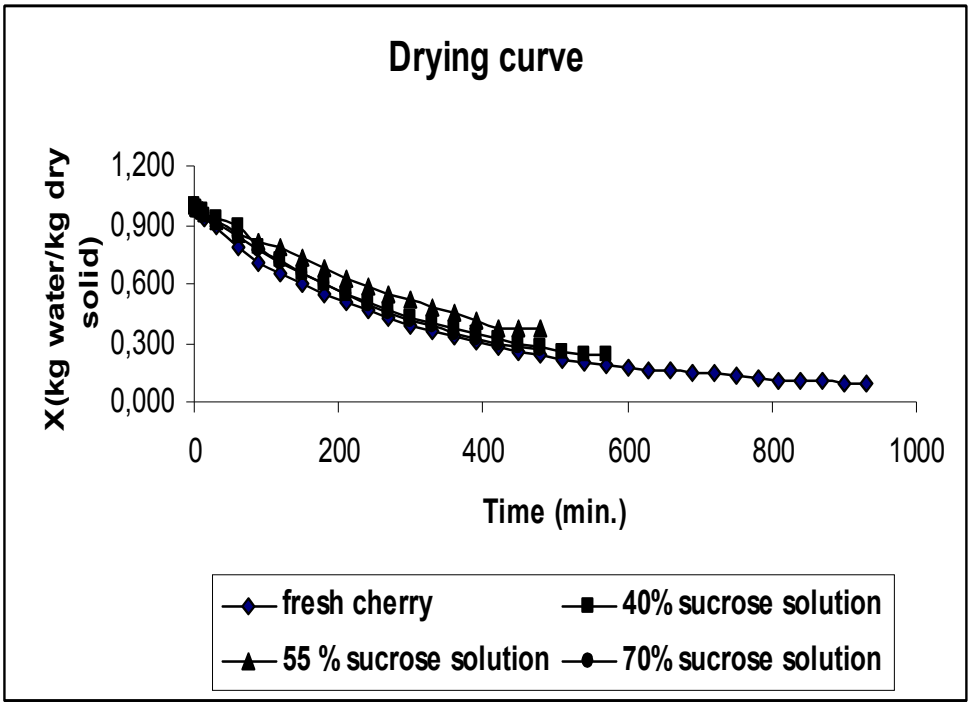


Figure 3.13. Drying curves of fresh cherry, osmotically dehydrated cherries in 40%, 55% and 70% sucrose solutions

Drying of osmotically pre-treated cherries was much faster than fresh cherries. This may be due to disruption of cherry structure by osmotic pretreatment. The drying time required to reduce the moisture from initial moisture content of about 82 % (w.b.) to final moisture content, approximately 18 % was 930, 570, 510,480 minutes, respectively for fresh (untreated) surface solution pretreated, 40% sucrose solution pretreated, 55% sucrose solution pretreated, 70% sucrose solution pretreated samples, respectively.. These results demonstrated that drying times of pretreated samples was 360 minutes shorter than that of untreated samples. It is evident from drying curves (Figure 3.13 and 3.14) that, moisture content decreases continuously with the drying time. As expected, concentration of sugar solution for osmotic treatment had a significant effect on the moisture of samples. The increase in sucrose concentration in osmotic dehydration pretreatment resulted in a decrease in the

drying time. Similar results was observed by Fernandes et al., (2005) who studied optimization of osmotic dehydration of bananas followed by air-drying. Their results showed the advantage of using high sucrose concentration for the osmotic solution and the use of the osmotic treatment to reduce the total processing time of fruit drying. Rodrigues et al., (2007) also observed that use of the osmotic treatment reduced the total processing time of fruit drying

Drying conditions (air temperature and air velocities) in the tray dryer were identical for both samples (see Table 2.)

Figure 3.14 shows the variation of drying rate with moisture content for cherry halves. In this study,we assumed that there was no shrinkage of cherries during drying in the tray dryer.
Drying rate (R) was calculated with following equation

$$R= (L_s/A)x(dX/dt) \quad (18)$$

L_s: kg dry solid/kg sample A:surface area of sample
X: kg water/ kg dry solid t: time (minute)

Moisture content decreases continuously with diminishing drying time. This shows that diffusion is the dominant physical mechanism governing moisture movement in the samples.
Drying behaviors of pre-treated and untreated cherries were similar. A constant rate periods were not observed for all experimental runs, therefore the entire drying process for cherry halves occurred in the range of the falling-rate period. . Similar drying behaviors are observed in the literature for various fruits, such as chestnut (Singh et al., 2008), tapioca roots (Chirife and Cachero, 1970).

Initially both samples dry at similar drying rates until the free moisture in both samples was evaporated. This free moisture in fresh cherry was the natural juice available for evaporation from cut surfaces. The free moisture in osmotically dehydrated cherry comes from the water during washing the cherry from residual syrup.

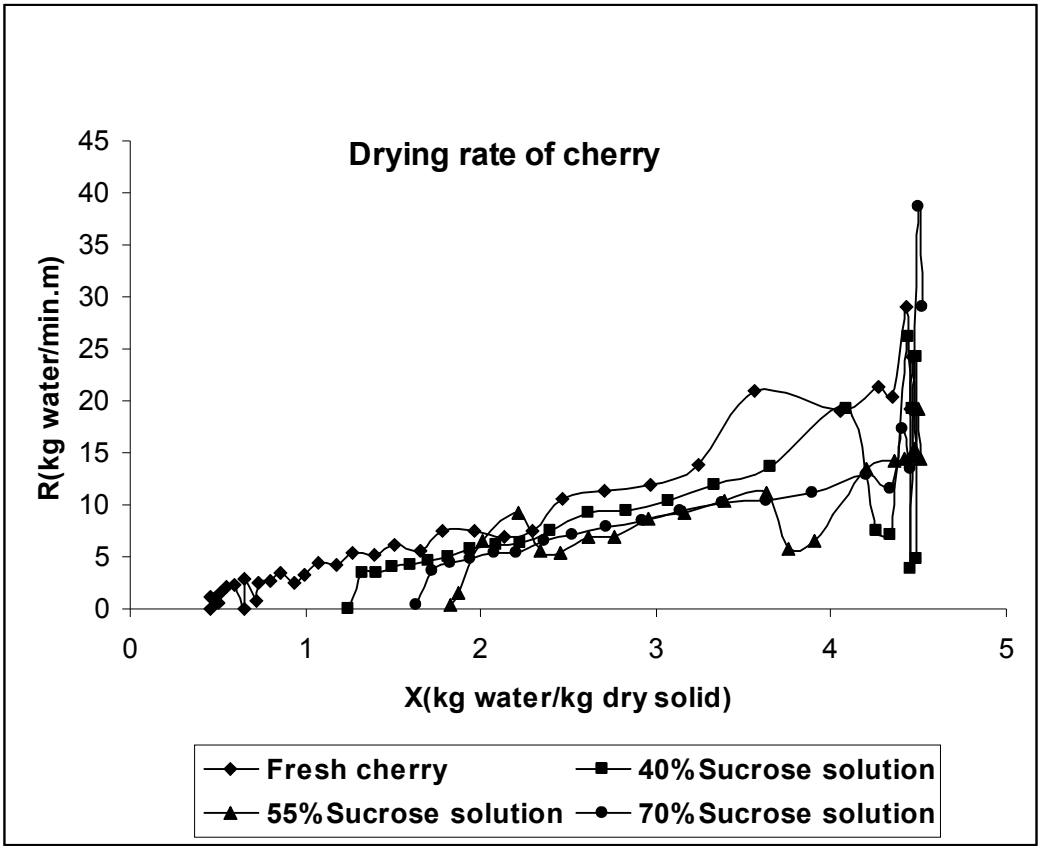


Figure 3.14 Drying rate vs. mositure content of cherry in air drying

Fluidization of sticky sugar infused cherry at the beginning of drying was not homogeneous, which reduces the air-to- particle contact area and thus the drying rates. Because evaporation of water was related to the interfacial area, the rate of drying increased with time.

Rapid falling rate periods could also be due to heat indicated damage of fruit surface during the early stages of drying. In addition, cutting cherries into halves provided substantial increase in moisture loss, because the surface area for mass transfer is greater.

As a result, drying behavior for osmotically pretreated cherry was similar for tray dryer and followed the general pattern with initial drying period, and the falling drying rate period. In drying kinetics of cherry; both of osmotically pretreated and fresh cherry constant rate period was not obtained..

Drying kinetics were also studied plotting moisture content and time versus (Figure 3.14) so as to emphasize the differences in water release mechanisms. Usually this approach was applied to inspect the different stages of a drying process (heating of foods, constant rate period, falling rate period). In this case, no constant rate period was observed while falling rate stages was present. This phenomenon could be due to heat induced damage of fruit surface during the early stages of drying.

The result showed that the use of osmotic dehydration followed by air drying was an advantage when a high concentration of sucrose solution (55 and 70 %) was used in the osmotic dehydration process. Table 2.6. represented the total processing times and the fruit solute concentration for the final product. Use of an osmotic treatment with high sucrose concentration speeded up the process, reduced the drying period if compared to solely using the air drying process to dry cherry.

3.6. Water Effective Diffusivity Coefficient

Drying of moist materials is a complicated process involving simultaneous, coupled heat and a mass transfer phenomenon, which occurs inside the material being, dried. Moisture transport has been found to vary widely in food materials, due to mainly to different physical structure. The drying curves obtained from drying experiments under controlled conditions provide useful information on the mechanism of moisture transport and they are utilized for the determination of water effective diffusion coefficient. Moisture diffusivity in solid foods can be determined by different methods involving defined geometries, and well-defined experimental conditions (steady state or transient conditions). These methods, which have been used to estimate water diffusivity are based on drying kinetics, sorption or desorption kinetics, and moisture profile analysis (Crank, 1975; Zogzas et al., 1994).

Fick's second law of diffusion has been widely used to describe the moisture diffusion process for food products by many researches (Maskan et al., 2002). The solution of Fick's second law of diffusion from a flat plate results in the following equation for the transfer of water (Crank, 1975).

$$MR = \frac{X - Xe}{Xo - Xe} = 8/\prod^2 \exp(-\prod^2 Df\, t/L^2) \quad (19)$$

where MR is the moisture ratio, X is the moisture content at any time, Xe and Xo are equilibrium and initial moisture contents, respectively; Df is the effective diffusion coefficient and L is the half-thickness of the slab for drying from both top and bottom sides and t is the drying time. The water effective diffusivities of cherry were determined from experimental drying curves. Figure 3.15. shows a typical plot of In $\frac{X - Xe}{Xo - Xe}$ against time for determination of diffusivity. The rest of the In $\frac{X - Xe}{Xo - Xe}$ against time plots are shown Figures D1, D2 and D3 in appendices. The non-linear shape of the drying curves indicates variable moisture diffusivity. Three linear falling rate periods were determined by a linear regression analysis. From the slopes of these determined three lines, diffusion coefficients were determined. However, only one diffusion coefficient was determined for drying of fresh cherry. This is possibly due to less damaged tissue structure of cherry.

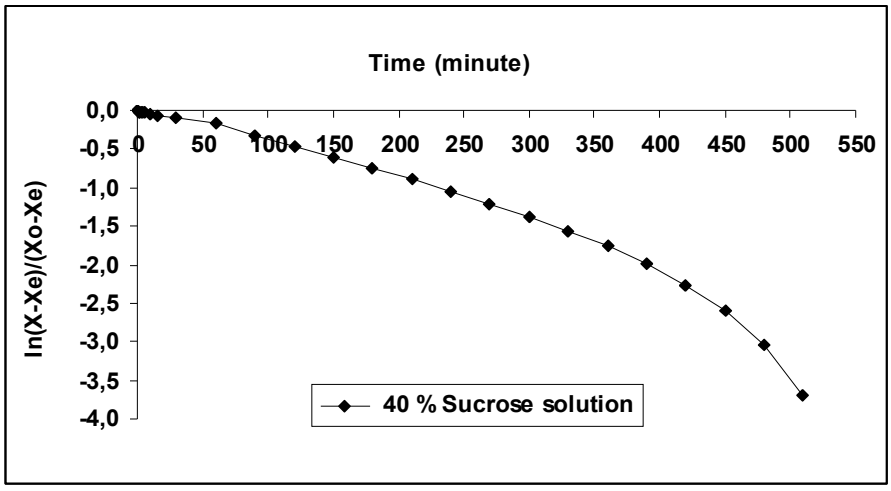


Figure 3.15 In $\frac{X - Xe}{Xo - Xe}$ against time for osmoticallydehydrated cherry in 40% sucrose solution

Water effective diffusion coefficients of cherry were shown in Table 3.5 where DF_1, DF_2 and DF_3 represent diffusion coefficients for first, second and third falling rate periods, respectively. The water effective diffusion coefficients for fresh cherry range from 1.28×10^{-6} to 7.91×10^{-8} m^2/s. These values close to the normally expected

range of DF (10^{-12} to 10^{-6} m^2/s) for dehydrated foods (Zogzas et al, 1996). Water effective diffusivities ranged between 1.66 x 10^{-10} to 1.44 x 10^{-10} m^2/s for osmotic dehydration of pumpkins (*Cucurbita moschata*) in 40 to 60% (w/w) sucrose solutions (Garcia et al., 2007) It can be seen that water effective diffusion coefficients decrease with osmotic pretreatment in sucrose solution (Table 3.5). No trend for diffusivity values was observed with increasing sucrose concentration. It is a fact that the higher sucrose concentration, the higher damage tissue, which makes sucrose diffusion easier.

A comparison of air-drying curves for non-treated and osmotically treated cherries is shown in Figure 3.14. Figure 3.14. shows the effect of pre-treatment on convective drying enhanced the water transfer. Pre- treatment of fruits in sugar solutions usually reduces the convective drying rates (Simal et al., 1997; Rahman and Lamb, 2007). However, Park et al. (2002) found that the water diffusion coefficients in osmotically dehydrated pears were greater than in the fresh fruit while the air-drying velocity was 2 m/s, but not for 1 m/s. In this study, similar result is observed since the water diffusion coefficients in osmotically dehydrated cherries were lower than that in the fresh fruit. This is probably due to less reduction in the effect of shrinkage and surface hardening due to osmotic treatment.

Table 3.6. Water effective diffusion coefficients of cherry at different sucrose concentrations.

	DF_1 (m^2/s)	DF_2 (m^2/s)	DF_3 (m^2/s)
Fresh cherry	$1{,}28x10^{-6}$	-	-
40 % sucrose solution	$5{,}47x10^{-8}$	$1{,}36x10^{-6}$	$3{,}17x10^{-6}$
55 % sucrose solution	$5{,}17x10^{-8}$	$1{,}05x10^{-6}$	$7{,}26x10^{-6}$
70 % sucrose solution	$7{,}91x10^{-8}$	$1{,}20x10^{-6}$	$3{,}95x10^{-6}$

It can be seen from Table 3.6. that diffusivity values increase as drying progress. Mazza (1984) has stated that, in the low moisture range, the drying is so slow that the cooling effect of evaporation is insignificant and drying material assumes the dry bulb temperature of the air. In this phase of drying, the rate of moisture movement to

the surface of the material increases with temperature. Therefore, even at very low moisture content, the drying rate is appreciably greater. This is the reason that we assume for high value of diffusivity at the third falling rate period. Another reason for the greater diffusivity at low moisture content may be due to the cell wall destruction, because wet bulb temperature of the samples approaches the dry bulb temperature and therefore decreases the resistance to the moisture diffusion within the sample. This means that heating leads to changes in the physical properties of tissue, among them destroying the semi-permeability of the cell membranes (Vaccarezza et al., 1974).

CHAPTER IV
CONCLUSIONS

The study of osmotic dehydration of fruit and vegetables revealed the following conclusions:

1. Osmotic dehydration can be used as a pretreatment before air drying of fruit and vegetables
2. Ultrasound and magnetic agitation increase the mass transfer during osmotic dehydration
3. Osmotic pretreatment preserves color of fruit and vegetable during air drying
4. Osmotic pretreatment reduce the total drying time in tray dryer compared to drying of untreated sample
5. The main parameters affecting the mass transfer during osmotic dehydration is the solution concentration in this study
6. Temperature is not a parameter affecting the mass transfer during the osmotic dehydration.
7. In view of color values, cherry dehydrated at 25°C and zucchini dehydrated at 15, 25, and 35°C provided product with better quality.
8. Drying took place entirely in the falling period.
9. Water loses increased as osmotic solution concentration increased. Water loss with ultrasound effect was faster than water losses with agitation using for zucchini studies.
10. Sucrose concentration and immersion time were the main effects on the mass transfer mechanism for cherry.

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APPENDICES

Table A.1. Fitting Model for Water Loss of Zucchini

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	42.70	1	42.70		
Linear	3.11	3	1.04	34.53	<0.0001
2FI	4.635E-003	3	1.545E-003	0.14	0.9637
Quadratic	0.15	3	3.92	4.75	0.0195
Cubic	0.13	8	1.49	1.22	0.2301

Table A.2. Model Summary Statistics for Water Loss of Zucchini

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.12	0.8638	0.8510	0.8326
2FI	0.13	0.8650	0.8371	0.8055
Quadratic	0.11	0.9071	0.8749	0.8332
Cubic	0.11	0.9441	0.8912	0.7894

Table A.3. ANOVA for Response Surface Quadratic Model for Water Loss of Zucchini

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.036	1	0.036	2.77	0.1079
B	2.97	1	2.97	230.86	<0.0001
C	0.097	1	0.097	7.54	0.0108
A^2	3.11E-004	1	3.11E-004	0.026	0.8738
B^2	0.15	1	0.15	11.32	0.0024
C^2	5.414E-003	1	5.414E-003	0.42	0.5221
AB	6.093E-005	1	6.093E-005	4.738E-003	0.9456
AC	4.165E-005	1	4.165E-005	3.239E-003	0.9551
BC	4.532E-003	1	4.532E-003	0.35	0.5579

A: Temperature B: Concentration C: Time

AB: Interaction between temperature and concentration

AC: Interaction between temperature and time

BC: Interaction between time and concentration

Table A.4. Fitting Model Weight Reduction of Zucchini

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	27.46	1	27.46		
Linear	3.09	3	1.03	59.00	<0.0001
2FI	5.341E-003	3	1.780E-003	0.093	0.9631
Quadratic	0.2	3	0.068	5.02	0.0071
Cubic	0.13	8	0.017	1.37	0.3730

Table A.5.Model Summary Statistics for Weight Reduction of Zucchini

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.13	0.8469	0.8325	0.8128
2FI	0.14	0.8484	0.8170	0.7823
Quadratic	0.12	0.9039	0.8707	0.8296
Cubic	0.11	0.9403	0.8840	0.7628

Table A.6. ANOVA for Response Surface Quadratic Model for Weight Reduction of Zucchini

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.066	1	0.026	7.98	0.009
B	2.94	1	2.95	888.1	<0.0001
C	0.068	1	0.12	36.20	<0.0001
A^2	0.014	1	3.71E-003	1.13	0.2969
B^2	0.18	1	0.29	87.60	<0.0001
C^2	7.369E-003	1	0.04	12.20	0.0017
AB	6.770E-004	1	6.77E-004	0.2	0.6553
AC	1.222E-003	1	8.443E-003	2.54	0.1228
BC	3.442E-003	1	4.33E-003	1.31	0.2637

Table A.7. Fitting Model Solid Gain of Zucchini

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	60.05	1	60.05		
Linear	3.17	3	1.06	34.53	<0.0001
2FI	0.014	3	4.799E-003	0.14	0.9325
Quadratic	0.34	3	0.11	4.75	0.0090
Cubic	0.22	8	0.027	1.22	0.3404

Table A.8. Model Summary Statistics for Solid Gain of Zucchini

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.17	0.7640	0.7419	0.7106
2FI	0.15	0.7675	0.7194	0.6631
Quadratic	0.18	0.8498	0.7978	0.7335
Cubic	0.15	0.9027	0.8109	0.5956

Table A.9. ANOVA for Response Surface Quadratic Model for Solid Gain of Zucchini

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.13	1	1.05	1.60	0.2168
B	2.98	1	96.49	147.13	<0.0001
C	0.034	1	3.54	5.4	0.0283
A^2	0.1	1	1.72	2.62	0.1178
B^2	0.23	1	22.08	33.67	<0.0001
C^2	9.035E-003	1	2.92	4.45	0.0447
AB	3.615E-003	1	0.8	1.22	0.2787
AC	9.193E-003	1	2.59	3.96	0.0573
BC	1.590E-003	1	0.47	0.72	0.4047

Table B.1. Fitting Model for Weight Reduction of Cherry

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	0.21	1	0.21		
Linear	0.038	2	0.019	200.04	<0.0001
2FI	5509E-004	1	5509E-004	8.24	0.0106
Quadratic	4.436E004	2	4.436E004	4.8	0.0245
Cubic	2.021E-004	3	2.021E-004	1.65	0.2306

Table B. 2.Model Summary Statistics for Weight Reduction of Cherry

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	9.683E-003	0.9569	0.9522	0.9362
2FI	8.177E-003	0.971	0.9659	0.9535
Quadratic	6.797E-003	0.9823	0.9764	0.9643
Cubic	6.396E-003	0.9875	0.9791	0.9435

Table B.3. ANOVA for Response Surface Quadratic Model for Weight Reduction of Cherry

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.018	1	0.018	381.99	<0.0001
B	0.02	1	0.02	440.54	<0.0001
A^2	5509E-004	1	5509E-004	8.35	0.0112
B^2	4.436E004	1	2.218E-004	1.25	0.2812
AB	2.021E-004	1	6.737E-005	11.92	0.0035

Table B.4. Fitting Model for Water Loss of Cherry

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	0.042	1	0.042		
Linear	0.04	2	0.02	21.92	<0.0001
2FI	4E-003	1	4E-003	5.45	0.0321
Quadratic	9.72E-003	2	4.86E-003	26.48	<0.0001
Cubic	16E-003	3	5.332E-004	5.55	0.0127

Table B. 5.Model Summary Statistics for Water Loss of Cherry

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.03	0.7089	0.6766	0.5834
2FI	0.027	0.7796	0.7407	0.6453
Quadratic	0.014	0.9514	0.9351	0.8697
Cubic	9.803E-003	0.9796	0.9660	0.8953

Table B.6. ANOVA for Response Surface Quadratic Model for Water Loss of Cherry

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.04	1	0.04	22.01	<0.0001
B	3.233E-003	1	3.233E-003	17.62	0.0008
A^2	9.716E-003	1	9.716E-003	52.94	<0.0001
B^2	3.854E-006	1	3.854E-006	0.021	0.8867
AB	4E-003	1	4E-003	21.80	0.0003

Table B.7. Fitting Model Solid Gain of Cherry

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	0.063	1	0.063		
Linear	0.013	2	6.308E-003	6.07	0.0096
2FI	1.617E-003	1	1.617E-003	1.61	0.2215
Quadratic	0.012	2	6.149E-003	19.31	<0.0001
Cubic	3.284E-003	3	1.095E-003	8.8	0.0023

Table B. 8. Model Summary Statistics for Solid Gain of Cherry

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.032	0.4029	0.3366	0.1810
2FI	0.032	0.4546	0.3584	0.1301
Quadratic	0.018	0.8474	0.7966	0.6363
Cubic	0.011	0.9523	0.9205	0.7966

Table B.9. ANOVA for Response Surface Quadratic Model for Solid Gain of Cherry

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.04	1	0.04	22.01	<0.0001
B	3.233E-003	1	3.233E-003	17.62	0.0008
A^2	9.716E-003	1	9.716E-003	52.94	<0.0001
B^2	3.854E-006	1	3.854E-006	0.021	0.8867
AB	4E-003	1	4E-003	21.80	0.0003

B: Concentration C: Time

BC: Interaction between temperature and concentration

Table C.1. Fitting Model Water Loss of Zucchini with Ultrasound

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	146.87	1	146.87		
Linear	4.10	3	1.37	7.94	0.0018
2FI	0.026	3	8.609E-003	0.041	0.9884
Quadratic	1.73	3	0.58	5.79	0.0147
Cubic	0.61	6	0.15	2.36	0.1658

Table C.2.Model Summary Statistics for Water Loss of Zucchini with Ultrasound

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.41	0.5983	0.5230	0.4146
2FI	0.46	0.6020	0.4184	0.2374
Quadratic	0.32	0.8545	0.7236	0.0328
Cubic	0.25	0.9435	0.8212	0.6837

Table C.3. ANOVA for Response Surface Quadratic Model Water Loss of Zucchini with Ultrasound

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.092	1	0.092	0.93	0.3584
B	2.97	1	2.97	29.82	0.0003
C	1.04	1	1.04	10.38	0.0091
AB	2.414E-003	1	2.414E-003	0.024	0.8795
AC	8.410E-003	1	8.410E-003	0.084	0.7775
BC	0.015	1	0.015	0.15	0.7063
A^2	0.11	1	0.11	1.14	0.3101
B^2	1.32	1	1.32	13.28	0.0045
C^2	4.522E-004	1	4.522E-004	4.534E-003	0.9476

Table C.4. Fitting Model Solid Gain of Zucchini with Ultrasound

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	194.52	1	194.52		
Linear	1.89	3	0.63	2.12	0.1375
2FI	1.21	3	0.40	1.48	0.2659
Quadratic	1.77	3	0.59	3.35	0.0639
Cubic	0.41	4	0.1	0.46	0.7636

Table C.5. Model Summary Statistics for Solid Gain of Zucchini with Ultrasound

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.54	0.2847	0.1505	0.1437
2FI	0.52	0.4668	0.2207	0.0812
Quadratic	0.42	0.7340	0.4946	0.3364
Cubic	0.47	0.7964	0.3554	0.2490

Table C.6. ANOVA for Response Surface Quadratic Model Solid Gain of Zucchini with Ultrasound

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.036	1	0.036	0.20	0.6624
B	1.35	1	1.35	7.66	0.0199
C	0.50	1	0.50	2.84	0.1227
AB	0.24	1	0.24	1.37	0.2692
AC	0.82	1	0.82	4.66	0.0562
BC	0.14	1	0.14	0.82	0.3874
A^2	0.095	1	0.095	0.54	0.4792
B^2	1.11	1	1.11	630	0.0309
C^2	0.36	1	0.36	2.06	0.1814

Table C.7. Fitting Model Weight Reduction of Zucchini with Ultrasound

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
Mean	3.29	3	1.10	5.71	0.0075
Linear	0.23	3	0.076	0.35	0.7905
2FI	2.02	3	0.67	8.15	0.0048
Quadratic	0.39	4	0.098	1.35	0.3538

Table C. 8. Model Summary Statistics for Weight Reduction of Zucchini with Ultrasound

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared
Linear	0.44	0.5170	0.4265	0.2786
2FI	0.47	0.5530	0.3467	0.2481
Quadratic	0.29	0.8703	0.7536	0.1909
Cubic	0.27	0.9317	0.7836	0.0896

Table C.9. ANOVA for Response Surface Quadratic Model Weight Reduction of Zucchini with Ultrasound

Source	Sum of Squares	DF	Mean Squares	F Values	Prob>F
A	0.069	1	0.069	0.84	0.3821
B	2.25	1	2.25	27.28	0.0004
C	0.97	1	0.97	11.74	0.0065
AB	0.022	1	0.022	0.27	0.6143
AC	0.17	1	0.17	2.06	0.1815
BC	0.037	1	0.037	0.44	0.5208
A^2	1.826E-005	1	1.826E-005	2.211E-004	0.9884
B^2	1.62	1	1.62	19.62	0.0013
C^2	0.23	1	0.23	2.84	0.1231

A: Temperature B: Concentration C: Time

AB: Interaction between temperature and concentration

AC: Interaction between temperature and time

BC: Interaction between time and concentration

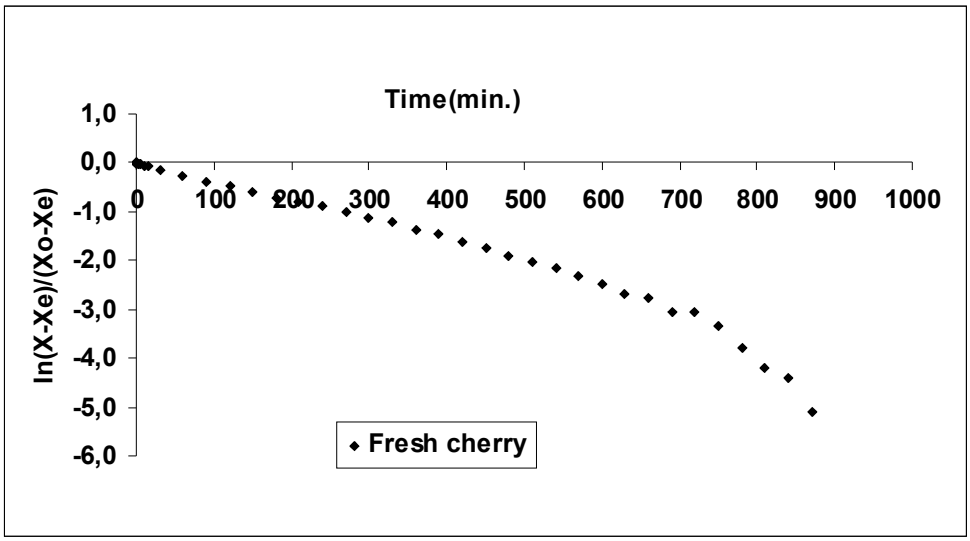
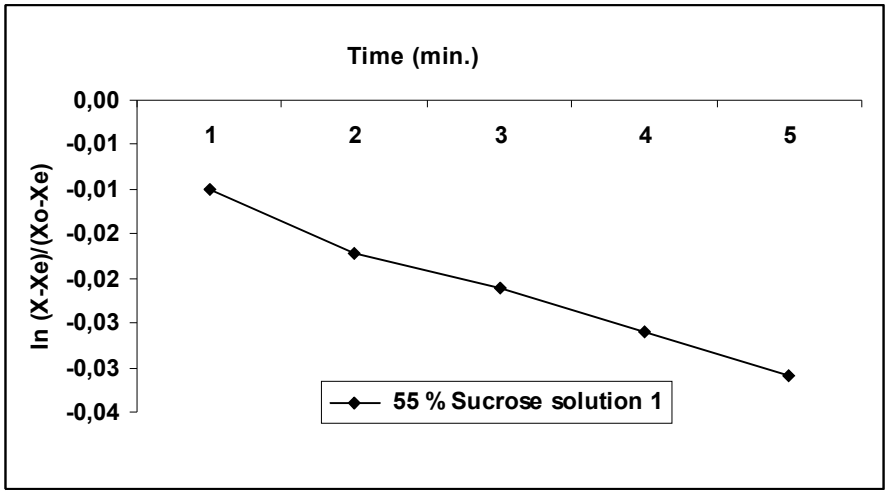
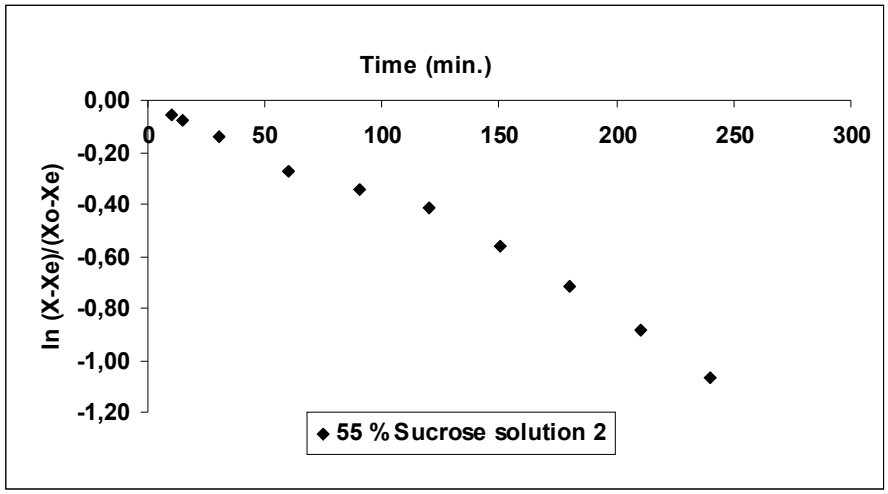


Figure D1. Diffusivity of fresh cherry





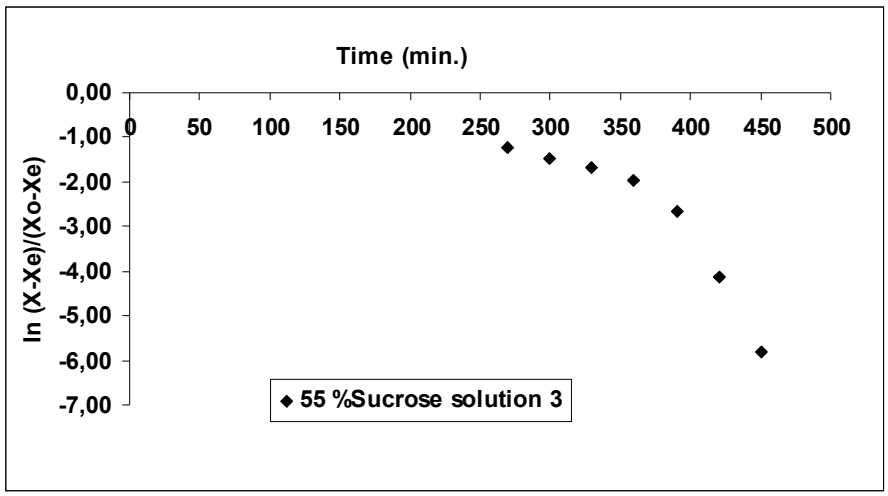
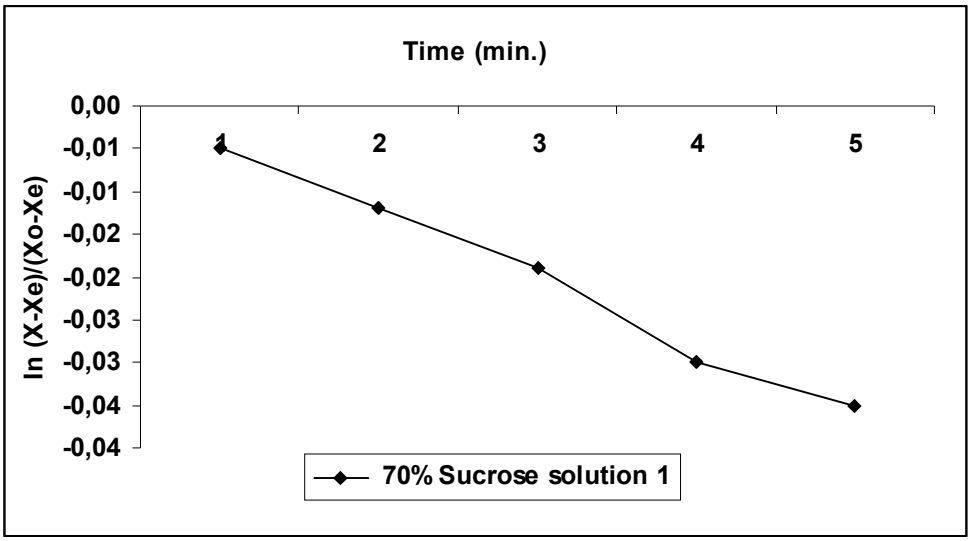
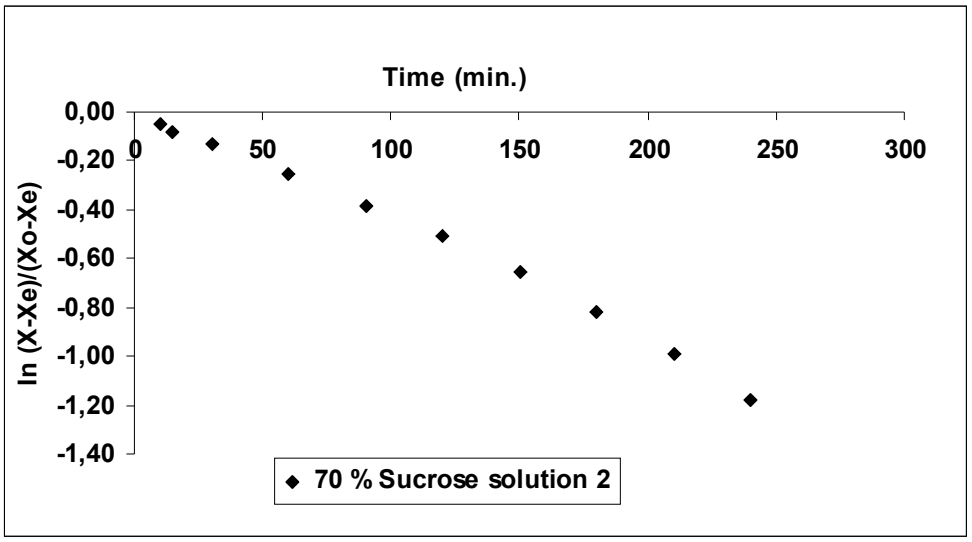


Figure D2. Diffusivity of osmotically dehydrated in 55 % sucrose solution





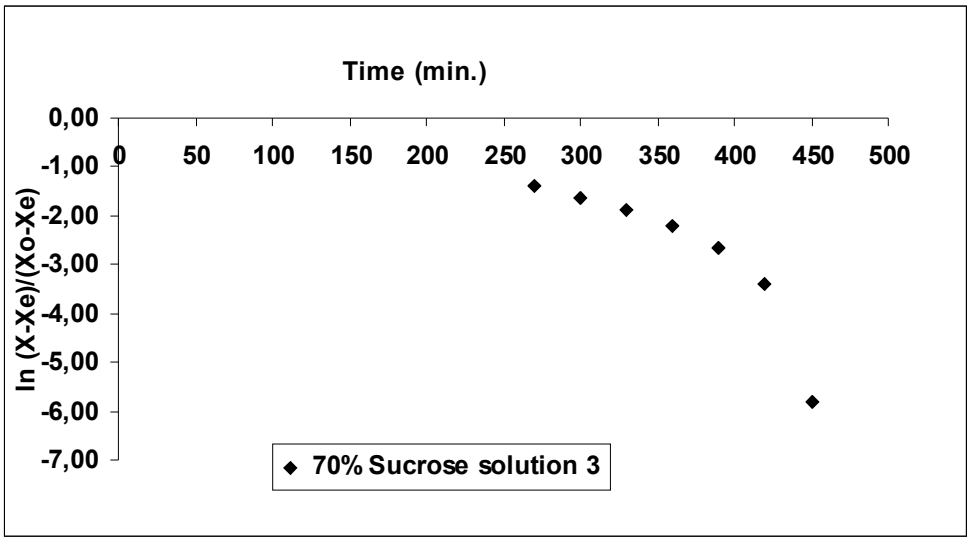


Figure D3. Diffusivity of osmotically dehydrated in 70 % sucrose solution

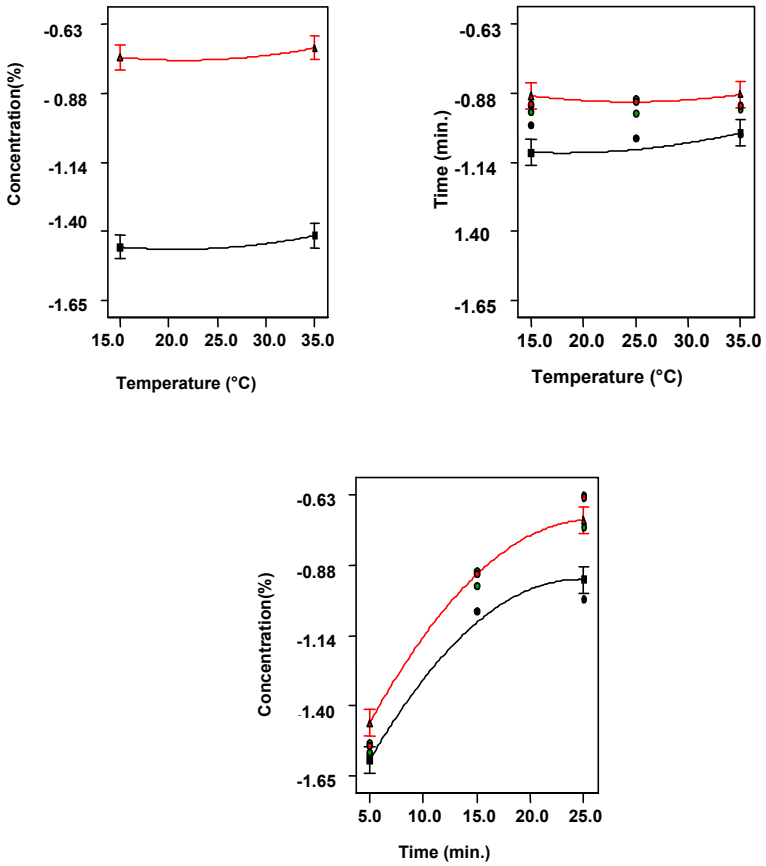


Figure D4. Interaction of time, temperature and salt concentration for water loss of zucchini during osmotic dehydration