OSMO-CONVECTIVE DEHYDRATION OF CARROTS (*Daucus carota* L.)

Dissertation

Submitted to the Punjab Agricultural University
in partial fulfilment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in

AGRO INDUSTRIAL PROCESSING
(Minor Subject: Food science and Technology)

By

Bahadur Singh
(L-2001-AE-77-D)

Department of Processing and Food Engineering
College of Agricultural Engineering
PUNJAB AGRICULTURAL UNIVERSITY
LUDHIANA -141004
2005

CERTIFICATE I

This is to certify that the dissertation entitled, "**Osmo-Convective Dehydration of Carrots (*Daucus carota* L.)**" submitted for the degree of Ph.D., in the subject of Agro Industrial Processing, (Minor subject: Food Science and Technology) of Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by Bahadur Singh (L-2001- AE-77-D) under my supervision and that no part of this dissertation has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

a.k. Gupta
14.1.05

(Dr. A. K. Gupta)
Major Advisor
Professor
Department of Processing and Food Engineering
Punjab Agricultural University
Ludhiana – 141004

CERTIFICATE II

This is to certify that the dissertation entitled, "**Osmo-Convective Dehydration of Carrots (*Daucus carota* L.)**" submitted by Bahadur Singh (L-2001- AE-77-D) to the Punjab Agricultural University, Ludhiana, in the partial fulfillment of the requirements for the degree of Ph.D., in the subject of Agro Industrial Processing, (Minor subject: Food Science and Technology) has been approved by the Student's Advisory Committee after an oral examination on the same, in collaboration with an External Examiner.

BSGhuman 17/2/05

(DR. B. S. GHUMAN)
MAJOR ADVISOR

17/2/05

EXTERNAL EXAMINER

Dr. O. D. Wanjari,
Head, FG&OP Division
CIPHET ,PAU Campus
Ludhiana

BSGhuman 17/2/05

(Dr. B. S. GHUMAN)
HEAD OF THE DEPARTMENT

5/3/05

(Dr. DARSHAN SINGH)
DEAN POSTGRADUATE STUDIES

ACKNOWLEDGEMENT

I express my deep sense of gratitude, indebtedness and sincere thanks to Dr. A.K. Gupta, Professor, and Department of Processing and Food Engineering, Punjab Agricultural University, Ludhiana, for his untiring help, constant inspiration, dynamic guidance and constructive criticism, which led my work to its successful completion. It has been my proud privilege to work under his kind and judicious guidance.

I am thankful to the members of my Advisory Committee, Dr. K.S. Minhas, Professor, Department of Food Science and Technology, Dr. A.K. Jain, Professor, School of Energy Studies for Agriculture, Dr. A.K. Singh, Associate Professor, Dr. Jarnail Singh, Professor, Department of Processing and Food Engineering and Dr. M.B. Bera, Dean, SLIET, Longowal, for their valuable suggestions and critically reviewing the manuscript.

Thanks are also due to Dr. B.S. Ghuman, H.O.D, Prof. V.K. Sehgal, Dr. Shashi Paul, Prof. Sadhna Arora, Prof. P.C. Grover, Dr. V.K. Thaper, Professors, Dr. Ashok Kumar, Research Engineer, Dr. Amarjit Singh, Extension Engineer, Department of Processing and Food Engineering, for their ever willing help during the course of my project work. The cooperation received from Er. M.S. Bhatti, Er. Salamdin, Er. Darminder Singh, Er. Gurinder Singh, Dr. Sanjeev Mehta, Dr. H.S. Sidhu, Mr Rajiv Sharma, Er. Manpreet Singh, and Er. Iqbal Singh, P. A. U., Ludhiana is also fully acknowledged.

The cooperation and encouragement received from Dr. Manohar Singh, Dean, Punjab Technical University, Jalandhar, Dr. B.C. Sarkar, Head, Department of Food Technology, SLIET, Longowal is fully acknowledged. I acknowledge with thanks Er. Rajinder Soni, Dr. Vikas Nanda, , Er. Avinash Thakur, Er. Damanpreet Singh, Mr. Charanjiv Singh, Dr. P.S. Paneser, Er. Rashminder Singh, Dr. Hrydesh Pandey, Er. Ashish Sharma, Mr. L.N. Singh, Sh. Manoj Kumar Pandey, Mr. Harpreet Singh, Mr. Devinder Singh and Mr. Om Chand of SLIET, Longowal for their kind cooperation.

My vocabulary talks fall short of adequate words to acknowledge the ever encouraging and moral support that I have received throughout my life from Er. Bhupinder Singh Dhillon, S. Tara Singh Marahar, Dr. Navdeep Singh Sodhi, Dr. Abdul Shakoor, Er. Abdul Sattar, S. Rajinder Singh, Sh. Bhagwant Sarup, S. Yadwinder Singh.

I must acknowledge thanks to all the staff members of Department, especially to Sh. Parkash Chand, Sh. Charan Das, S. Ajit Singh, Mr. Nachhattar Singh, Mr. Paramjit Singh, Mr. Mukesh Kumar, Mr. Surinder Singh, Mr. Satinder Mohan, Mr. Surjit Singh, Mr. Inderjit Singh, Mr. Mahal Singh, Mr. Harnam Singh, Sh. Ram Lochan and Mr. Bhag Singh.

The invaluable blessings, interest and selfless but untold sacrifice of my respected parents, and other family members could never be forgotten.

(BAHADUR SINGH)

Title of the dissertation : Osmo-Convective Dehydration of Carrots (*Daucus carota L.*)
Name of the student and : Bahadur Singh
Admission No. : L-2001-AE-77-D
Name of Major Advisor and : Dr. A. K. Gupta
Designation : Professor
Major subject : Agricultural Engineering (Agro Industrial Processing)
Minor subject : Food Science and Technology
Degree to be awarded : Ph. D.
Year of award of degree : 2005
Total pages in dissertation : 204+LV (Appendices)
Name of the University : Punjab Agricultural University
Ludhiana – 141004, Punjab (India).

ABSTRACT

Response surface methodology (RSM) was employed for optimization of osmotic dehydration process for un-blanched carrot cubes in solutions of salt, sugar and sugar-salt mixture, followed by convective dehydration, rehydration, sorption isotherm and storage study. Diffusivity of moisture and solute during osmotic and convective dehydration processes was calculated by using analytical solution of un- steady state Fick's law equation by using computer programs. Convective dehydration of un-osmosed and pre-osmosed carrot cubes was carried out at 55, 65 and 75°C temperature and air velocity of 1.6-m/s. The osmotic dehydration resulted in increased convective dehydration time, improvement in colour, texture, overall acceptability, and lowered the shrinkage and activation energy for the convective dehydration. Out of all the osmotic pretreatments, sugar-salt solution pretreatment gave the rehydrated product similar to fresh product even after storage period of 10 months. The osmotic pretreatment in salt solution resulted in increase of EMC, whereas osmotic pretreatment in sugar solution decreased the EMC of the product. The samples, which were osmotically pretreated with sugar and sugar-salt mixture solution, remained acceptable up to 10 months storage under ambient condition. Whereas, all the samples stored at low temperature remained acceptable regardless of packaging material even after storage of 10 months. The juice remained fit for consumption at ambient temperature after 10 months. Gazrella (an Indian sweetmeat), which was prepared from left over material, had overall response of acceptability between moderate to excellent.

Key words: Carrots; osmotic dehydration; Convective dehydration; drying; optimization; Response surface methodology; Diffusivity; Activation energy; EMC; sorption isotherms.

a.k. Gupta
14.1.05
Signature of Major Advisor

Signature of the Student

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

In India more than 40 kinds of vegetables belonging to different groups, namely, Solanaceous, Cucurbitaceous, Leguminous, Cruciferous (Cole crops), root crops and leafy vegetables are grown in tropical, subtropical and temperate regions. In 2000-01, the total production of vegetables is 98.5 million tones and it mainly consists of tomato, onion, bringle, cabbage, cauliflower, okra, peas and carrots. India is the only next to China in the production of vegetables and contributes about 13% of the world vegetable production. It occupies first position in the production of Cauliflower, second in Onion and third in cabbage in the world (Anonymous 2003a). In India, only 2% of the total vegetable and fruit produce is processed (Firodia 2004).

Carrot (*Daucus carota* L.) is one of the most important cool season root vegetables grown extensively in various countries particularly during winter season in tropical regions while, during summer season in temperate countries (Kalra *et al* 1987). Southwestern Asia especially Afghanistan is considered to be the main center of origin of this crop. The area under carrot in India is reported to be 20,000 hectare with an annual production of 4.14 Lakh tones. In Punjab during the year 2002, the total area under vegetable cultivation was 145097 hectare with total vegetable production including carrots of 2437459 M tones (Punjab Horticulture Department 2003). Carrot is known for its nutrient contents viz. carotene and carotenoids besides appreciable amounts of vitamins B_1, B_2, B_6 and B_{12} vitamins and minerals. Carrots are a good source of 'vitamin A', which prevents night blindness and promotes healthy skin and hair, strong teeth and bones and resistance to infection (Anonymous 2003b). Carrot roots are used as salad, cooked vegetables, in preparation of soups, stews, curries, sweetmeats, juices, flakes, fermented pickles and soups. A sweet preparation called Gajar halwa is a very famous dish in north India. Carrot juice is a rich source of carotene and is used for coloring butter and other food articles (Kalra *et al* 1987). Hence, it occupies an important place in the root vegetables for its multifaced application, which have in turn resulted in development of various processing operations for making different products and/ or to extend the shelf life (Walde *et al* 1992).

Fresh carrots cannot be stored for more than 3-4 days under ordinary conditions, but shelf life can be extended to 7-8 months if stored in crates covered with perforated plastic film at 0^{O}C and 93-96% relative humidity (Chadha 2002). The other methods of extending shelf life are fermenting, pickling, canning or cold storage freeze drying etc (Mudahar *et al* 1989). Out of theses methods freeze-drying produces the highest quality food products but it is the expensive method of preservation. So there is a need for simple and inexpensive alternate process, which are not only energy intensive and low capital investment but also offer a way to save highly perishable products and make them available for the regions away from production zones. The osmotic dehydration is one of these new methods (Shi and Maguer 2002).

Osmotic dehydration is the process by which there is partial removal of water from the cellular materials when these are placed in a concentrated solution of soluble solute. Osmotic dehydration, which is effective even at ambient temperature and saves the colour, flavour and texture of food from heat, is used as a pretreatment to improve the nutritional, sensorial and functional properties of food. The food, which has been osmotically dehydrated, can be further processed by freezing, freeze-drying, vacuum drying and air drying (Nanjundaswamy *et al* 1978).

Sugar, glucose, fructose, corn syrup and sodium chloride are the common osmotic agents and out of these sucrose solution is commonly used for the fruits and sodium chloride solution for the vegetables. Only limited efforts have so far been made to study osmotic dehydration of carrots. Mazza (1983) reported the effect of dipping carrot dices in sucrose and sodium chloride solution for 30 minutes prior to air-drying on moisture transport during dehydration and product quality while studying the effect of several pre-drying treatments. Effect of varying sizes of carrot pieces osmosed in cane sugar solution and of their subsequent vacuum drying on the osmo and vacuum drying characteristics and on the product quality was reported by Chopra and Verma (1994). Singh (2001) dehydrated carrot shreds by concentrating the material in sucrose solution at room temperature prior to hot air drying at 55°C in view of preparing Gazrella, a sweet dish. Thus, mass transfer kinetics of osmotic dehydration of carrots has not yet been studied and mathematical modeling of the process has not been attempted. Though, mathematical modeling of osmotic mass transfer in some other fruit and vegetable products like banana, apple, pineapple, green beans, green peas, and potato have been reported using different approaches (Lenart and Flink 1984; Beristain *et al* 1990; Biswal *et al* 1991, Biswal and Bozorgmehr 1992; Azuara *et al* 1992; Pokharkar and Prasad 1998; Salvatori *et al* 1999b, Pokharkar 2001; Matusek and Meresz 2002). Further, osmo-hot air-drying process for carrots has not been developed.

Keeping in view the above aspects, the present study is proposed to be undertaken with the following objectives:

1. Comparative study of Osmo-convective and convective dehydration of carrots.
2. Packaging of dehydrated carrots in different packaging materials and subsequent storage studies under different conditions.

CHAPTER II

REVIEW OF LITERATURE

Drying degrades the quality attributes like texture, colour, flavour, and nutritional value Mazza (1983). To get high quality dehydrated product, it is important to start with either high quality raw material or use delicate drying process. Osmotic dehydration is one such noble technique with which wholesomeness of the final product can be achieved. Osmotic dehydration is the process of water removal by immersion of water containing cellular solid in a concentrated aqueous solution of high osmotic pressure (hypertonic media) for a specified time and temperature.

2.1 Osmotic dehydration

In osmotic dehydration, the driving force for water removal is the concentration gradient between the solution and the intracellular fluid. If the membrane is perfectly semi permeable, solute is unable to diffuse through the membrane into the cells. However, it is difficult to obtain a perfect semi permeable membrane in food systems due to their complex internal structure, and there is always some solid diffusion into the food, which means that osmotic dehydration, is actually combination of simultaneous water and solute diffusion process (Rahman and Lamb 1991). This type of membrane could be classified as differential permeable, rather than semi-permeable.

The potential advantages of this method of drying as compared with hot air drying or direct contact techniques are: less heat damage and enzymatic browning, better retention of flavour compounds and energy savings. On the other hand products cannot be dried to completion by this method and some means of stabilizing them is required to extend their shelf lives (Brennen 1989). Despite the large amount of research work that has been published in the area of osmotic processing, industrial scale applications are held back by fundamental issues, which have to be faced. Such issues include efficient, environment friendly solution management, microbiologic validation, and satisfactory process control.

2.1.1 Process variables effecting osmotic dehydration

Osmotic dehydration is affected by several factors such as the variety, pretreatment applied to food, chemical composition of the osmotic solution, solute concentration, solution temperature, immersion time, size, shape and tissue compactness of the material, the level of solution agitation (Sablani and Rahman 2003; Azoubel and Murr 2004). The effects of some important factors have been described in the following paragraphs.

2.1.1.1 Species, variety and maturity level of fruit

The differences in natural tissue structure due to difference in species, variety, and maturity level substantially affect diffusional mass exchange between product and osmotic medium. Not only different species, but also different varieties of the same species with different maturity levels have been found to give substantially different response to osmotic dehydration. The stage of maturity of vegetables to be dried is also an important factor. Dehydration of young carrot requires a longer period than for a more mature carrot. On the other hand, a carrot that has remained in the ground until the end of the season, and has become woody, will probably yield an unsatisfactory dehydrated product (Loesecke 2001).

2.1.1.2 Size and shape of fruit

Size and shape also played a significant role in mass exchange, since they result in different specific surface areas or surface to thickness ratio (Lazarides *et al* 1999). Lerici *et al* (1985) had reported that up to a certain total surface/ half-thickness ratio, sample of higher specific surface (i.e., rings) gave higher water loss and sugar gain values compared to lower specific surface shapes (i.e., slice and stick). Past this total surface/ half thickness ratio limit, however, higher specific surface samples (i.e. Cubes) favour sugar gain at the expense of lower water loss, resulting in lower weight reduction. The lowest water loss associated with the highest surface/ half-thickness ratio was explained as the result of reduced water diffusivity due to high sugar uptake.

2.1.1.3 Product pretreatment

Product pretreatments and process conditions affecting the integrity of natural tissue have a severe effect on mass exchange. Various researchers had reported that disruption of structural barriers due to product pretreatment improved water and solute diffusivities within the product, resulting in faster equilibrium in favour of higher solute uptake. Blanching, freeze/ thawing, sulfiting, acidification and higher process temperature all favour solid uptake yielding lower water loss/solute gain ratios (Ponting 1973; Biswal and Maguer 1989; Lazarides and Mavroudis 1995).

It was found that pretreatment step might be detrimental to osmotic dehydration process as it causes the death of living cells resulting in the loss of semi permeability of the cell membrane. A significant reduction in β-carotene of carrots during blanching was found by many investigators (Kalra e 1990; Walde *et al* 1992; Bao and Chang 1994b; Negi and Roy 2000).

2.1.1.4 Composition and concentration of osmotic solution

The osmotic solutions should be harmless, tasty, less costly, and highly soluble and should have low water activity (Lerici *et al* 1985). The molecular weight or ionic behavior of osmotic solution strongly affects the kinetics of water removal, the solid gain and the equilibrium moisture content. Several solutes, alone or in combinations, had been used in hypertonic solutions for osmotic dehydration. Based on effectiveness, convenience, and flavour, salt and sugar solutions proved to be the best choices. Sodium chloride was found an excellent osmotic agent for vegetables as it changes cell permeability but it has limited use for fruits due to salty taste (Hawkes and Flink 1978; Lerici *et al* 1985). Speck *et al* (1977) reported that salt treatment before air-drying significantly improved color, texture, flavor and carotenoid stability in dehydrated carrots. Sucrose, among saccharides, had been widely used for fruits as an osmotic agent as it prevents food discoloration to a large extent by enzymatic oxidative browning (Ponting 1973). Further, it imparted good taste to the final product; however, sweetness prevents it for vegetable processing (Farkas and Lazar 1969; Bolin *et al* 1983). Moreover, due to lower diffusivity, sucrose was absorbed less by the food materials (Lazarides *et al* 1995a; Karathanos *et al* 1995). Relatively little work was carried out on vegetables using sucrose-salt mixtures (Hawkes and Flink 1978; Biswal *et al* 1991; Sereno *et al* 2001b; Azoubel Murr 2004). Chopra (2001) found that addition of sodium chloride of 0.5 to 2.5 % in 70°B sugar solution during osmotic dehydration of carrot pieces reduced non-enzymatic browning during vacuum drying.

Several researchers also used other osmotic agents like calcium chloride, ethanol, fructose, corn syrup, invert sugar, lactose, and malt dextrin. Ponting *et al* (1966) reported that the osmotic pretreatment of apple pieces in solution calcium chloride increased firmness and preserved texture during storage. Laroche and Gervais (2003) osmotically dehydrated *Saccharomyces cerevisiae* by mixture of malt and glycerol. A number of researchers like Sereno *et al* (2001a) and Chenlo *et al* (2002) had investigated the physical properties of various osmotic solutions having different compositions, concentrations and solution temperatures.

Sodium metabisulphite could be added in the osmotic solution as it was found to be very effective in preserving the carotenoids content of dried carrots (Mohammed and Hussein 1994). It also protected the product from non-enzymatic browning or scorching during dehydration and increases the storage life of the product under adverse temperature conditions (Anonymous 1989).

2.1.1.5 Process temperature

Several researchers concluded that effect of temperature was more pronounced between 30 to 60°C for fruits and vegetables in the kinetic rate of moisture loss without affecting solid gain (Ponting 1973; Bongirwar and Sreenivasan 1977; Conway *et al* 1983; Biswal and Bozorgmehr 1992; Lazarides *et al* 1995a; Pokharkar and Prasad 1998; Panagiotou *et al* 1999). At high temperature damage of heat sensitive materials, tissue softening, enzymatic browning, loss of color, flavor and aroma would take place (Ponting 1966; Lenart and Flink 1984; Rahman and Lamb 1991; Shi and Maupoey 1993; Rastogi and Raghavarao 1995).

2.1.1.6 Duration of osmotic dehydration process

In general, with increase of time of osmotic dehydration, the weight loss increases with decreasing rate (Chaudhuri *et al* 1993). Azuara *et al* (1992) reported that typical osmotic dehydration runs require several hours to reach equilibrium and in some cases it is not possible to attain equilibrium due to biological and/or physical instability.

Most of the investigators worked on osmo-dehydration of fruits and vegetables and found an exponential nature of water diffusion with time during initial period varies from 2 to 4h depending upon nature of the solution and other conditions, after which solute started penetrating significantly (Hawkes and Flink 1978; Bolin *et al* 1983; Conway *et al* 1983; Biswal and Bozorgmehr 1992; Saurel *et al* 1994; Rastogi and Raghavarao 1995). It was also observed that further dipping helped in reaching equilibrium after 8 to 20h, which was characterized by an equality of soluble solids concentration in the product and the solution (Lenart and Flink 1984; Lazarides *et al* 1995a; Ertekin and Cakaloz 1996a).

2.1.1.7 Agitation/ circulation of osmotic solution

It had been reported by Bongirwar and Sreenivasan (1977); Azoubel and Murr (2004) that agitation of osmotic solutions reduced the mass-transfer resistance at the surface of the solids and to provide a uniform distribution of water removal, throughout the solution. Lazarides *et al* (1995a) reported that, thorough agitation had also been necessary for good mixing and close control of temperature in the osmotic medium. Saurel *et al* (1994); Ertekin and Cakaloz (1996a); Panagioutou *et al* (1998) agitated osmotic solution at 100-200 rpm and reported that agitation had a positive effect on the water loss and solid gain during osmotic dehydration and faster speed would result in decreasing the immersion time to reach equilibrium.

2.1.1.8 Osmotic solution and food mass ratio

It had been reported that, increase in the solution to fruit ratio increased osmosis rate up to certain limit and then levels off. Most workers used solution to product ratio of 4:1 to 5:1 in order to study mass transfer kinetics by following changes in concentration of solution and other factors (Islam and Flink 1982; Bolin *et al* 1983; Conway *et al* 1983; Lerici *et al* 1985; Beristain *et al* 1990; Rastogi and Raghavarao 1995; Ertekin and Cakaloz 1996 a and b; Pokharkar and Prasad 1998). A few studies had also been done by using higher ratio of 10:1 to 50:1 in order to avoid significant dilution of the medium due to uptake of water from samples and loss of solutes to the samples, and subsequent decrease of the osmotic driving force during the osmotic dehydration (Biswal *et al* 1997; Hawkes and Flink 1978; Saurel *et al* 1994; Lazarides *et al* 1995a).

Lenart and Flink (1984) reported 4:1 ratio for the optimal conditions of water loss, solid gain, change in water activity and economics from their study in potato cubes at different sugar concentration. Kar and Gupta (2001) reported that a salt-solution ratio of 6 was the best among the studied range of 4-8 for the osmo-air dehydration of button mushrooms. Singh (2001) osmosed carrots shreds in 50^0B sugar solution with 4:1 ratio for product preparation prior to hot air drying.

The work of some scientists on osmotic dehydration of fruits and vegetables in the past is sited below:

Andrzej (1991) evaluated the effects of osmo-dehydration (0-20 h in 61.5% sucrose solution, with mixing at 30°C) on reconstitution properties of Nantejska cv. carrots. Results indicated that osmotic dehydration reduced the rate and degree of rehydration, the water vapour adsorption rate and the equilibrium water content of the carrots, largely due to the sucrose levels in surface layers of the material, the extent of these effects being related to the degree of osmo-dehydration.

Bhuvaneswari *et al* (1999) studied osmotic dehydration of peas using solutions of 30% sucrose, 40% sucrose, 30% sucrose + 20% trisodium citrate and 40% sucrose + 20% trisodium citrate at temperature of 50-70°C for 30-120 min, under static and agitated conditions. Results indicated that the rate of osmosis increased with increasing solution concentration and temperature, and with agitation. Rehydration ratios of osmotically treated samples were higher than those of untreated samples. Sensory evaluation showed that the quality of treated air-dried samples was good compared with untreated dried samples.

Saputra and Tambunan (2001) studied the osmotic dehydration process of pie shape 7mm thick slices of fresh pineapple (Queen variety) in solutions of glucose and sucrose having 50, 60, and 70% concentration at 30, 50, and 70°C for an immersion time of 3, 6 and 9 hours. The highest mass transfer of pineapple was found by using sucrose at the concentration of 70%, temperature 50°C and 9 hr(s) of immersion time

Kowalska and Lenart (2001) performed osmotic dehydration of carrot cubes at 30°C in a 61.5% sugar solution. It was reported that the reduction of moisture content was 47 % during the first 30 min of osmotic drying and thereafter moisture loss proceeded more slowly. It had also been reported that, in all samples, rate of moisture loss during osmotic drying was 5-10 times higher than rate of solids gain, depending on the level of advancement of the drying process.

Pokharkar (2001) osmotically dehydrated green peas in 5, 10 and 17 % Sodium chloride solution at 20, 30 and 40°C. It was concluded that moisture loss and solute uptake in peas increased with increasing temperature and solution concentration. To assess the effects of osmotic drying in Sodium chloride solutions on sensory quality, green peas were dipped in 10% Sodium chloride at 30°C for 30 minutes and air-dried in a fluidized bed dryer. The dried product was reported to be acceptable based on colour, texture, flavour and overall acceptability scores.

Singh (2001) carried out the osmotic drying of carrot shreds in sucrose solution (50° B) at room temperature prior to drying in cabinet drier at 55 ±1° C. It was revealed that half of the initial moisture content was removed during the initial 30 min of osmosis; an additional 6 h were required to reduce the moisture content of the osmotically pretreated carrot shreds to 5.8%. For non-osmotically treated samples, drying time was 12 h at 55±1° C. Moisture sorption isotherm studies revealed that non-osmotically treated carrot shreds were more hygroscopic than osmotically dried samples, and required a lower RH for safe storage.

Torringa *et al* (2001) conducted the studies to investigate the added value of an osmotic drying step of mushrooms prior to combined microwave hot air drying. Halved mushrooms were osmotically dried in Sodium chloride solutions (10-20%) for 10-110 min at temperature of 20 and 45°C. Osmotic pretreatment resulted in up to 30% moisture content removal and a salt gain of up to 0.5 g Sodium chloride/g (dry matter basis). Microwave heating profiles of osmotically treated mushrooms demonstrated a shorter drying time as a result of the lower initial moisture content in samples. Due to osmotic dehydration, shrinkage in products was slightly reduced and rehydration properties were improved compared to non-osmotically dried samples and those dried by hot air treatment alone.

Ozen *et al* (2002) investigated the effect of salt (2-10%), sorbitol (0-10%) concentration, agitation (0-80 r.p.m.), fruit to solution ratio (1:3 to 1:6), and temperature (20-50°C) on weight loss, solids gain etc during osmotic dehydration of diced green peppers. Results showed that salt and sorbitol concentration and solution temperature were the most significant factors. In the first 30 minutes of the osmotic process, salt and sorbitol significantly increased weight loss, solids gain and decreased water activity. Agitation and fruit to solution ratio were less important.

2.2 Modeling of osmotic dehydration process

Some authors used models developed for flat plate geometry as defined by Crank (1975). In addition to Crank (1975) models, other equations had also been proposed for specific foodstuffs by Lenart and Flink (1984); Reyes *et al* (2002); Matteo *et al* (2003). Their major restriction was narrow applicability, besides the fact that they were derived from Crank's equation for a semi-infinite medium, carrying along its limitations. The works of few research workers on mathematical modeling of osmotic dehydration of foodstuffs are sited below:

Azuara *et al* (1992) developed a mathematical model based on mass balances to study the kinetics of osmotic dehydration. The equation obtained for water loss in terms of time is useful for any geometrical configuration. The model was successfully tested using published data on dehydration of apple by 51°Brix sucrose syrup or 50°Brix glucose syrup at ambient temperature; pineapple by 50°Bx sucrose at 30°C, and beef by glycerol/salt/sorbate at 85°C. Rastogi and Raghavarao (1995) proposed a semi-empirical relation for kinetics of osmotic dehydration of coconut, which indicated moisture diffusion as a function of concentration of osmotic solution and its temperature for coconut over a range of osmotic solution concentration (40-70°B) and temperature (25-45°C). A good agreement was observed between observed and predicted values. The model estimated effective diffusion coefficients of water and activation energy in coconut during osmotic dehydration. Yao and Maguer (1996) developed a mechanistic model based on physical parameters and does not contain empirical constants. It provided a mathematical description of physical characteristics of mass transfer changes in the cellular structure with time and position of concentrations, bulk flow-velocity, trans-membrane flux and shrinkage.

Spiazzi and Mascheroni (1997) developed a mathematical model in order to establish general rules about the variables affecting osmotic dehydration. Apple dehydration with polyethylene glycol was successfully simulated with the developed model. Good agreement between calculated and experimental results was also obtained when mass transfer and diffusion coefficient under different conditions were fitted to data obtained during potato dehydration. Waliszewski *et al* (1997) fitted the diffusion model for osmotic dehydration process to study the effects of temperature (50, 60 and 70°C), sucrose concentration (50, 60 and 70°Brix) and pH (6, 7 and 8) on the mass transfer during osmotic dehydration of banana chips. It had been reported that model gave apparent diffusivity values ranged from 2.77-to 2.65 x 10^{-9} m^2 s^{-1} depending on temperature and sucrose concentration but not on pH changes. The effect of syrup/product volume ratio on the mass transfer kinetics was also investigated.

Rastogi *et al* (1997) modeled the effective diffusion coefficient of water during osmotic dehydration using a cylindrical configuration of a banana at temperature of 25-35°C and osmotic solution concentration of 40-70°B. Effective diffusion coefficient were calculated using Fick's law for unsteady state mass transfer and Arrhenius equation was used to empirically correlate effective diffusion coefficient with temperature and concentration of the osmotic solution. Using this model, predicted and experimental values for effective diffusion coefficient gave a good level of agreement.

Similarly, Teixeria and Tobinaga (1998) proposed a diffusional model for water transport phenomena from inside the squid muscle. Viberg *et al* (1998) presented a simplified mathematical model in which the shrinkage factor was correlated to changes in weight for osmotic pretreatments of strawberries (cultivars Honeoye and Dania) in aqueous sucrose solutions (20-85% w/w) and granulated sucrose. The behavior of both types of strawberries was well described by the proposed model.

Nsonzi and Ramaswamy (1998) modeled the Kinetics of moisture loss and solids gain during osmotic drying of blueberries under different temperature (37-60°C), sucrose solution concentration (47-70°Brix) and contact time between fruit and sucrose solution (0.5-5.5 h), based on Fick's law of unsteady state diffusion. Based on the diffusion model, effective moisture diffusivity ranged from 1.98×10^{-10} to 5.10×10^{-10} m^2/s and effective solids diffusivity ranged from 2.54×10^{-11} to 2.22×10^{-10} m^2/s. They reported that both moisture and solute diffusivities increased with temperature and sucrose concentration, and could be modeled as quadratic functions of temperature and sucrose concentration.

Hernandez *et al* (2000) found analytical solution of mass transfer equation considering shrinkage of the food during drying. They reported that the activation energy calculated by considering shrinkage during drying was more than the values calculated with out shrinkage. Sereno *et al* (2001b) described the changes in moisture content and solids gain with time during the early stages of osmotic drying using a simplified diffusional model for apple (var. Golden Delicious) cylinders (length 24 mm; diameter 8 mm) immersed in osmotic solutions of sucrose (40, 50 and 60% w/w) and Sodium chloride (15, 22, 26.5 w/w). It had been reported that, in the case of Sodium chloride solutions, the same model was able to describe moisture transfer coefficient, but not transfer of Sodium chloride to samples, may be due to higher penetration of smaller molecules into apple tissue, particularly at high temperature.

Waliszewski *et al* (2002) analyzed the solute gain, weight and water loss of 6 mm thick pineapple slabs during osmotic dehydration in sucrose solution at different temperatures (50, 60 and 70°C), sucrose concentrations (50, 60 and 70°Bx) and pH's (6, 7 and 8). These results were fitted to a modified Azuara equation to obtain water and sucrose diffusivity results at equilibrium condition. Mean result of water diffusivity was 1.717×10^{-5} cm^2 s^{-1} and sucrose diffusivity varied from 2.0 to 4.6×10^{-5} cm^2s^{-1}. The results from mathematical modeling were compared to experimental results with R^2=0.94.

Ade-Omowaye *et al* (2002a) determined effective diffusion coefficient for water and solute using the slope method based on the Fickian diffusion model for osmotic drying of red paprika using a combined sucrose (5-45 g/100 g) and sodium chloride (0-15 g/100 g) solution. It was concluded that osmotic drying was influenced by sucrose and Sodium chloride concentration, and that the model equations developed for diffusion coefficients for water and solute and equilibrium moisture and solids contents could predict values close to experimental ones.

Vivanco *et al* (2002) modeled the effects of Sodium chloride (0-35.14 g/100 g water) and sucrose (1-100 g/100 g water) concentration on a_w, moisture content reduction, solute uptake kinetics and mass transfer during osmotic drying of tilapia (*Oreochromis niloticus*) fillets at 20°C in salt-sugar-water ternary solutions (solution to fillet ratio 4:1). Diffusion coefficients were modeled and good agreement was observed between theoretical and experimental values. It had been reported that Sodium chloride had a significant effect on fillet a_w, while sucrose exerted only a minimal effect. Sucrose promoted a reduction in water content and reduced Sodium chloride uptake.

2.3 Treatments after osmotic dehydration

Depending on raw material properties, osmotic solution characteristics and process parameters up to 70% of the initial water could be removed from a plant tissue by osmotic dehydration. The amount of water remaining in the material, however, does not ensure its stability, as water activity is generally higher than 0.9. When shelf stability is an ultimate process objective, other, complementary methods of water removal, such as convective drying, freeze drying, freezing etc are suggested (Brennen 1989; Lenart and Cerkowniak 1996). Few employed methods are briefly described below.

2.3.1 Hot air drying

The drying rates and effective diffusion coefficient of osmo air dried fruits using 50-70 °C were significantly decreased with the increase in solid gain during osmosis and increased with the drying temperature, the drying time to considerably reduced for the pretreated samples (Rahman and Lamb 1991, Karathanos *et al* 1995). Vijayanand *et al* (1995) optimized osmo-air drying of cauliflower at 40-90°C and found that optimum conditions were achieved at 80°C.

2.3.2 Vacuum drying

Osmotic dehydration followed by vacuum drying produces puffy products with a crispy, honey comb-like texture at low cost and also helps in retaining a bright, natural color and good flavor in comparison to freeze drying. It has also been observed that osmo-vac foods can be produced without using SO_2 or other means of enzyme inactivation (Ponting *et al* 1966; Ponting 1973; Bongirawr and Sreenivasan 1977; Chopra 2001; Erle and Schubert 2001). Dixon and Jen (1977) reported that the flavour retention in case of osmovac drying was more than of freeze-drying. Chopra and Verma (1994) and Livtin *et al* (1998) also studied osmo-vac drying of the cylindrical shaped carrot pieces. Osmo-vac foods are stable in storage and lasts longer at least a year at room temperature and three years or more at 1°C (Ponting, 1973).

2.3.3 Freeze drying

The combination of osmotic dehydration with freeze-drying is economically viable only at laboratory scale. Owing to the solid gain and the volume reduction of the dehydrated products, there is a three-fold increase in the freeze dryer load and the process yield. An increase of up to 25 % of the soluble solids content greatly improves the retention of volatiles (Flink 1979; Lerici *et al* 1985; Hawkes and Flink 1978).

2.3.4 Fluidized bed drying

Walde *et al* (1992) reported that fluidized bed drying is unsuitable for the pretreated diced carrots, potatoes etc. because of their natural characteristics viz. coarse size and sticky particles.

2.3.5 Freezing

A reduction in moisture content of the material by partially concentrating prior to freezing has certain advantages: savings in packaging, shipping and storage costs; reduction in thawing and drip losses; and increased plant capacity. The products obtained are termed as 'dehydrofrozen' (Farkas and Lazar 1969; Biswal *et al* 1991).

2.4 Effect of osmotic dehydration on colour of product

Colour is the major appearance attribute of most foods and as such is an important characteristic of food quality. The major causative factor of colour in most foods is the presence of a broad array of natural pigments like flavonoids (anthocyanins and flavonoids), chlorophylls, caroenoids, and betalaines, while those in meats are based upon hemoglobin. There are some notable exceptions, such as carmelization and browning reactions that occur in many foods. The affects of osmotic dehydration on color of fruits and vegetables are discussed below.

Waliszewski *et al* (1999) investigated the effects of sucrose concentration (50, 60 and 70°Brix), temperature (50, 60 and 70°C) and pH (6, 7 and 8) on colour (L, hue, chroma and total difference) of banana slices during a 4 h osmotic drying process. Statistical analysis of L, hue and chrome changes in banana slices indicated that the following five treatments were most suitable for producing fruit similar in color to the raw material: 50°B, 70°C and pH 6.0; 60°B, 50°C and pH 6.0; 60°B, 70°C and pH 7.0; 60°B, 60° C and pH 8.0; and 70°B, 50°C and pH 8.0.

Bawa and Gujral (2000) conducted experiments on osmo- convective dehydration of grapes in sucrose solution and honey to produce raisins. The sensory scores indicated that the honey-treated samples gave better flavour while sugar-treated ones gave better colour (appearance) and overall acceptability. Krokida *et al* (2000) investigated the effects of various pre-treatments viz. osmotic, microwave, sulphite, water blanching and steam blanching on the three Hunter colour parameters lightness (L), redness (a) and yellowness (b) of apple, banana, potato and carrot during subsequent drying. Osmotic, sulphite, and water- and steam-blanching suppressed browning during drying, resulting in constant, or only slightly increased, L, a, and b values.

2.5 Effect of osmotic dehydration on texture of product

From the textural standpoint, vegetables represent a very diversified group of products. In the form in which they are consumed, they can be hard and crisp (raw carrots); firm, crisp, and juicy (cucumber); soft and mealy (cooked peas); soft, pulpy, and fibrous (cooked asparagus). The textural properties of vegetables are affected largely during processing. Bidaisee and Badrie (2001) investigated the effects of soaking the cashew apple fruit in 5% Sodium chloride solution (A), 10% Sodium chloride solution (B) or without Sodium chloride solution (C). Subsequently, osmotic dehydration of the fruits was accomplished in 30°Brix sucrose syrup, increased by 10°Brix daily to 70°Brix, followed by convection drying at 60°C for 48 h. It was concluded that the effect of brining pre-treatment was significant on texture, with resultant firmer textured candied products. Pre-treatment C (no brine) had significantly higher sensory scores for texture and was rated highest for acceptability.

2.6 Methods to increase efficiency of osmotic dehydration

Osmotic dehydration is relatively slow process. Therefore, acceleration of mass transfer would be advantageous. Application of vacuum during osmotic dehydration, high pressure, High intensity electrical field pulse (HELP) could increase mass transfer rates during osmotic dehydration due to increased permeability of plant cells (Rastogi *et al* 1999; Tedjo *et al* 2002). The brief description of works to increase mass transfer during osmotic dehydration of few research workers are sited below

Fito (1994) carried out osmotic dehydration of foods at 8-20°C lower than conventional procedures by applying alternating pressures to improve exchanges of water and solutes between the foods and surrounding medium. Air was removed from pores in the food by vacuum, and pressure is applied to pump the solution into the pores. It was concluded that the resulting foods have better taste, aroma and nutritional quality than conventionally treated foods and the osmotic dehydration was 2-4 times faster than conventional methods.

Simal *et al* (1998) investigated the effect of ultrasound on osmotic drying of apple cubes of size 1cm^3 in 70°Brix sucrose solution at 40, 50, 60 or 70°C. When samples were sonicated, water transport was dependent on temperature with water diffusivity coefficient ranging from 2.6 x 10^{-10} m^2/s at 40 ° C to 6.8 x 10^{-10} m^2/s at 70°C. In contrast, sucrose gain was constant at different temperature and average effective sucrose diffusivity coefficient was $7.9 \pm 0.2 \times 10^{-11}$ m^2/s. In addition, ultrasound had no effect on the flavour, colour and heat-labile components of apples.

Rastogi and Niranjan (1998) applied high pressure pretreatment (100-700 MPa) to enhance mass transfer rates during osmotic drying of pineapples and a 4-fold increase of water diffusivity and 2-fold sugar diffusivity. The increase was attributed to breaking-up of cells walls, which facilitated the transport of water. Rastogi *et al* (1999) tested High intensity electrical field pulse (0.22 to 1.60 kV/cm) pretreatment to accelerate the osmotic dehydration of carrot with sucrose solution. The rise in effective diffusion coefficient might be attributed to an increase in cell wall permeability, facilitating transport of water and solute.

Escriche *et al* (2000) studied Pulsed-Vacuum-Osmotic-Dehydration of kiwifruit (Actinidia chinensis) using sucrose (65°B) and concentrated grape juice (63°B), at 25, 35 and 45°C and vacuum pulse times of 0, 5, 10 and 15 minutes. The impregnation of samples, because of the vacuum pulse, was higher when concentrated grape juice was used as the osmotic solution, probably due to its lower viscosity. Rastogi *et al* (2000a) reported that high pressure (HP) processing of foods has a damaging effect on cell walls, which increases their permeability, resulting in increased mass transfer rates during subsequent osmotic drying.

Ade-Omowaye *et al* (2002b) studied the effects of high-intensity electric field pulse treatment (HELP) and elevated osmotic solution temperature on mass transfer and nutrients composition of bell peppers (Capsicum annuum) during osmotic dehydration. It was concluded that HELP enhanced mass transfer rate during osmotic dehydration. Diffusion kinetics obtained at 2.5 kV/cm were comparable to those achieved at elevated temperature up to 55°C. Results suggested that HELP was an effective technique for enhancing mass transfer during osmotic dehydration of bell peppers. Taiwo *et al* (2002a) studied the effects of high intensity electric field pulses (20 pulses at 48 J/kg for 400 mus/pulse) and osmotic drying (50% sucrose solution, 4 h immersion) on rehydration behaviour, texture and colour of apples (*cv. Jonagold*) discs. It was observed that rehydration capacity of samples subjected to HELP + osmotic dehydration was 10-30%

higher than that of samples subjected to osmotic dehydration alone.

2.7 Rehydration kinetics and shrinkage

Rehydration is a complex phenomenon that involves different physical mechanisms such as internal diffusion, convection at surface and within large open pores, and relaxation of the solid matrix. Structural and chemical changes, food preparation, and food composition influence the rehydration process (McMinn and Magee 1997). During rehydration water moves inside the food material and soluble solids are lost and porosity also gained. The study of the rehydration kinetics, as a quality indicator, could be used to optimize the dehydration process.

The study of the rehydration behavior of different products has recently been a subject of interest for various investigators. For example, grapes (Gabas *et al* 1999), Nameko and shitake (Kalbarczyk and Widenska 2000), carrots (Ramos *et al* 1992; Reyes *et al* 2002), vegetables like potato, carrots, celery and parsley roots (Bobic *et al* 2002), osmotically dehydrated pineapple (Rastogi *et al* 2000b), Maharaj and Sankat 2000 (dasheen leaves) and brocolli florets (Sanjuan *et al* 2001). These researchers had used different process parameters like time of immersion and temperature of water.

2.8 Equilibrium moisture content, packaging and storage of dehydrated product

Knowledge of sorption characteristics is essential for designing complementary process (i.e. convection, vacuum or freeze dehydration), assuring proper rehydration characteristics and for determination of packaging requirements to provide a desired shelf life (Lazarides *et al* 1999). Literature on sorption isotherms study of grains and dehydrated fruits and vegetables is available. For example, mushroom (Pandey and Aich 1989), pumpkin seeds (Akritidis *et al* 1988), strawberries (Moraga *et al* 2004), cauliflower and banana (Kechaou and Maalej 1999). Despite the large volume of work on osmotic pretreatment, publications on sorption characteristics of osmotically dehydrated products are rather limited (Menkov 2000; Uzman and Sehbaz 2000 and Prothon and Ahrne 2004).

Increased shelf life and quality improvement due to in-package desiccation accomplished by packaging the dehydrated vegetables in a hermetically sealed container with a quantity of desiccant sufficient to absorb substantially all of the residual moisture in the product had been reported by Loesecke (2001). The preferred desiccant is Calcium Oxide because of its high moisture absorption capacity at low RH of from 1 to 5% (Loesecke 2001). The works of few scientists on EMC, packaging and storage of dehydrated products was sited below:

Sagar (2001) produced onion powder by osmotic drying of onion slices of 5 mm thickness in salt solutions (5, 10, 15 and 20%) for 6 h prior to drying in a cabinet drier at 60°C for 10 h. The effects of various packaging materials (HDPE and LDPE; 200 and 400 gauge) on their storage stability at room temperature (18-35°C; 50-60% RH) or low temperature (7° C; 85% RH) up to 6 months were also studies. 15% salt solution was found to be the optimal osmotic treatment for dried onion quality. At low storage temperature, all onion powder samples were of acceptable quality after 6 months of storage regardless of the packaging material used. At low temperature, shelf life and pungency was highest in powders stored at 7°C in 200 gauge HDPE pouches, next highest was samples in 400 gauge LDPE pouches followed by those in 200 gauge LDPE pouches. For onion powder with 3.85% moisture content, optimal storage RH was 47.5

Park *et al* (2001) obtained desorption isotherms at 40, 60 and 80°C for fresh and osmotically dehydrated pears (cv. d'Anjou) in 55°B at 40°C for 120 min. Henderson model provided the best fit to the data. However, desorption isotherms for dried pears at 80°C were modeled closest by the Oswin model and isotherms for fresh pears at 40°C by the GAB model.

2.9 Application of response surface methodology for process optimization

The response surface methodology (RSM) has proved to a very useful tool in product design. In RSM, tests are performed using different combinations of levels of the experiments according to the predetermined design, and an appropriate data is fitted to the data by the method of least squares. Three-dimensional plots provide a useful visual aid for checking the adequacy of the model and for examining the response surface and location of the optimum. RSM is reported to be an efficient tool for optimizing a process when the independent variables have the joint effect on the responses (Mudahar *et al* 1989). Madamba and Lopez (2002) performed response surface methodology (RSM) to analyze and predict the optimum conditions of osmotic dehydration process of mango (Mangifera indica) slices using 4 treatment variables: treatment time, temperature, sugar concentration and slice thickness. The effects of low temperature long-time blanching of diced jalapeno pepper prior to freezing on extrusion force, colour and pH of the product were evaluated and optimized by response surface methodology (Ramos *et al* 1998). Similarly, Ibanoglu and Ainsworth (2004) applied RSM for studying the viscosity changes during canning of tarhana, a cereal based food. Rai *et al* (2004) optimized pectinase usage in pretreatment of mosambi juice for clarification by RSM. Floros and Chinnan (1987, 1988) applied RSM for optimization of lye peeling process for pimiento peppers.

CHAPTER III

MATERIALS AND METHODS

The work presented in this chapter was undertaken to study the effect of various pre-treatments on osmo-convective dehydration and the quality of the carrot cubes. The effects of packaging materials on storability at different temperature conditions of dehydrated carrot cubes were also investigated. The experiments were conducted in the Laboratories of Department of Processing and Food Engineering, Punjab Agricultural University, Ludhiana from October 2003 onwards. The following is the list of the experiments, which were conducted to fulfill the desired objectives:

1. Study of osmotic dehydration kinetics of carrot cubes in solutions of different osmotic agents having different concentrations, temperatures and solution to fruit ratios.
2. Optimization of osmotic dehydration process parameters for each osmotic agent used for osmotic dehydration of carrot cube.
3. Convective dehydration characteristics of osmosed and un-osmosed carrot cubes at different drying air temperatures.
4. Effect of addition of $CaCl_2$ in osmotic solution on drying behavior, textural strength and shrinkage of the rehydrated product.
5. Effect of step-drying on drying behaviour of carrot cubes
6. Impact of osmotic dehydration on water sorption isotherms on dehydrated product
7. Study of rehydration kinetics of dehydrated product.
8. Study on processing of carrot juice extracted from the left over material of carrot cubes.

9. Osmo-convective dehydration of carrot pomace and its subsequent use for preparation of gazrella.
10. Packaging and storage of dehydrated product in different packaging materials at different storage temperatures

The detailed description of materials and methods is as follow:

3.1 Study of osmotic dehydration kinetics of carrot cubes

3.1.1 Various steps for experimentation of osmotic dehydration kinetics

3.1.1.1 Procurement of raw materials

Fresh well-graded, carrots of locally grown variety Viz. Local Red were procured from the local market on daily basis prior to each set of experiments. The weight of individual carrot varied between 40-70 g, the diameter between 2-3 cm and lengths between 15-20 cm.

3.1.1.2 Peeling and removal of green parts

After washing, peeling was accomplished manually by stainless steel hand peeler. The green parts of carrots (if any) were removed with the help of stainless steel knife, to retain the final quality of the product. The peeling losses were varied from 17-20%.

3.1.1.3 Dicing of carrots

A vegetable dicer (Fig 3.1) designed and fabricated in the department was used to prepare carrot cubes of dimensions 1 cm x 1cm x 1 cm (Fig 3.2). The carrot cubes were washed with fresh water to remove the carrot fines adhered to the surface of the fruit. The left over material of carrot cubes was separated manually and was used for the juice extraction. The carrot pomace (residue after extraction of juice) was also dehydrated osmo-convectively and was further used for preparation of gazrella. The recovery of carrot cubes varied from 40-46% depending on the size of fresh carrots. The percentage of left over of carrot cubes varied from 32-36%.

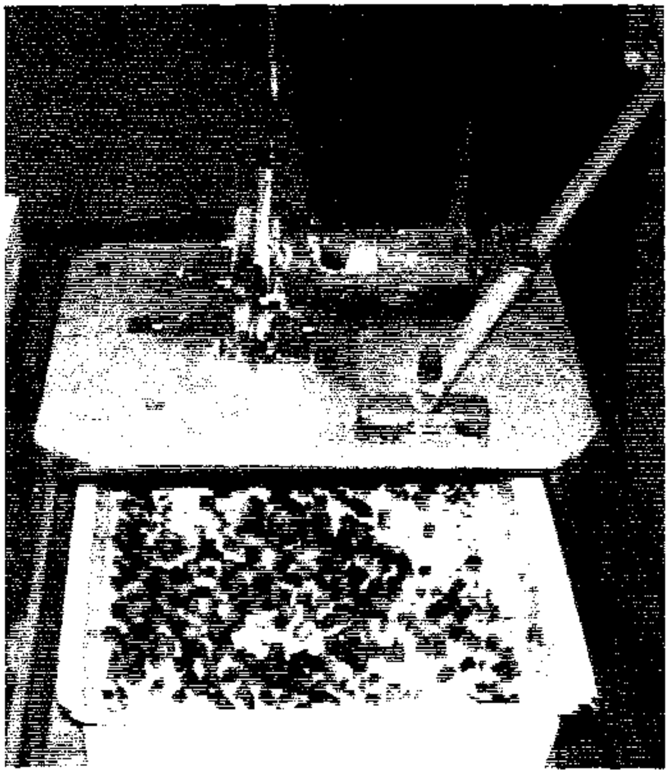
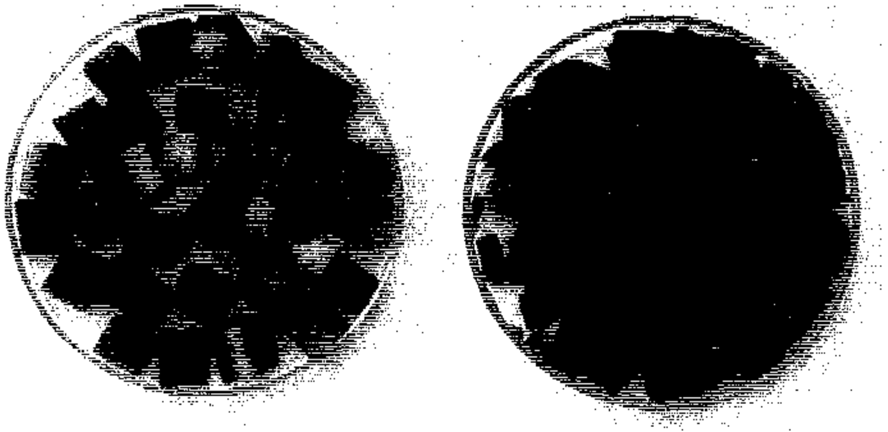


Fig 3.1 Manually operated carrot dicer.



CARROT CUBES

LEFT MATERIAL OF CUBES

Fig 3.2 Carrot cubes and left over material of carrot cubes

3.1.1.4 Osmotic dehydration of carrot cubes

Osmotic dehydration of unblanched carrot cubes was done in solutions of different osmotic agents (viz. salt, sugar and their combination) having different concentrations (5, 10 and 15% for salt solution; 45, 50 and 55°B for sugar solution; 50°B+5%, 50°B+10% and 50°B+15% salt for sugar-salt mixture solution), solution to fruit ratio (4, 5 and 6) and processing temperatures (35, 45 and 55°C). Sodium Meta bisulphite (0.3%) was also added to the each osmotic solution. The temperature of the osmotic solution was maintained by hot water bath agitating @ 52 oscillations per minute. Agitation was given during osmosis for reducing the mass transfer resistance at the surface of the fruit and for good mixing and close temperature control in osmotic medium (Karel 1976, Bongirwar and Sreenivasan 1977, Mavroudis *et al* 1998a and b; Chopra 2001). Stainsless steel containers (of approximately 150 ml capacity) containing osmotic solution were kept in hot water bath (Fig 3.3). After attainment of desired temperature of the solution, the carrot cubes of any known weight (15-18 g) were put in to the container.

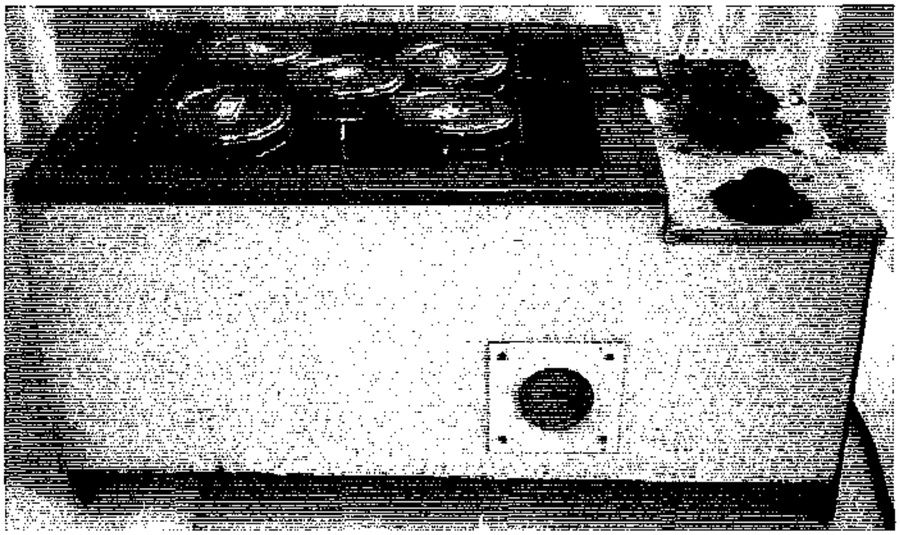


Fig 3.3 Experimental set up to study osmotic dehydration of carrot cubes.

The volume of different known weights of carrot cubes was measured by water displacement method and the following equation was developed to maintain the desired solution to fruit ratio for each experiment.

Volume of carrot cubes = 0.993 * weight of carrot cubes – 0.5211 (3.1)

To study osmotic dehydration kinetics of carrot cubes, the experimental design used was face-centered central composite design (CCF). This design is one of the three types of Box-Wilson Central Composite designs. The process variables used for osmotic dehydration kinetics of carrot cubes were solution concentration (5, 10 and 15% for salt s; 45, 50 and 50°B for sugar; and 50°B+5, 50°B+10 and 50°B+15 for sugar-salt mixture solution), temperature (35, 45 and 55°C) and solution to fruit ratio (4, 5 and 6). This design required three levels for each independent variable. Three different Levels for each experiment in coded form are -1, 0, +1. Where,

$$Coded\ \ value = \frac{(Un\ \ Coded\ \ Value - Central\ \ Value)}{(Interval\ \ between\ \ two\ \ successive\ \ Intervals\ \ )}$$

Total No. of experiments = 2 No. of variable +2*No of variables + Central points

Total No. of experiments $=2^3+2*3+6=20$

Instead of six experiments central point experiments, only one experiment was conducted. The detailed description of performed experiments for different osmotic agents was as given below in the Table 3.1.

Table 3.1 Experimental plan for study of osmotic dehydration kinetics of carrot cubes

Coded process variables			Un coded process variables				
Conc.	Temp	STFR	Solution Concentration			Temp (°C)	STFR
			Salt(%)	Sugar(°B)	Sugar-salt		
+1	+1	+1	15	55°B	50°B+15% salt	55	6
-1	+1	+1	5	45°B	50°B+5% salt	55	6
+1	-1	+1	15	55°B	50°B+15% salt	35	6
-1	-1	+1	5	45°B	50°B+5% salt	35	6
+1	+1	-1	15	55°B	50°B+15% salt	55	4
-1	+1	-1	5	45°B	50°B+5% salt	55	4
+1	-1	-1	15	55°B	50°B+15% salt	35	4
-1	-1	-1	5	45°B	50°B+5% salt	35	4
+1	0	0	15	55°B	50°B+15% salt	45	5
-1	0	0	5	45°B	50°B+5% salt	45	5
0	+1	0	10	50°B	50°B+10% salt	55	5
0	-1	0	10	50°B	50°B+10% salt	35	5
0	0	+1	10	50°B	50°B+10% salt	45	6
0	0	-1	10	50°B	50°B+10% salt	45	4
0	0	0	10	50°B	50°B+10% salt	45	5

The carrot cubes from each container were removed after a regular interval of between 0-240 minutes and were immediately rinsed with running water to remove the solute adhered to fruit surface. The cubes were then put in to the measuring cylinder containing known quantity of water for the measurement of fruit volume. The carrot cubes were then spread on absorbent paper to remove the free water from the outer surface of the fruit. The cubes were then put in the pre-weighed petridish for determination of dry matter by oven method. Similarly, 10 ml of osmotic solution was put in pre-weighed petridish for the determination of total solids by oven method. The water loss and solute uptake was measured by gravimetric method.

During experimentation, it was assumed that the amount of solid (sugars, acids, minerals, vitamins) leaching out of product into the medium, although recognized as affecting the organoleptic and nutritional characteristics of the product, was considered quantitatively negligible (Biswal and Bozorgmehr 1992; Singh *et al* 1999).

3.1.2 Calculation of water loss and solute gain during osmotic dehydration process

Let initial dry matter of fresh fruit $= Z\,\%$

Initial weight of fruit taken for osmotic dehydration $= W_o$ (g)

$\therefore$ Initial dry matter of fruit $= \frac{W_o * Z}{100} = So$ (say)

Let the weight of fruit after osmotic dehydration for any time t $= W_t$ (g)

And let the dry matter of fruit after osmotic dehydration for time t $= S_t$ (g)

Then

Weight Reduction $= WR = W_o - W_t$ (g)

Solute Gain after osmotic dehydration for time t $= SG = S_t - S_o$ (g)

Water Loss $= WL = WR + SG$

Water loss in g/100 g Fresh Fruit $= \frac{WL}{W_o} * 100$

Solute gain in g/100g Fresh Fruit $= \frac{SG}{W_o} * 100$

The Performa for the various observations to be recorded during experimentation along with the sample calculations for osmotic dehydration kinetics is given in Appendix-A.

In case of osmotic dehydration with combined sugar and salt solution, the salt contents of solution and fruit were determined by Mohr's method.

3.1.3 Calculation of effective diffusivity of water and solute during osmotic dehydration process

The effective diffusivity of water and solute was calculated by using the analytical solution of Fick's un-steady state equation for slab geometry being placed in an agitating liquid medium as given by Crank (1975). The equation was solved for effective diffusivity by a computer program as given in Appendix-B. The average apparent diffusion coefficient was calculated by equation $D_{avg} = \frac{\sum_{1}^{n} D_t}{n}$.

Where n is the number of data points used only for positive values of D.

3.1.4 Validation of empirical models for osmotic dehydration of carrot cubes

The validity of following empirical models was checked by non-linear regression technique to predict the kinetics of water loss and solute gain of osmotic dehydration process.

i) Power Law model MR or SGR = $K^* t^N$

ii) Page model MR or SGR = $\mathrm{Exp}(-K^* t^N)$

iii) Newton (Lewis) model MR or SGR = $\mathrm{Exp}(-K^* t)$

iv) Generalized Exponential model MR or SGR = $A^* \mathrm{Exp}(-K^* t)$

Where MR = Moisture Ratio = $\frac{(M_t - M_e)}{(M_o - M_e)}$

SGR = Solute Gain Ratio = $\frac{(C_t - C_e)}{(C_o - C_e)}$

v) Penetration model $WL(\%)\ or\ SG(\%) = K * \sqrt{t}$

vi) Magee Model $WL(\%)\ or\ SG(\%) = A + K * \sqrt{t}$

A= Model parameter or Shape factor

and K=Rate Constant

vii) General Model

MR or SGR or WL or SG = $A*(Conc.)^{B}*(Temp)^{C}*(Ratio)^{D}$

All these models are derived from Fick's second law of diffusion with different boundary conditions. Page, Newton and GEM Models are based on the concept that a concentration gradient exists between the surface and centre of the sample, which induce mass transfer during processing. Whereas Power, Penetration and Magee models are based on the idea, that concentration changes only near the surface of the sample (Rahman 1992). Number of authors studied the spatial distribution of solute in the sample to give a clear idea about the kinetics. All experimental evidence indicated that the solute concentration exists only near surface of the sample and thus justifies the basis of Power, Penetration and Magee models (Rahman 1992). The drying constant will depend on the type and properties of the osmotic solute and food, geometry of the food and process conditions, such as concentrations, temperature, agitation and syrup to fruit ratio.

Azuara *et al* (1992) developed a model from mass balance considerations to predict the kinetics and final equilibrium point of osmotic dehydration by using data obtained during relatively short period of osmosis. The model could characterize osmotic dehydration of different types of foodstuffs without restrictions of geometric considerations. The other published models (Lenart and Flink, 1984; Beristain *et al* 1990; Biswal *et al* 1991; Ertekin and Cakaloz, 1996a; Pokharkar and Prasad, 1997, 1998) for osmotic dehydration were usually specific to processing conditions and geometric considerations. The model proposed by Azuara *et al* (1992) was of the following form

$$WL_t = \frac{\beta_1 t(WL_\infty)}{1+\beta_1 t} = \frac{(WL_\infty)\,t}{\frac{1}{\beta_1}+t} \tag{3.2}$$

$$SG_t = \frac{\beta_2 t(SG_\infty)}{1+\beta_2 t} = \frac{(SG_\infty)\,t}{\frac{1}{\beta_2}+t} \tag{3.3}$$

Where β_1 and β_2= Constants related to the rates of water or solids diffusion out or in the carrots respectively, min $^{-1}$.

The equations (3.2) and (3.3) indicate that $\frac{1}{\beta_1}$ or $\frac{1}{\beta_2}$ represent the time required for half of the diffusible matter (water or solids) to diffuse out or in the product respectively. Further, as the time, t, becomes much greater than the values of $\frac{1}{\beta_1}$ or $\frac{1}{\beta_2}$, (that is, $t \to \propto$), the water loss or the solid gain WL_t or SG_t, approaches equilibrium value, WL_∞ or SG_∞, asymptotically.

Equation (3.2) and (3.3) can be linearized in the following form

$$\frac{t}{WL_t} = \frac{1}{WL_\infty}(t) + \frac{1}{\beta_1 WL_\infty}$$

This is an equation of straight line between t and $\left(\frac{t}{WL_t}\right)$ having

$$Slope = \frac{1}{WL_\infty}$$

$$and \ \ Intercept = \frac{1}{\beta_1 WL_\infty}$$

Similarly $\frac{t}{SG_t} = \frac{1}{SG_\infty}(t) + \frac{1}{\beta_2 SG_\infty}$

It is also an equation of straight line between t and $\left(\frac{t}{SG_t}\right)$

Where $SG_{\infty} = \frac{1}{Slope}$

$and\ \ Intercept = \frac{1}{\beta_2 SG_{\infty}}$

So, if the experimental plots of $\left(\frac{t}{WL_t}\right)$ vs. t and $\left(\frac{t}{SG_t}\right)$ vs. t were to show linearity, the parameter values could be determined from the intercept and the slope. Higher values of β's indicate a higher diffusion of material per unit of time. The model equations (3.2) and (3.3) could then be used to predict the mass transfer kinetics

The equation that gives the best fit to the experimental data is selected as the function that will characterize the osmotic dehydration process.

3.2 Design of experiments for optimization of osmotic dehydration process

For the optimization of osmotic dehydration process for each osmotic agent, the experiments were conducted according to Central Composite Rotatable Design (CCRD) (Khuri and Cornell 1987) with three variables at five levels each. The variables were process temperature, solute concentration and duration of osmotic dehydration process. The solution to fruit ratio was kept 6 for salt solution and 5 for both sugar as well as for combination of sugar and salt solution (Simal *et al* 1997a and b; Pokharkar and Prasad 2002; Kar and Gupta 2001,2003; Azoubel and Murr 2004). For each experiment, the carrots were washed, peeled and diced in to 1cm x 1cm x 1cm size. After manual separation, the carrot cubes were washed in water to remove the carrot fines adhered to the surface of the cubes. No blanching was done prior to osmosis as it has been reported to be detrimental to osmotic dehydration process due to loss of semi-permeability of cell membrane (Ponting 1973) and reduction of β-carotene (Kalra 1990, Bao and Chang 1994, Negi and Roy 2000). Salt solution was chosen for osmosis, as it is an excellent osmotic agent for vegetables retarding oxidative and non-enzymatic browning (Jackson and

Mohammed 1971; Arya *et al* 1979) and the sugar was used to prevent bleaching effect of salt (Jackson and Mohammed 1971). Sodium metabisulphite (0.3%) was added to help retain carotenoids content of dried carrots (Mohammed and Hussein 1994) and to increase the storage life of products under adverse temperature conditions (Anonymous 1989).

The details of concentrations and processing temperatures of different osmotic solutions are given in the Table 3.2 and 3.3.

Total number of experiment $= 2^{\text{No of Variables}} + 2\text{x No of variables} + \text{Central Points}$

For three variables

Total No. of experiments for each solute $= 2^3 + 2\text{x}3 + 6 = 20$

Five different Levels for each experiment in coded form are

$-\alpha, -1, 0, +1, +\alpha$

Where $\alpha = 2^{\text{No. of variables} / 4} = 2^{3/4} = 1.682$

$$\textit{Coded value} = \frac{(\textit{Un Coded Value} - \textit{Central Value})}{(\textit{Interval between two successive Intervals})}$$

The experiments plan in coded and un-coded form of process variables is as given in Tables 3.2 and 3.3, respectively. The experiments were conducted randomly.

For each experiment, known weight of carrot cubes was put in stainless steel containers (of capacity 1200 ml each) having calculated volume of osmotic solution of different concentrations pre set at the desired temperature by agitating hot water bath. The temperature of the osmotic solution was maintained by hot water bath agitating @ 52 oscillations per minute (Fig 3.3).

The carrot cubes were removed from the container at the specified time and rinsed with water to remove the solute adhered to the surface. The osmotically dehydrated cubes were then spread on the absorbent paper to remove the free water present on the surface. Then out of the total fruit, about 12-15 g sample was put in the pre weighed petridish for determination of dry matter by oven method. The remaining part of the sample was dried in perforated sieves of size 18 cm x 10 cm x 2cm to final moisture of 5% (wet basis) in hot air drier pre set at 65°C air temperature and 1.6 m/s air velocity (Andrzej 1991). The pieces of size 18cm x10 cm were removed from a thermocol sheet to exactly fit the sieves for the effective utilization of hot air in the drier. The dried samples were cooled in a desiccators containing silica gel for one hr, packed in HDPE bags and kept at ambient temperature for quality analysis.

Table 3.2 Experimental design in coded form of process variables for optimization of osmotic dehydration process.

Process variable			Responses				
Conc (X_1)	Time (X_2)	Temp (X_3)	Water loss	Solute gain	Rehydration ratio	Shrinkage (%)	Overall acceptability (%)
-1	-1	-1					
1	-1	-1					
-1	1	-1					
1	1	-1					
-1	-1	1					
1	-1	1					
-1	1	1					
1	1	1					
-1.682	0	0					
1.682	0	0					
0	-1.682	0					
0	1.682	0					
770	0	-1.682					
0	0	1.682					
0	0	0					
0	0	0					
0	0	0					
0	0	0					
0	0	0					

Table 3.3 Experimental design in un-coded form of process variables for optimization of osmotic dehydration process.

Type of Osmotic agent	Concentration (%) or °Brix					Temp (°C)					Time (minutes)				
Salt	1.6	5	10	15	18.4	23.8	30	40	50	56.8	69.5	90	120	150	170.5
Sugar	46.6	50	55	60	63.4	28.2	35	45	55	61.8	79	120	180	240	281
Sugar – salt mixture	50°B + 1.59 %	50°B + 5%	50°B + 10%	50°B + 15%	50°B + 18.4%	28.2	35	45	55	61.8	79	120	180	240	281

The process conditions for osmotic dehydration were optimizes by Response Surface Methodology for various quality parameters like water loss in g/100g FF, solid gain in g/100g FF, rehydration ratio, shrinkage (%) and overall acceptability of rehydrated product.

The Performa for the various observations to be recorded during experimentation along with the sample calculations for osmotic dehydration process is given in Appendix-C.

3.3 Convective dehydration of carrot cubes

3.3.1 Convective dehydration of osmotically dehydrated carrot cubes

The convective dehydration was carried out at different drying air temperatures after osmotic dehydration of samples at optimum values of various process parameters.

For each experiment, about 150g of carrot cubes were osmotically dehydrated in solutions of different osmotic agents at their respective optimum conditions. After osmotic dehydration, the fruits were washed in water to remove the solute adhered to the fruit surface and were spread on the absorbent paper to remove the free water present on the surface. Then out this, about 12-15 g sample was put in the pre weighed petridish for determination of dry matter by oven method. The remaining sample was convectively dehydrated in perforated sieves (18cm x 10 cm x 2 cm) at 55, 65 and 75° C temperature with an air velocity of 1.6 m/s (Fig 3.4). The samples were placed in thin layer. The weights of the sieves along with fruit sample were recorded at regular interval of time until the final moisture content reduces to 4-5% (wet basis). The dried samples were cooled in a desiccators containing silica gel for one hr, packed in HDPE bags and kept at ambient temperature for quality analysis.

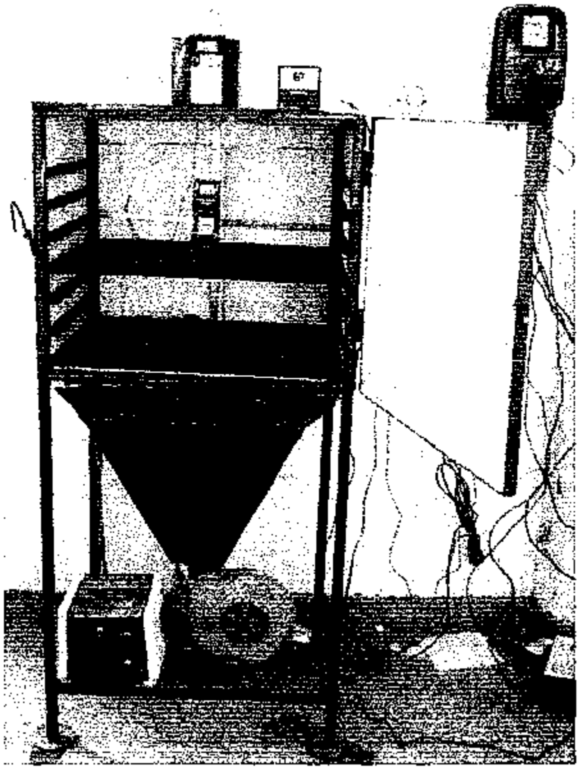


Fig. 3.4 Cabinet (Tray) dryer with airflow through the product for convective dehydration.

3.3.2 Convective dehydration kinetics for un-osmosed carrot cubes

Procurement of raw material, washing, peeling, removal of green parts and dicing of carrots was done as explained in section 3.1.1.1 to 3.1.1.3 followed by following steps.

3.3.2.1 Blanching of carrot cubes

Blanching is a critical step in the processing of fruits and vegetables due to the changes it causes such as enzyme inactivation, air removal and leaching of nutrients. Blanching minimized enzymatic reaction, although loss of carotenoids and texture of the product were observed as a function of the blanching conditions (Roy *et al* 2001). Hass *et al* (1974) informed that blanching also improves the rehydration characteristics of carrots, especially if it incorporates certain additives. The carrots cubes were blanched in hot water (near boiling water) for 3 minutes to inactivate enzymes. The optimum blanching time was calculated by testing of browning with the Guiacole solution. The carrots were immediately rinsed with cold water to stop the reaction.

3.3.2.2 Sulphitation of carrot cubes

The carrot cubes were dipped in 0.3% solution of Sodium metabisulphite for 3 minutes to retain the colour and vitamins (Mohammed and Hussein 1994). In addition to colour preservation, the presence of small amount of sulfite in blanched, cut vegetables improves storage stability and makes it possible to increase the drying temperature during dehydration, thus decreasing the drying time and increasing the drier capacity without exceeding the tolerance for heat damage (Francis 2000).

3.3.2.3 Convective dehydration at different temperatures

After blanching and sulphitation, the samples were dried in a similar fashion as discussed in section 3.3.1.

3.3.3 Effect of $CaCl_2$ addition on drying behaviour of carrot cubes

In these experiments, in addition to osmotic agent and 0.3% sodium metabisulfite, 0.5 % $CaCl_2$ was also added because it is known to increase the textural strength of the fruit (Lenart 1996). Procedure adopted for osmo-convective dehydration was the same as in section 3.3. The rehydrated fruit samples were analyzed for its textural strength, colour, shrinkage and overall acceptability etc.

3.3.4 Step drying of carrot Cubes

The experiments were conducted adopting the same procedure as in section 3.3.1 and 3.3.2 except that convective dehydration was done in two stages. In the first stage the product was dried at 80°C air temperature for first 90 minutes, followed by drying at an air temperature of 60°C for the remaining time until the final moisture content has been reached to 4-5% (w.b.) (Dauthy 1995).

3.3.5 Analysis of drying data

The evaluation of drying rate is very useful in understanding the mechanism of moisture movement within food as well as the transport of moisture from the food to the surrounding air. To study the dying behavoiur at different drying air temperature, percentage moisture content, and drying rates were calculated. The drying curves (moisture content vs. time) were plotted to observe the effect of process variables. Corresponding to the drying curves, the drying rate curves (drying rate vs. moisture content) were also plotted.

The drying rates were calculated from the drying data by estimating the change in the moisture content, which occurred in each consecutive time interval and was expressed as g water/g dry matter/minutes.

The overall drying rate and instant drying rate were calculated as:

$$Overall\ \ drying\ \ rate = \left(\frac{\delta M}{\delta t}\right) = \frac{M_i - M_f}{t_t}$$

$$Instant\ \ drying\ rate = \left(\frac{\delta M}{\delta t}\right) = \frac{M_i - M_{i+1}}{t_{i+1} - t_i}$$

Where, $(\delta M/\delta t)$ = Instantaneous drying rate, % minutes^{-1}.

M_t=Moisture content at time t_i, % d.b.

M_{t+i}= Moisture content at time $t_{(i+1)}$, % d.b.

M_i and M_f are the initial and final moisture contents % (db)

t_t is the total time of convective dehydration process.

3.3.6 Validation of convective drying models

The following empirical models has been used to describe convective drying kinetics of thin layer drying of grapes (Tulasidas *et al* 1993), carrots (Prabhanjan *et al* 1995), egg plant (Ertekin and Yaldiz 2004) and for garlic cloves (Sharma *et al* 2003).

Page Model	$MR= Exp (- K*t^N)$
GEM	$MR=A*Exp (-K*t)$
Logarithmic Model	$MR=A*Exp (-K*t)+C$
Two Term	$MR=A*Exp (-K_0*t)+B*Exp (-K_1*t)$

Midilli *et al* (2002) $MR = A*Exp(-K*t^N)+C*t$

Where K, N, A, B and C are model constants.

Drying curves were fitted to the experimental data using these moisture ratio equations. However, moisture ratio (MR) was simplified to M/Mo instead of (M-Me)/(Mo-Me) (Islam and Flink 1982; Rahman and Lamb 1991; Diamente and Munro 1993; Thakor *et al* 1999; Yaldiz *et al* 2001; Pokharkar and Prasad 2002; Doymaz 2004a and b).

The exponential model considers only the surface resistance and assumes that the internal resistance to moisture movement and thus the moisture gradient within the material are negligible (Chinnan 1984; Colson and Young 1990). This model over predicts the early stages and under predicts the later stages of the drying curves. The Page model is an empirical modification of the general exponential model to correct for its shortcomings and has been used by several authors (Chinnan 1984; Shephered and Bhardwaj 1988; Pathak *et al* 1991). The two-term diffusion model is applied regardless of particle geometry and boundary conditions, but assumes that diffusivity is constant. The Midilli *et al* (2002) model can predict the entire convective drying process with higher accuracy.

3.3.7 Effective moisture diffusivity during convective dehydration

For one-dimensional water diffusion the following equation was used for determination of effective diffusivity of water. The equation was solved by a computer program only for positive values of Fourier number ($F_o = D_{eff}*t/L^2$) (Sharma *et al* 2003) as given in Appendix-D.

$$\frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\exp\left[\frac{-(2n+1)^2\pi^2 D_e t}{4L^2}\right]$$

The average apparent diffusion coefficient was calculated by

$$D_{avg} = \frac{\sum_{1}^{n} D_t}{n}$$

Where n is the number of data points used.

The validity of Arrhenious model $D_e = ae^{-E/RT}$ was also checked.

3.4 Study of sorption isotherms (EMC) of dehydrated product

The static equilibrium method was used for determining characteristics of dried carrot cubes. Incubator was used as temperature control chamber and the desiccators were used as humidity control chamber. The desired level of humidity was controlled through appropriate concentrations of Sulfuric acid (Reugg 1980) as given in Appendix-E.

Experiments were conducted at six levels of water activities (ERH) at four temperatures (12, 25, 40 and 50°C) for four types of dehydrated samples. The selected temperature and water activities were corresponding to the conditions commonly encountered in the storage of dehydrated carrots.

The prepared concentrations of H_2SO_4 (10, 20, 30, 40, 50 and 60%) were transferred into the desiccators and the desiccators were covered with lid and kept as such for moisture equilibration at room temperature for some time. The vapors observed at the inner side of the desiccators were wiped off with a clean and dry cloth. Then about 5-7 g of dried sample was taken in each petridish and are then covered by lids. The desiccators were then transferred in to incubator set at a predetermined temperature. The petridishes were weighed after every 48 hours until the change in weight was less than 0.025% with respect to the initial weight of the sample. Final moisture content (i.e. EMC) of the samples was measure by oven method.

Sorption isotherm data of osmo-convectively dehydrated carrot cubes were fitted to the Chung-Pfost, Modified Henderson, modified Halsey and Modified exponential models. These models are three parameter models and consider the effect of both a_w and temperature on equilibrium moisture content. These models are

Chung Pfost $$M = -\frac{1}{B}\ln\left[\ln a_w \frac{-(T+C)}{A}\right]$$

Modified Henderson: $$M = \left[\frac{\ln(1-a_w)}{-A(T+C)}\right]^{1/C}$$

Modified Halsey: $$M = \left[\frac{\exp(A-BT)}{-\ln a_w}\right]^{1/C}$$

Modified exponential: $M = (A-BT)\exp(Ca_w)$

Where M = equilibrium moisture content, decimal (dry basis),

a_w = equilibrium relative humidity or water activity, decimal,

T= temperature (K), and

A, B, C = equilibrium constants.

Each of three constants of models has a specific physical meaning. The parameter A represents the overall sorption capacity of the material at low a_w. The parameter B represents the effect of temperature and parameter C represents the effect of a_w.

3.5 Rehydration kinetics of dehydrated carrot cubes

Rehydration kinetics study was carried out at 30°C water temperature assuming that the average temperature of the water in the summer season would be 30°C. The beakers containing water and fruit were kept in water bath pre set at 30°C. The approximate ratio of dried fruit and water volume was kept as 1:30 (Mazza 1983). The rehydrated fruit was spread on absorbent paper for the removal of free water on the surface of fruit. The change in weight and volume were recorded after a regular interval of time. Then the rehydrated samples were put in pre-weighed petridish for determination of water gain and solid loss by hot air oven method. The maximum time of immersion of fruit sample was 10-12 hours. The validity of Peleg's model (1988) was checked to study the kinetics of water gain and solute loss during rehydration (Maharaj and Sankat 2000).

3.6 Processing of left over material of carrot cubes

After dicing, the left over material of carrot cubes was separated manually and was used for the juice extraction. The pomace (residue after extraction of juice) of carrots was dehydrated osmo-convectively and was further used for preparation of gazrella.

3.6.1 Processing of carrot juice extracted from left overs of carrot cubes

The juice was extracted from left over material of carrot cubes. The juice was processed and filled in bottles and stored at ambient temperature. The total Soluble Solids (TSS) of the extracted juice was maintained at 12°Brix by addition of sugar and Citric acid (0.25%) was also added to the juice. The juice was heated at 80°C for 4 minutes for exhausting followed by addition of 2mg of Sodium Benzoate/liter (200 ppm) of juice. The hot juice was filled in sterilized glass bottles of 200 ml capacity and the bottles were capped immediately. The pasteurization of juice bottles was done in boiling water for 30 minutes. No blanching of the fruit was done prior to juice extraction and the juice was extracted with juicer mixer. The samples were analyzed for T.S.S., acidity, colour, and organoleptic evaluation at regular interval of time.

3.6.2 Processing of carrot pomace for gazrella preparation

After the extraction of juice, the carrot pomace was osmo-convectively dehydrated by two methods. Firstly, the pomace was put in sugar solution of 60°B containing 0.3% Sodium metabisulphite followed by convective drying. Secondly, the dry sugar @ 35% of weight of Carrot pomace and 0.3 % Sodium metabisulfite were added, followed by convective drying. The convective dehydration was performed at 60°C temperature with direction of airflow over the product (Fig 3.5). It was concluded that out of these two methods, the second method gave best results as for as economics and wastage of sugar solution is concerned. The convective drying was done in blind Aluminum Trays. Refined oil was applied at the bottom of the tray to avoid stickiness of material at the surface. The dried product was packaged in aluminum-laminated envelopes and stored at ambient temperature. The dried pomace was used for the preparation of gazrella at regular interval of time (Fig 3.6).

The gazrella (a sweetmeat) was prepared by rehydrating the osmotically dehydrated carrot pomace in limited volume (1:1) hot/ boiling water for 30 minutes. After proper rehydration the carrot pomace was cooked in desi ghee, till the appearance of brown colour. Then on cooling, desired quantity of khoa and dry fruit were mixed and served for sensory evaluation.

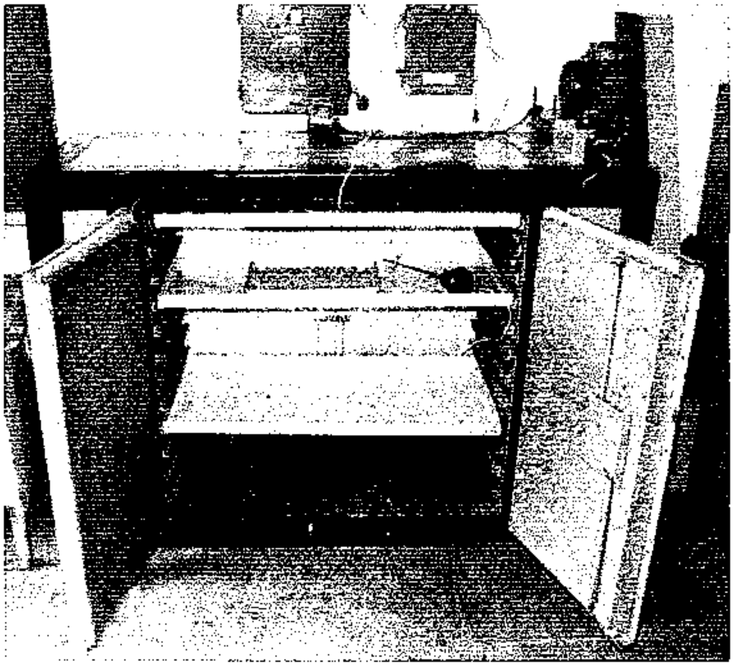


Fig. 3.5 Cabinet (Tray) dryer with airflow over the product for convective dehydration of carrot pomace.

3.7 Packaging and storage of dehydrated samples

The in- package desiccation of dehydrated samples was done in High Density Polyethylene (HDPE) of 80 micron and Low density Polyethylene (LDPE) of 100-micron gauge and laminated pouches under atmospheric conditions. A small amount of Calcium

Oxide (CaO_2) lumps was packed in thick muslin cloth pouches and was placed in each package (Loesecke 2001). The packaged samples were stored at room temperature as well refrigerated temperature. The vacuum packaging of dehydrated carrot cubes was done only in laminated packages, as the other packaging materials were damaged on application of high vacuum due to sharp edges of dehydrated cubes. The samples were analyzed for rehydration ratio, color, texture, weight loss etc at a regular interval of each month.

The dried fruit with blanching and osmo-convective dehydration were also prepared and stored in different packages for comparison of colour of the product. However no data were recoded for the osmotic dehydration of blanched samples.

3.8 Adequacy of fit of various emperical models

The correlation coefficient (R^2) was one of the primary criteria, to select the best equation to account for variation in the drying curves of dried samples (Yaldiz *et al* 2001; Doymaz 2004 a and b). In addition to R^2, the various statistical parameters such as reduced chi- square (χ^2) and root mean square error (RMSE) were also used as primary criterion to select the best equation. Reduced chi-square (χ^2) is the mean square of the deviations between experimental and predicted values for the models and was used to determine the goodness of fit. The lower the values of reduced chi-square, the better the goodness of fit. The RMSE gives the deviation between the predicted and experimental and it is required to reach zero (Ertekin and Yaldiz 2004).

R^2 is a measure of the amount of variation around the mean explained by model.

$$R^2 = 1 - \left\{ \frac{SS_{residual}}{\left(SS_{model} + SS_{residual}\right)} \right\}$$

Adj R^2 is a measure of the amount of variation around the mean explained by the model, adjusted for the number of terms in the model. The adjusted R2 decreases as the number of terms in the model increases if those additional terms don't add value to the model.

$$Adj\ R^2 = 1 - \left\{ \frac{\left(SS_{residual} \Big/ DF_{residual} \right)}{\left(SS_{model} + SS_{residual} \right) \Big/ \left(DF_{model} + DF_{residual} \right)} \right\}$$

$$Chi\ Square = \chi^2 = \sum_{i=1}^{N} \left[\frac{(Experimental\ Value - predicted\ \ value)^2}{(N-n)} \right]$$

$$RMSE = Root\ mean\ square\ error = \sum_{i=1}^{N} \left[\sqrt{\frac{(Experimental\ \ value - predicted\ value)^2}{N}} \right]$$

As these parameters are not a good criterion for evaluating non-linear mathematical models (Chen and Morey 1989), therefore the percent mean relative deviation modulus (E) was also used to select the best equation to account for variation in the drying curves of the dried samples as recommended by several authors recently in their drying studies (Vazquez *et al* 1999a; Sarsavadia *et al* 1999; Yaldiz *et al* 2001; Dandamrongrak *et al* 2002; Ertekin and Yaldiz 2004) that indicate the deviation of the observed data from the predicted line. Therefore, the best model was chosen as one with the highest coefficient of correlation (R^2); and the least χ^2, RMSE and mean relative deviation modulus (E).

The average percent difference between the experimental and predicted values mean relative deviation modulus, E, defined by following equation.

$$E(\%) = \frac{100}{N} \sum_{i=1}^{N} \left| \frac{Experimental\ Value - predicted\ value}{Experimental\ value} \right|$$

The values of E less than 5.0 indicate an excellent fit, while values greater than 10 are indicative of a poor fit.

3.9 Physical and biochemical analysis

3.9.1 Estimation of dry matter and moisture content

The samples were oven dried at 103±2°C for 16 hours in uncovered pre-weighed petridishes (AOAC: 984.25, 2000). After drying, petridishes were covered with lid and cooled in desiccators containing silica gel for 1 hr before weighing. Moisture content of the whole sample was calculated by

$$\text{Dry matter (\%)} = \frac{W_3 - W_1}{W_2 - W_1} * 100$$

$$\text{Moisture Content (\%d.b.)} = \frac{W_2 - W_3}{W_3 - W_1} * 100$$

$$\text{Moisture Content (\%w.b.)} = \frac{W_2 - W_3}{W_2 - W_1} * 100$$

Where W_1, W_2, and W_3 respectively are weights of empty petridish, petridish + sample before drying and petridish + sample after drying.

Conversion formulae

(a) Wet basis to dry basis

$$\text{\% Moisture Content (Dry basis)} = \text{\% M.C.(D.B)} = \frac{100 * \%M.C.(W.B.)}{100 - \%M.C(W.B.)}$$

(b) Dry basis to wet basis

$$\text{\% Moisture Content (Wet basis)} = \text{\% M.C.(W.B.)} = \frac{100 * \%M.C.(D.B)}{100 + \%M.C.(D.B.)}$$

3.9.2 Peroxidase test

To determine the optimum blanching time for the un-osmosed carrot cubes, peroxidase test was performed. Peroxidase is the most heat resistant enzyme and its inactivation is taken as index of blanching. The test was performed according to Bureau of Indian standards (IS: 4625, 1968)

For the test 25 g of carrot cubes were taken periodically at ½ minutes interval while blanching was in progress in hot water. Enough quantity of 1% guaiacol solution was added to wet all the cut surfaces. Immediately after this equal amount of 1% hydrogen peroxide (H_2O_2) solution was added. The sample was then examined for development of reddish brown color. If the reddish brown color developed within 3 minutes, the peroxidase activity was taken as positive indicating insufficient blanching. If no such color developed within 3 minutes, the test was taken as negative indicating that the carrots were adequately blanched. In Laboratory test, 3 minutes blanching was found to be adequate and hence used in all experiments.

3.9.3 Rehydration ratio

The rehydration of dried carrot cubes was determined by soaking known weight (5-8 g) of each sample in sufficient volume of water (approximately 30 times the weight of dried carrots) at room temperature (Mazza 1983). At the end of the rehydration period i.e. 12 hours, which was found to be adequate for the cubes to reach a constant weight, the cubes were weighed after removing excess water with the help of absorbent paper. Before taking weights, the volume of the rehydrated carrot cubes was also measured by water displacement method. The rehydration ratio and rehydration coefficients were computed by using the equations:

$$\text{Rehydration Ratio} = \frac{Weight\ of\ rehydrated\ carrots\,(g)}{Weight\ of\ dehydrated\ carrots\ (g)}$$

3.9.4 Shrinkage of product

The shrinkage was measured by Toluene displacement method during convective drying, and by water displacement method during osmotic dehydration and rehydration process. Shrinkage was calculated as the percentage change from the initial apparent volume.

$$\text{Shrinkage} = \frac{V_t}{V_o}$$

$$\% \ Shrinkage = \left[1 - \left(\frac{V_t}{V_o}\right)\right] * 100$$

Where V_t = Volume displaced by 100 g rehydrated carrot cubes at time t.

And V_0 = Volume displace by 100 g fresh carrot cubes.

3.9.5 Estimation of salt by Mohr's method

A known weight of osmotically oven dried fruit was dipped in sufficient amount of water for the extraction of solute (mixture of salt, sugar and preservatives) present in fruit. The solution containing fruit was boiled and crushed for complete extraction. The extract was filtered through Wattman No 1 filter paper and the fruit residue was washed 2-3 times with distilled water to remove the traces of the solute. Then the filtered extract was made up to 250 ml in volumetric flak.

Then 10 ml of the above solution was pipetted in titration flask and few drops of 5% Potassium Chromate (Indicator) were added. The solution was titerated against $\frac{N}{10}$ $AgNO_3$ solution until the brown or Permanent orange pink colour appears. $\frac{N}{10}$ AgNo$_3$ was prepared by addition of 16.98 g of salt in to 1000ml of distilled water.

$$\text{NaCl \%} = \frac{\text{(Sample titre – Blank titre) * Normality of } AgNO_3\text{* Volume make up*58.45*100}}{\text{ml of sample taken * Wt or volume solution *1000}}$$

For fruit, the final calculations were made for g of salt/100 g of fresh fruit as described below:

Let the % of NaCl in oven dried fruit = X (Determined by above formula)

Wt of oven dried fruit after osmotic dehydration = Y (g) (As in column N of Appendix-A)

Wt of fresh fruit taken for osmotic dehydration = Z (g) (As in column B of Appendix-A)

$$\text{Amount of NaCl/100 g fresh fruit} = \frac{X * Y}{Z}$$

In case of solution 1ml of solution was diluted and titerated as described above.

3.9.6 Colour measurement

Colour is most important parameter for the acceptability of the product. The colour of rehydrated carrot was measured in terms of 'L', 'a' and 'b' value after grinding the samples. Variation in the values of 'L', 'a', and 'b' values were observed due to different osmotic pretreatments and also due the different proportion of xylem (central core of carrot) and phloem (red portion) present in samples. To reduce this variation, observations were recorded in triplicate after proper mixing of grinded sample. The colour properties of the fresh and rehydrated product were measured using a HunterLab MiniScan XE Plus Colourimeter (U.S.A.), Model No. 45/o-L. The grinded material of fresh and rehydrated carrot cubes was completely filled in plane petridish. The 'L', 'a', 'b' values were recorded at D 65/10° and were compared to the standard values of carrot colour. In Hunter scale L measures whiteness or darkness. The chromatic portion of the solid is defined by: +a (red); -a (green); +b (yellow); -b (blue) (Fig 3.6).

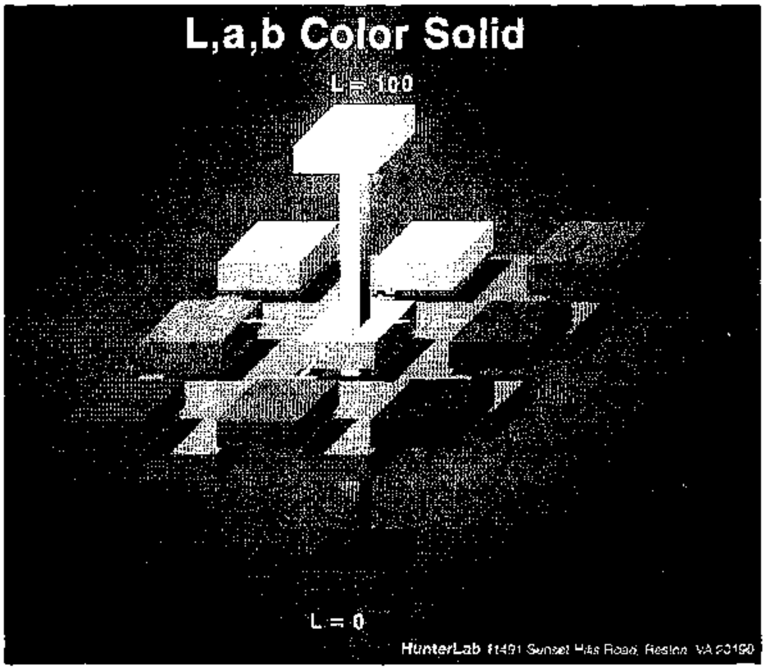


Fig 3.6. Representation of colour solid in terms of 'L', 'a' and 'b' values

3.9.7 Texture/ firmness measurement

The firmness of fresh and rehydrated samples was recorded with the Texture Analyzer (TA-Hdi). The samples were compressed by probe P75 compression to 25% compression as described for fruits (Roy *et al* 2001).

The speed before compression was set at 5mm/sec, during compression 1mm/sec and post compression as 10 mm/sec. The value of maximum force (g) for 25% compression was recorded in quadruplets.

3.9.8 Sensory evaluation of dried and rehydrated carrot cubes

Organoleptic quality of dried carrot cubes and gazrella was determined with the help of a ten-member consumer panel using a 9-point hedonic scale following standard procedure given by Bureau of Indian Standards (IS: 6273, 1971). The evaluation of dried product was done in its two forms- as dried cubes, and as rehydrated cubes. In case of dried cubes, the organoleptic aspects evaluated were colour, appearance, odour, and acceptability to purchase. The aspects considered for rehydrated carrots and gazrella were colour, appearance, taste, flavour, and overall acceptability. In between testing different samples, the panel members were served bland puffed rice and fresh water to rinse the mouth. The average scores of all the 10 panelists were computed for different characteristics.

3.9.9 Physiological loss (or gain) in weight

The physiological loss in weight (PLW) or physiological gain in weight (PGW) after duration of one month was calculated as:

$$PLW(\%)\ or\ PGW\ (\%) = \frac{(Initial\ weight - Final\ weight)}{Initial\ weight} x100$$

CHAPTER IV

RESULTS AND DISCUSSION

The present study was undertaken to optimize the process parameters viz. osmotic solution concentration, process temperature and duration for osmo-convective dehydration of carrot cubes of size 1cm x 1cm x 1cm in solutions of salt, sugar and sugar-salt mixture. Osmotic dehydration kinetics for water loss and solute gain, convective drying kinetics, rehydration kinetics, sorption isotherm and storage studies of processed carrot cubes were also investigated. The carrot pomace (pulp) thus obtained was further dehydrated osmo-convectively and used to prepare gazrella. The results of the study along with relevant discussion are included in this chapter.

4.1 Mass transfer kinetics of carrot cubes during osmotic dehydration

The experiments were conducted in solutions of different osmotic agents viz. salt, sugar and sugar-salt mixture, having different concentrations (5, 10, 15% for salt; 45, 50 and 55°B for sugar; 50°B+5%, 50°B+10% and 50°B+15% for sugar-salt mixture). The osmotic solution temperatures (35, 45 and 55°C) and solution to fruit ratios (4,5 and 6) were also adjusted. The temperature of the osmotic solution was maintained using hot water bath agitating @ 52 oscillations per minute. The detailed description of experiments is given in Table 3.1. The data pertaining to osmotic dehydration kinetics of carrot cubes was as given in Appendix-F.

4.1.1 Effect of various process parameters on osmotic dehydration kinetics

The effects of various process parameters on kinetics of water loss and solute gain during osmotic dehydration of carrot cubes are discussed below:

4.1.1.1 Effect of composition and concentration of osmotic solution

In all the osmotic dehydration processes of carrot cubes, an increase in concentration of osmotic solution gave higher water loss and solute gain at all the temperatures and process durations with few exceptions. The effect of osmotic solution composition and concentration on kinetics of water loss and solute gain during osmotic dehydration for different osmotic agents is given below.

(a) Salt solution

The effect of salt concentration on water loss and solute gain during osmotic dehydration solution temperature maintained at 45°C and solution to fruit ratio at 5 is shown in Fig 4.1 and 4.2. The figures indicate that with increase in salt concentration, the rate of water loss and solute gain also increased. The minimum water loss was observed for 5% salt concentration and almost same for 10% and 15% salt concentration. The negligible difference in water loss at 10 and 15% salt concentration might be due to closing of pores (i.e. compactness of fruit tissue) by fast penetration of low molecular weight salt, which imparted resistance to water out flow. For all the experiments, a continuous increase in solute gain was observed with increase in salt concentration, because the salt penetrated deeply into the fruit tissues due to lower molecular weight, which was similar to the results of Lenart and Flink (1984); Chang *et al* (2003); Sachetti *et al* (2001). Similar results were also reported by Lenart and Flink (1984) for potatoes, Vijayanand *et al* (1995) for cauliflower, Kar and Gupta (2001, 2003) for mushrooms.

(b) Sugar solution

The water loss increased with increase in sugar concentration from 45 to 55°B except for 50°B concentration at 45°C solution temperature and solution to fruit ratio of 5 (Fig 4.1). This was because the sucrose having higher molecular weight remained primarily at the surface, creating a concentration difference between surface and tissue interior and promoted the diffusion of water from the product. Further, an increase in the concentration of sugar solution resulted in osmotic pressure gradient, which increased the

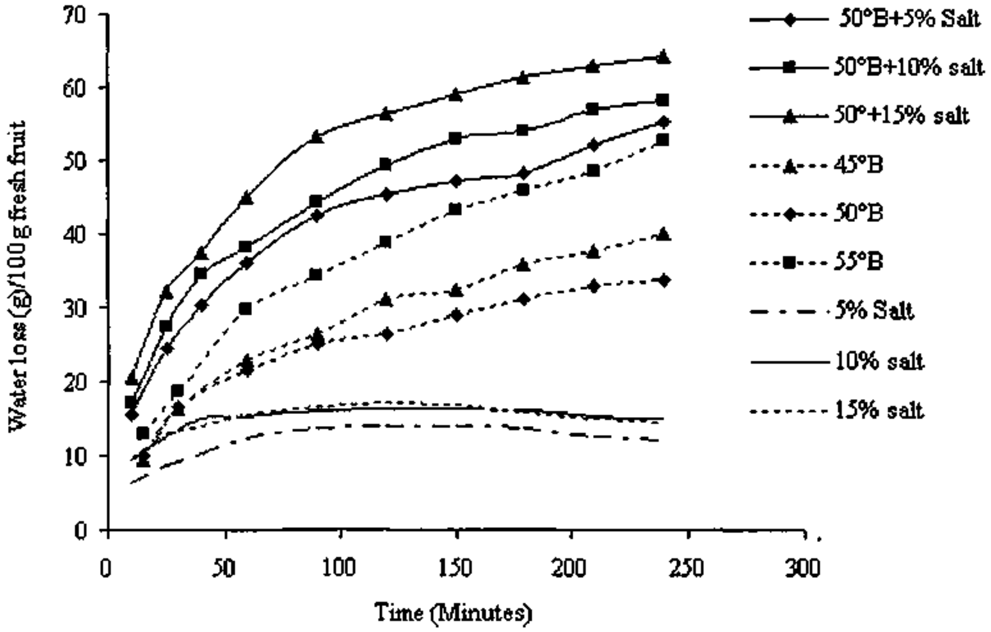


Fig 4.1 Effect of osmotic solution concentration and time on water loss at 45°C & STFR =5

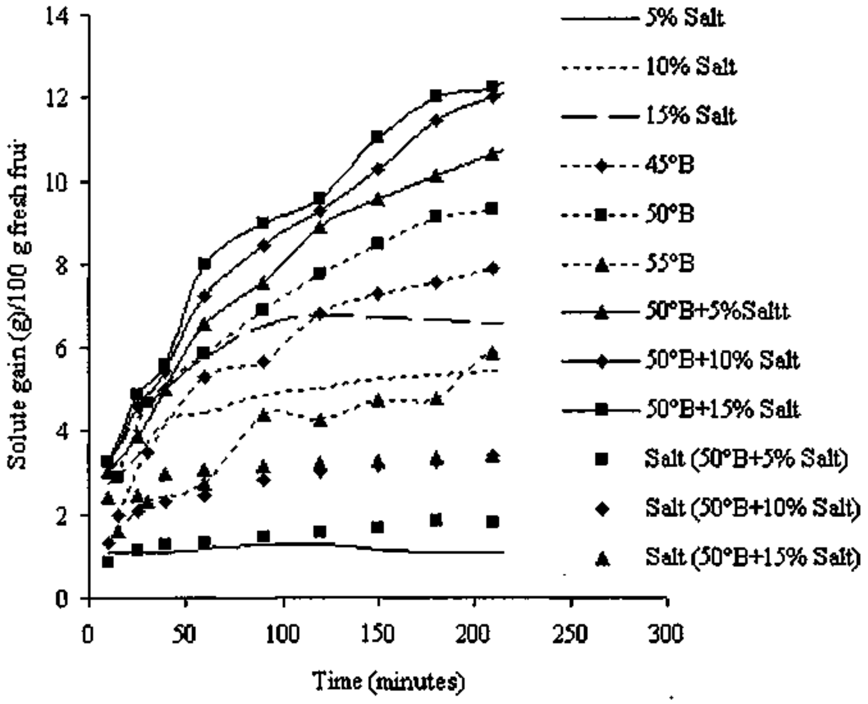


Fig 4.2 Effect of osmotic solution concentration and time on solute gain at 45°C & STFR =5

driving force for water removal between solution and fruit, and thereby giving higher mass transfer rates, which were in agreement with the results of Rastogi and Raghavarao (1997) for carrot cubes; Videv *et al* (1990), Reppa *et al* (1999) for cylindrical apple; Rahman and Lamb (1990) for pineapples and Kaleemullah *et al* (2002a and b) for papaya in sucrose solution. The decrease in water loss in osmotic solution of 50°B as compared to 45°B could be attributed to the boundary phase that occurred on the product surface at higher solution concentrations and lower temperatures, which decreased the driving force between the solution and the product, providing hindrance to water outflow during osmotic dehydration. It was also observed that the solute gain was minimum at 55°B as compared to 45 and 50°B at 45°C temperatures, and it might be due to high viscosity of more concentrated sugar solution, which imparted resistance to the solute penetration at solution and fruit interface. The results were consistent with the findings of Hawkes and Flink (1978); Lenart and Flink (1984). The values of solute gain were much lower than the water loss for all the process parameters during osmotic dehydration, because sucrose having larger ionic radius could not diffuse easily through the cell membrane and thus the approach to osmotic equilibrium was achieved primarily by flow of water from the cell. Similar results were reported by Lenart and Flink (1984), Ozen *et al* (2002) for potatoes and green pepper, respectively during osmotic dehydration using sugar solution.

(c) Solution of sugar-salt mixture

It was clear from the Fig 4.1 and 4.2 that, water loss and solute gain was increased with an increase in concentration of salt from 5 to 15% in 50°B sucrose solution at temperature of 45°C with solution to fruit ratio of 5. The increase in water loss and solute gain might be due to the synergistic effect of both sucrose and salt to develop high osmotic potential, which was in close agreement with the results of Dauthy (1995) and Sacchetti *et al* (2001). It was also observed that the addition of salt to sucrose solution resulted in reduction in viscosity of osmotic solution, which in turn resulted into high diffusion rates of both water and solute during osmotic dehydration in sugar-salt mixture. The decrease in viscosity of sucrose solution by addition of salt had also been reported by Vivanco *et al* (2002) and Chenlo *et al* (2002). Fig 4.2 indicates that, relative rate of increase in solute gain was more in solution of sucrose-salt mixture (10 to 12 g/100g of fresh fruit) as compared to sucrose solution of 50°B (8 g/100 g FF). This might be due the fact that salt molecule could diffuse more in the fruit tissue than sucrose molecule due to lower molecular weight, which was in close agreement with the results of Lenart and Flink (1984); Sacchetti *et al* (2001); Ade-Omowaye *et al* (2002a) and Chang *et al* 2003). Further, the salt combined with sucrose resulted in reduction of salt uptake during osmotic dehydration in sucrose-salt mixture solution as compared to salt solution alone. The decrease in salt gain was the result of the possible formation of a concentration gradient around the fruit tissue by sucrose, which hindered the entrance of salt in to the product. The results were consistent with the findings of Ade-Omowaye *et al* (2002a) and Ozen *et al* (2002) for osmotic dehydration of red paprika and green pepper in sugar-salt mixture solution.

Similar behaviours of water loss and solute gain were observed during osmotic dehydration of carrot cubes with solutions of salt, sugar and sugar-salt mixture at temperatures 35 and 55°C; and solution to fruit ratios 4 and 6 as indicated by the values tabulated in Appendix-F.

4.1.1.2 Effect of immersion time on water loss and solute gain

Increased water loss and solute gain in carrot cubes were observed with increase in immersion time for all the osmotic solutions, process temperatures and solution to fruit ratios. The effect of immersion time on water loss and solute gain during osmotic dehydration, having solution temperature 45°C, solution to fruit ratio 5 and 10 % for salt, 50°B for sugar and 50°B +10% for sugar-salt mixture concentration is indicated in Fig 4.1 and 4.2. Both water loss and solute gain were higher in the initial phase of osmosis than the later period. This might be due to the reason that with progression of time, as the moisture moved from the sample to solution and solute from solution to sample, the osmotic driving potentials for moisture and solute transfer decreased. Also the rapid loss of water and uptake of solids near the surface in the beginning might have been resulted in structural changes leading to compaction of these surface layers and increased mass transfer resistance for water and solids. Similar results were also reported by Lenart and Flink (1984) for osmotic dehydration of potatoes. Further, progressive solid uptake might have been resulted in the formation of high solids subsurface layer, which interfered with the concentration gradient across the product-solution interface and acted as a barrier against removal of water and uptake of solids, which was in close agreement with the results of Hawkes and Flink (1978).

For osmotic dehydration in salt solution, the rates of water loss and solute gain showed highest values in the beginning and then dropped drastically within the first 30 minutes and almost leveled off after 90 minutes. A possible explanation for this behavior was that salt, because of its lower molecular weight, entered the tissue faster and caused water to outflow from the product during the early stages of osmosis. Similar results were reported by Lenart and Flink (1984), Escriche *et al* (2000). The early equilibrium for water loss in salt solution could also be explained due to lower viscosity of salt solution as compared to sugar solution, which was consistent with the results of Biswal *et al* (1991) and Sereno *et al* (2001a). In some cases during osmotic dehydration in salt solution, an increase in moisture (instead of decrease) was observed with advancement of immersion time beyond 60 minutes, which was similar to the results of Sereno *et al* (2001b). Further, it was also observed that solute uptake mainly occurred within the first 30 minutes for salt, although it continued at slower rates for 2-3 hours, which was in close agreement with the results of Lenart and Flink (1984); Torreggiani *et al* (1988); Nabais *et al* (1996) and Sereno *et al* (2001b).

For osmotic dehydration with solutions of sucrose and sucrose-salt mixture, the rates of water loss and solute gain were extensive for first 3 hours of osmosis and gradually leveled off there after. The above results imply the existence of a high rate of water loss and solute uptake for a long processed period. Similar results were reported by Singh (2001) for moisture loss from carrot shreds osmosed in 50°B sugar solution at room temperature. In the osmosis of other fruits and vegetables similar trends had also been observed (Lazarides *et al* 1995a; Karathanos *et al* 1995; Ertekin and Cakaloz 1996a; Biswal *et al* 1991, 1997; Chopra 2001; Ozen *et al* 2002; Azoubel and Murr 2004).

Similar behaviours of water loss and solute gain were observed during osmotic dehydration of carrot cubes in salt, sugar and sugar-salt mixture solution having temperatures 35 and 55°C; and solution to fruit ratios 4 and 6 as indicated by the values tabulated in Appendix-F.

4.1.1.3 Effect of osmotic solution temperature on water loss and solute gain

The effect of osmotic solution temperature on water loss and solute gain during osmotic dehydration, osmotic solution concentration maintained as 10 % salt, 50°B for sugar and 50°B sugar +10% salt and solution to fruit ratio as 5. It was observed that, the osmotic solution temperature had strong effect on water loss and solute gain during osmotic dehydration process. It is clear from the Fig 4.3 and 4.4 that there was an increase in rate of water loss and solute gain with the increase in solution temperature for osmotic dehydration with solutions of sugar and sugar-salt mixture. The effect of increase of solution temperature of highly concentrated solution might be due to decrease in viscosity of the osmotic solution resulting in high diffusion rates of both water and solute. Lazarides

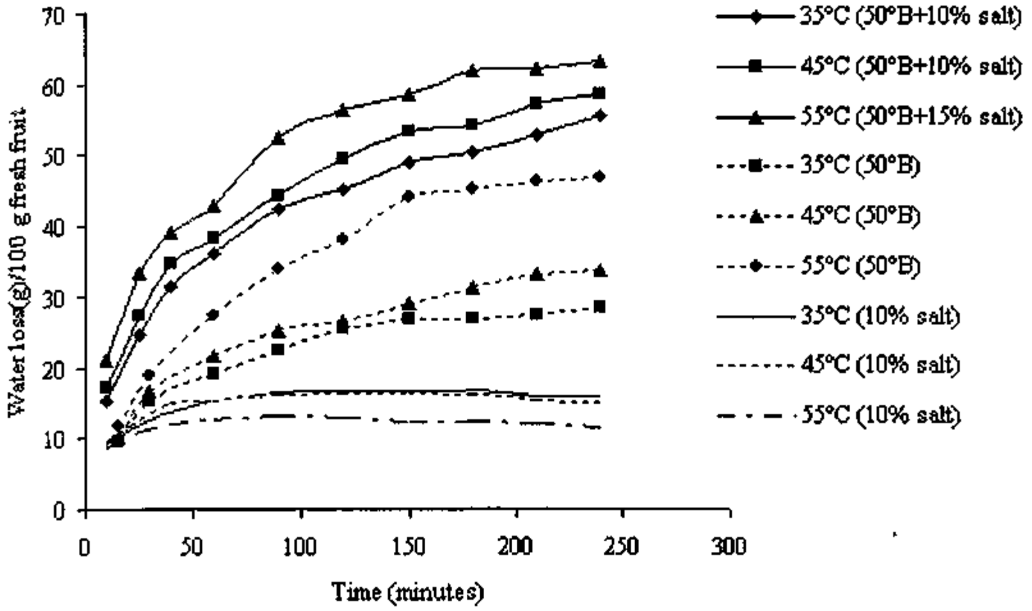


Fig 4.3 Effect of osmotic solution temperature on <u>water loss</u> at STFR=5

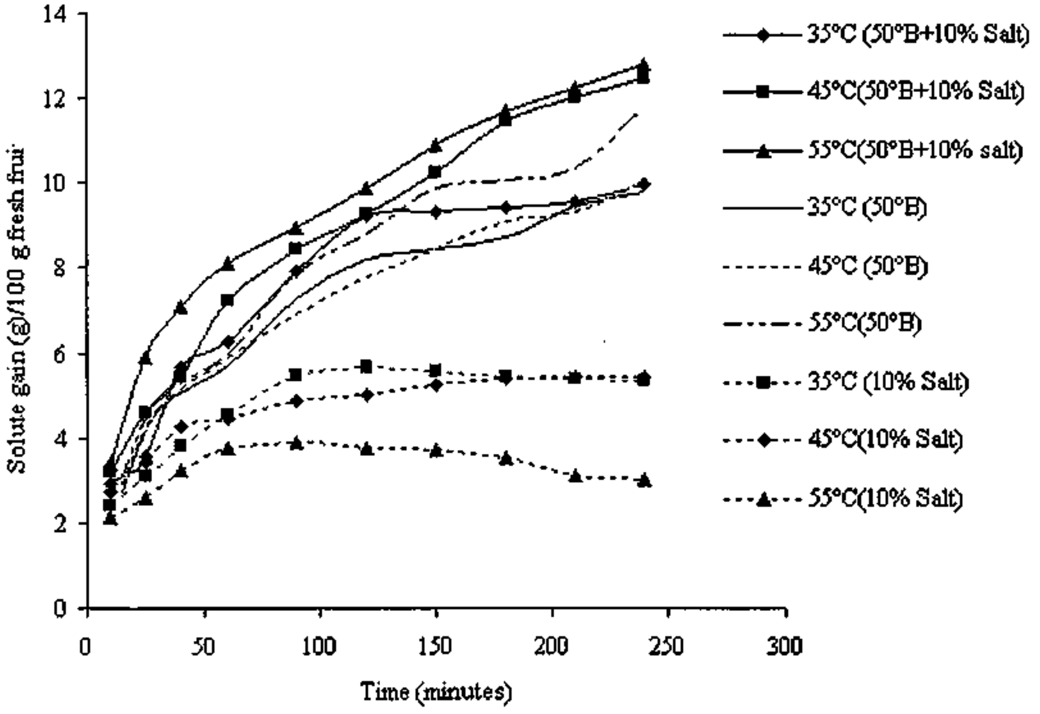


Fig 4.4 Effect of osmotic solution temperature on <u>solute gain</u> at STFR=5

and Mavroudis (1996); Barat *et al* (1998); Videv *et al* (1990); Reppa *et al* (1999); Ertekin and Sultanoglu (2000) and Telis *et al* (2003) also reported the similar results regarding effect of temperature on osmotic dehydration kinetics. Higher process temperatures (above 50°C) also promoted faster water loss through swelling and plasticizing of cell membrane, cell membrane damage (Karel 1976). Increased rates of water loss and relatively stable rates of solute uptake with increased temperatures have also been reported by several researchers working on potatoes (Islam and Flink 1982; Lenart and Flink 1984), fruits (Hawkes and Flink 1978; Lazarides *et al* 1995a). But, in case of osmotic dehydration with salt solution, a decrease in water loss and solute gain was observed with increase of solution temperature. In case of osmotic dehydration with salt solution, this abrupt phenomenon of water loss and solute gain might be due to very low viscosity of salt solution at high temperatures as reported by Sereno *et al* (2001b), Azoubel and Murr (2004) for osmotic dehydration of apples and cherry tomato using salt solution.

Similar behaviours of water loss and solute gain were observed during osmotic dehydration of carrot cubes in solution having concentration of 5 and 15% for salt; 45 and 55°B for sugar, 50°B+5% and 50°B+15% for sugar-salt mixture; and solution to fruit ratios of 4 and 6 as indicated by the values tabulated in Appendix-F.

4.1.1.4 Effect of solution to fruit ratio on water loss and solute gain

The effect of solution to fruit ratio on water loss and solute gain during osmotic dehydration with osmotic solutions having concentration as 10 % for salt, 50°B for sugar and 50°B+10% for sugar-salt mixture solution, and solution temperature 45°C is indicated in Fig 4.5 and 4.6. During experimentation of osmotic dehydration of carrot cubes in solutions of different osmotic agents having different concentrations, temperatures and immersion times, no significant effect of solution to fruit ratio was observed, except during the osmotic dehydration in solution of sugar-salt mixture. This different behavior

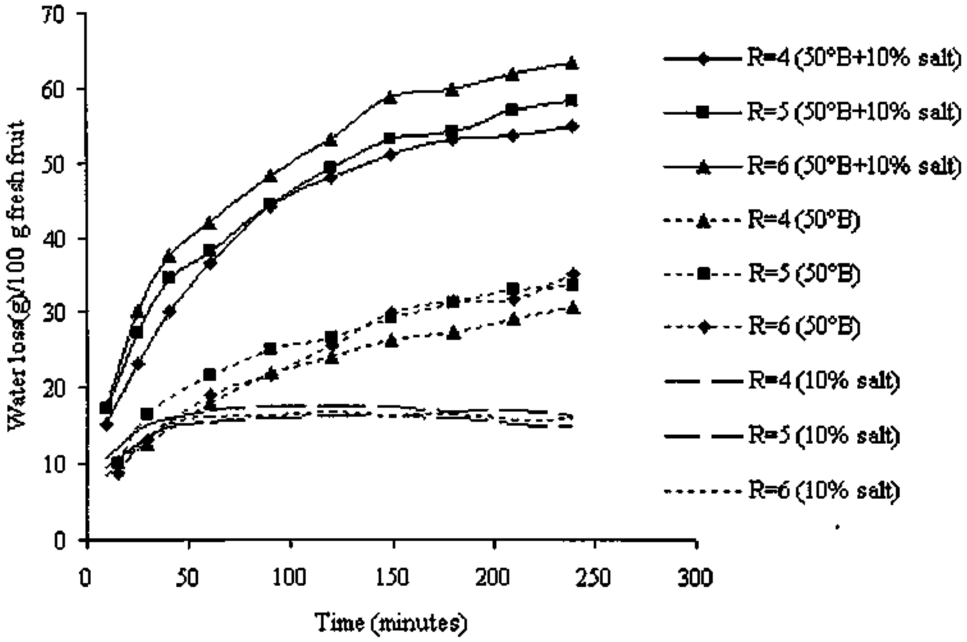


Fig 4.5 Effect of Solution to fruit ratio on
water loss at 45°C

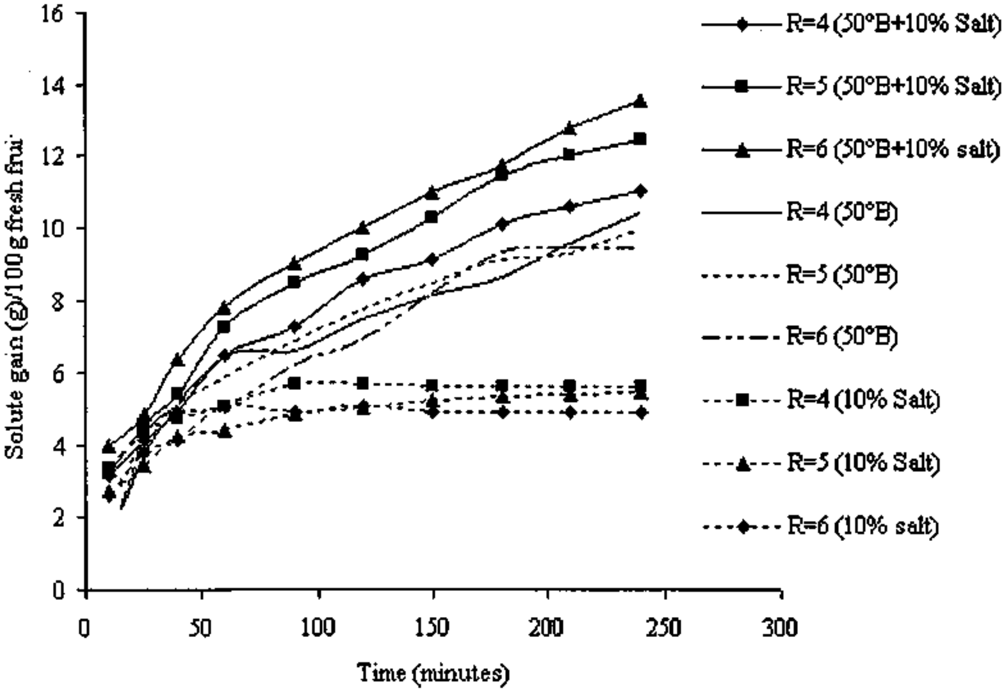


Fig 4.6 Effect of solution to fruit ratio on
solute gain at 45°C

could be explained on the basis that water loss and solute gain took longer time to acquire equilibrium during osmotic dehydration in solution of sugar-salt mixture. It is clear from the Fig 4.5 and 4.6, that the water loss and solute gain were almost same for solution to fruit ratio of 4, 5, and 6, as it was verified from the coincidence of the curves during osmotic dehydration process. Similar behaviour was observed by Vivanco *et al* (2002) in fish muscle of tilapia and Telis *et al* (2003) for pantanal caiman. However, contrary to this, various scientists reported that the rate of water loss and solute gain increased with increase of solution to fruit ratio (Islam and Flink 1982; Rastogi and Raghavarao 1995; Pokharkar and Prasad 1998). In present study, the deviation from these findings might be due the short durations and high temperatures employed during osmotic dehydration.

Similar behaviours of water loss and solute gain were observed during osmotic dehydration of carrot cubes in solution having concentration of 5 and 15% for salt; 45 and 55°B for sugar; 50°B+5% and 50°B+15% for sugar-salt mixture; and solution temperature of 35 and 55°C as indicated by the values tabulated in Appendix-F.

The above discussion indicates that Sodium chloride in osmotic solutions increased the driving force for osmotic dehydration, however, its use was limited due to bleaching action of Chlorine gas liberated from salt solution (Arya *et al* 1979) and saltiness (Lerici *et al* 1985). The effect of salt solution on water loss was not strong (as compared to sucrose) due to smaller contribution of salt concentration on solution viscosity, which was consistent with the results of Sereno *et al* (2001b). In case of osmotic dehydration in salt solution, the equilibrium for water loss achieved very fast due to small molecules of salt, while it took longer time in the solutions of sugar and sugar-salt mixture due to a marked difference in the way that sugar and salt penetrate the fruit tissue. The sucrose (having high molecular weight) accumulated in a thin subsurface layer, resulted in surface tissue compaction (an extra mass transfer barrier), whereas salt penetrated the osmosed tissue to a much greater depth, as reported by Lenart and Flink (1984). Thus the presence of salt along with sugar in the osmotic solution could hinder the formation of the compacted surface layer, allowing higher rates of water loss and solute gain. The use of sucrose-salt mixture had beneficial effects as it developed high osmotic potential thereby causing high water loss, retarded oxidative and non-enzymatic browning and reduced bleaching effect of coloured products as reported by Jackson and Mohammed (1971), Islam and Flink (1982).

The temperature had positive impact on water loss during osmotic dehydration in solutions of sugar and sugar-salt mixture. It was therefore possible to substantially decrease the processing time and increase product throughput by merely increasing temperature of osmotic solution except for salt solution (Lazarides and Mavroudis 1996). But, Ponting *et al* (1966) suggested that, in case of fruits and vegetables there was an upper temperature limit beyond which there could be a negative impact on final product quality due to softening, browning and flavour losses etc. This limit was specified by the sensitivity of each particular product and is conventionally placed around 50°C. A maximum temperature limit of 45°C was recommended by Dauthy (1995), beyond which there might be the browning of the product. However, the impact of temperature on water loss was observed to be negative during osmotic dehydration in salt solution. Optimum ratio of solution to fruit sample to be used was important for the economic considerations. During experimentation, it was observed that the possible economic combination of solution to fruit ratio might be 6 for salt solution and 5 for solution of sugar and sugar-salt mixture, which was in close agreement with the findings of Kar and Gupta (2001; 2003); and Azoubel and Murr (2004). However in most of the findings by Lenart and Flink (1984), Kowalska and Lenart (2001), optimum solution to fruit ratio reported were four. A few studies have reported use of higher ratio of 10 to 50 in order to avoid significant dilution of solution due to uptake of water from samples and loss of solutes to the fruit samples, and subsequent decrease of osmotic driving force during osmotic dehydration (Biswal *et al* 1997; Hawkes and Flink 1978; Saurel *et al* 1994; Lazarides *et al* 1995b; Sereno *et al* 2001b).

4.1.2 Statistical analysis of various process parameters on water loss and solute gain during osmotic dehydration

The regression analysis of the experimental data was carried out to observe the significance of the effect of various process parameters on water loss and solute gain during osmotic dehydration. The relative effect of each process parameter was compared from the β values corresponding to that parameter. The β coefficients were the regression coefficients obtained by first standardizing the process variables to a mean of zero and standard deviation to one. Thus, the advantage of using β coefficient (as compared to B coefficients which are not standardized) was that the magnitudes of these values allow us to compare the relative contribution of each independent variable in the prediction of the dependent variable (Statistica manual 1995). Higher the positive value of β of a parameter; higher would be the effect of that parameter and vice versa. The negative value of β indicates the negative effect of that parameter. The level of significance of the effects of various process parameters on water loss and solute gain during osmotic dehydration of carrot cubes in solutions of salt, sugar and sugar-salt mixture are given in the Tables 4.1 to 4.3

(a) Salt solution

Table 4.1 Regression summary for water loss and solute gain for osmotic dehydration with salt solution

	Water loss			Solute gain		
	R^2=0.33F (4,125)= 15.2;E=13.1%			R^2=0.77 F (4,125)=102.3;E=30.8%		
	β	B	p-level	β	B	p-level
Intercept	-	15.8415	8.45E-14	-	4.5990	8.11E-07
Time	0.4369	0.0144	2.45E-08	0.2438	0.0064	1.1E-07
Conc.	0.0442	0.0290	0.565848	0.6683	0.3490	4.18E-29
Temp	-0.3432	-0.1126	1.78E-05	-0.3423	-0.0894	7.99E-12
Ratio	0.0863	0.2780	0.2411**	-0.0730	-0.1870	0.0939**

** = Non-significant at 5%level

The Table 4.1 indicates that during osmotic dehydration of carrot cubes in salt solution; the effects of time, concentration and temperature were significant on water loss and solute gain. However, the effects of solution to fruit ratio were non-significant. The non-significant effect of solution to fruit ratio might be due to high processing temperature and short duration of osmotic dehydration process or might also be due to very small difference between two successive solution to fruit ratios. During experimentation, it was observed that during osmotic dehydration of carrot cubes in salt solution low process temperature was more effective, due to higher viscosity of salt solution at low temperature (Sereno *et al* 2001a; Chenlo *et al* 2002). The temperature has negative effect (β-values) on both water loss and solute gain. Therefore with increase of temperature the rate of water removal and solute gain decreased, which contradicts the general law of diffusion. The relative magnitude of β values indicated the highest contribution of time on water loss and solution concentration on solute gain.

(b) Sugar Solution

Table 4.2 Regression summary for water loss and solute gain for osmotic dehydration with sugar solution

	Water loss			Solute gain		
	R^2=0.72 F (4,130)= 82.7; E=21.8%			R^2=0.66 F (4,130)=61.4; E=28.3%		
	β	B	p-level	β	B	p-level
Intercept	-	-16.2028	0.0761	-	0.5454	0.7921
Time	0.7986	0.1392	3.5E-35	0.6961	0.0249	1.76E-26
Conc.	0.0507	0.1625	0.2779**	-0.0911	-0.0600	0.0797**
Temp	0.2747	0.4399	3E-08	0.3982	0.1312	2.75E-12
Ratio	0.0438	0.7015	0.3486**	-0.0496	-0.1634	0.3383**

** = Non-significant at 5%level

The Table 4.2 indicates that during osmotic dehydration of carrot cubes in sugar solution; the effects of time and temperature were significant on water loss and solute gain. However, the effects of solution to fruit ratio and concentration were non significant. The non-significant effect of concentration might be due to the very small difference in concentration (5°B) or might be due to the high viscosity of the solution having high concentration. It was clear from β-values that time and temperature have significant effect on both water loss and solute gain. The solution concentration has more contribution as compared to solution to fruit ratio on water loss and concentration on solute gain.

(C) Sugar-salt mixture solution

Table 4.3 Regression summary for water loss and solute gain for osmotic dehydration in solution of sugar-salt mixture

	Water loss			Solute gain		
	R^2=0.8; F (4,145)=193.3; E=13.6%			R^2=0.9; F (4,145)=342.6; E=11.2%		
	β	B	p-level	β	B	p-level
Intercept	-	1.5050	0.7061**	-	-3.3628	3.2E-06
Time	0.8881	0.1597	0	0.8545	0.0344	0
Conc	0.1275	0.4297	0.0002	0.3486	0.2628	1.35E-27
Temp	0.1682	0.2833	1.06E-06	0.2043	0.0770	4.69E-13
Ratio	0.0938	1.5806	0.0051	0.1038	0.3913	8.59E-05

** = Non-significant at 5% level

The Table 4.3 indicates that during osmotic dehydration of carrot cubes in sugar-salt mixture solution; the effects of all the process parameters were significant on water loss and solute gain. It might be due to increased diffusion rates of both water and solute the due to decreased viscosity of the solution by addition of salt to the sucrose solution, which was consistent with the results of Vivanco *et al* (2002) and Chenlo *et al* (2002). It is clear from β-values that the time has more pronounced effect on both water loss and solute gain as compared to the other process variables. The solution temperature and concentration have more contribution towards water loss as compared to solution to fruit ratio.

4.1.3 Effective diffusivity of water and solute during osmotic dehydration of carrot cubes

The basic equation of Fick's unsteady state law of diffusion is of the form

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial Z^2} \tag{4.1}$$

The different analytical solutions of equation (4.1) found by Crank (1975) for several geometries and boundary conditions relate the amount of mass transferred, in terms of a series of exponential functions. The analytical solution for slab geometry being placed in an agitating liquid medium is as below:

$$MR = \frac{M_t - M_\infty}{M_0 - M_\infty} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_e q_n^2 t}{L^2}\right] \tag{4.2}$$

$$SGR = \frac{C - C_e}{C_o - C_e} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_e q_n^2 t}{L^2}\right] \tag{4.3}$$

For very large value of α

$$MR = \frac{M - M_t}{M_0 - M_\infty} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left[\frac{-D_e (2n-1)^2 t}{L^2}\right] \tag{4.4}$$

The meanings of usual notations have been explained in Appendix-B.

Comparison of water or solute diffusivities during dehydration was difficult to compare with the literature values because of variation in food composition and physical structure and different methods and models employed to estimate diffusivity (Zogzas and Maroulis 1996; Sablani *et al* 2000; Shi and Maguer 2002). For example, the equation (4.1) was solved numerically by the Newton Raphson method by Karathanos *et al* (1990) and by Crank-Nicholson method by Ertekin and Sultanoglu (2000). Liu *et al* (2001) determined diffusion coefficient by using inverse moisture algorithim approach. Yao and Maguer (1997a and b) and Spiazzi and Mascheroni (1997) solved the Fick's unsteady state equation (4.1) by numerical simulation procedure by considering shrinkage of the tissue. Salvatori *et al* (1999a) proposed an "advancing disturbance front" mechanism for determination of diffusion coefficient. Effective diffusivity has also been calculated by the slope method (Rastogi *et al* 1997; Ade-Omowaye *et al* 2002a).

In slope method, they had taken log on both sides of equation (4.2-4.4) and presented the resulting equation as a straight line between log (MR) and time.

$$LogMR = Log\left[\frac{M - M_t}{M_o - M_\infty}\right] = Log\left(\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\right) - \left[\frac{D_e(2n-1)^2 t}{L^2}\right]$$

Where,

$$Slope\ of\ Line = \left[\frac{D_e(2n-1)^2}{L^2}\right]$$

and $Intercept\ on\ Line\ = Log\left[\frac{8}{\pi^2}\sum_{n=1}^{\infty}\ \frac{1}{(2n-1)^2}\right]$

This method of calculation contradicted the basic principle of mathematics, because Logarithm could be operated on the equations having multiplication and division only, and not on the operators like addition (+) and subtraction (-).

Some researchers calculated effective diffusivity by using only first term of the Fourier series of Fickian model (equations 4.2- 4.4) assuming that the effect of terms other than first one on value of diffusivity was non-significant (Nieto *et al* 1998, ,Dandamrongrak *et al* 2002; Maskan *et al* 2002, Sharma *et al* 2003), which might not always be true. Some scientists (Simal *et al* 1997a and b; Telis *et al* 2003, 2004; Vivanco *et al* 2002 and Park *et al* 2002b) calculated diffusion coefficients by fitting the experimental data to first three to nine terms of the Fourier series equations (4.2-4.4) by using non-linear regression analysis. This regression analysis gave only a single value of diffusivity for the entire process, which was also illogical, because the value of diffusivity has been reported to change with time and moisture of the commodity. Therefore, a single value of effective diffusivity could not predict the kinetics of entire osmotic dehydration process.

Keeping in view the above drawbacks employed in calculation of effective diffusivity, a computer program was developed in C++ language to solve the equations (4.2 and 4.3) as given in Appendix-B(ii). The equation was solved by an iteration technique, in which firstly the value of diffusivity (D) was calculated by using only first term of the Fourier series. Then the value of D was incremented in such a manner that the predicted value of moisture ratio (or Solute gain ratio) approached the experimental one. The program was executed only for positive values of Fourier number ($F_o = D_{eff}*t/L^2$) as reported by Sharma *et al* (2003). To observe the precision of accuracy of computer program, the values of various statistical parameters like Residual squares, RMSE and E% for experimental and predicted values of MR (or SGR) were calculated by using diffusivity determined The values of these statistical parameters in Appendix-G indicates the high precision of computer program.

The variation of water and solute diffusivity during osmotic dehydration in solutions of salt, sugar and sugar-salt mixture having different concentrations, temperatures and solution to fruit ratios are presented in the following section. It was observe that the effective diffusivity for water loss as well as solute gain decreased with decrease of moisture and increase of solute gain, which might be due to the presence of less amount of free moisture and saturation of solute in the carrot cubes. The decrease in diffusivity might also be due to resistance imparted by impregnated solute to the water out flow and solute gain. The average values of moisture and solute diffusivity are presented in Table 4.4 to 4.6.

(a) Salt solution

Table 4.4 Effective diffusivity of water and solute for osmotic dehydration of carrot cubes in salt solution

No	Conc	Temp	R	m	α	M.C∝	SG∝	D_w (m^2/s)	D_s (m^2/S)
I	10	45	4	1.5996	7.31348	72.1255	5.8377	3.9946E-09	4.6400E-09
II	10	45	5	1.6600	11.1151	74.6148	5.7971	6.2397E-09	3.1522E-09
III	10	45	6	2.2624	18.6409	72.2563	5.0916	3.4654E-09	4.4063E-09
IV	10	55	5	2.5199	27.9841	75.5685	3.1938	3.7424E-09	3.9640E-09
V	10	35	5	1.7755	9.6019	74.2637	5.8685	5.7237E-09	3.0924E-09
VI	15	35	4	1.5368	6.8609	72.2452	8.7260	3.4869E-09	2.5040E-09
VII	15	35	6	1.9803	11.4130	73.7223	7.4460	4.4665E-09	2.2606E-09
VIII	15	45	5	1.9229	9.9429	71.1225	6.9735	3.5960E-09	3.7083E-09
IX	15	55	4	2.5962	13.1123	73.2565	3.1718	3.6166E-09	4.1025E-09
X	15	55	6	2.3350	21.7148	72.2545	3.8314	3.7799E-09	3.9190E-09
XI	5	45	5	6.4325	47.6677	75.0214	1.0368	2.6323E-09	3.6886E-09
XII	5	55	4	6.0479	40.3584	76.2545	0.6492	3.5395E-09	6.4390E-09
XIII	5	55	6	4.8048	44.0348	73.2522	1.0383	3.3398E-09	3.4067E-09
XIV	5	35	4	5.9681	11.9723	71.4525	1.1933	2.9184E-09	3.5276E-09
XV	5	35	6	2.5597	17.2624	72.2584	1.9900	2.3800E-09	3.1716E-09

The Table 4.4 indicates that for salt as osmotic agent, the average effective diffusivity of water loss and solute gain varied from 2.3800×10^{-9} to 6.2397×10^{-9} m^2/s and 2.2606×10^{-9} to 6.4390×10^{-9} m^2/s respectively, over the ranges of temperature 35-55°C, concentration 5-15% and solution to fruit ratio 4 to 6. For above range of process conditions, the average values of effective diffusivity for water loss and solute gain were 3.7995×10^{-9} m^2/s and 3.73223×10^{-9} m^2/s respectively. This order of magnitude was comparable to the results reported in literature for salt diffusion in fruits, vegetables, meats and fish. Telis *et al* (2003) reported salt effective diffusivity coefficients for Caiman muscle ranged between 4.7×10^{-9} and 96.2×10^{-9} m^2/s. Initial brine concentration played an important role in mass transfer rates, lowering diffusion coefficients at low initial salt concentration in brine.

It is clear from the Fig 4.7 that the effective diffusivity for water loss as well as salt gain decreased with decrease of moisture content and increase of solute gain. Highest diffusivity of water was observed for solution of 10% salt concentration as compared to 5% and 15% salt concentration. The penetration of salt might impart resistance to the water out flow (Lenart and Flink 1984; Chang *et al* 2003). The values were high for solution to fruit ratio of 5 as compared to ratio of 4 and 6. It was observed that in case of salt the effect of temperature was negative on effective diffusivity of water during the osmotic dehydration process. The values of effective diffusivity were high at 45°C as compared to 35 and 55°C. However, contrary to the water diffusivity, the solute diffusivity was highest at higher temperature, concentration and solution to fruit ratio. Therefore, water loss and solute gain exhibited different behavior in the osmotic dehydration process with salt solution. Product pre treatments and process conditions affecting the integrity of natural tissue (i.e. sulphiting, acidification, high process temperatures) seemed to favour solid uptake, yielding lower water loss/solid gain ratio, which was consistent with the results of Ponting (1973), Biswal and Maguer (1989) and Lazarides and Mavroudis (1995, 1996).

Similar behaviours of effective diffusivities for water loss and solute gain were observed during osmotic dehydration of carrot cubes in 5% and 15% salt solution at temperatures 35 and 55°C; and solution to fruit ratios 4 and 6 as indicated by the values tabulated in Appendix-F.

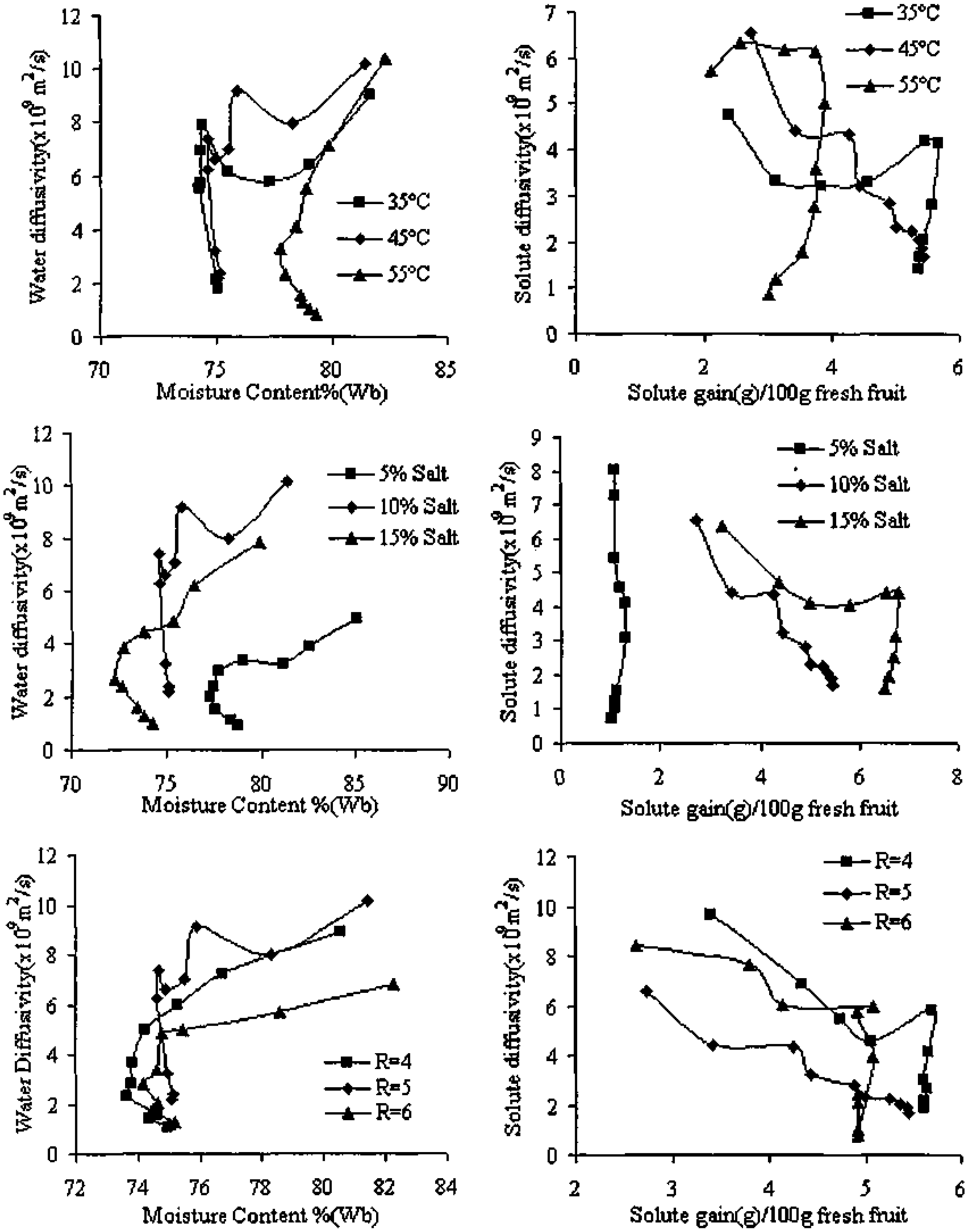


Fig 4.7 Effect of various process parameters on effective diffusivity of water and solute during osmotic dehydration of carrot cubes in osmotic solution of salt

(b) Sugar solution

Table 4.5 Effective diffusivity of water and solute for osmotic dehydration of carrot cubes in sugar solution

No	Conc.	Temp	R	m	α	MC∝	SG∝	Dw (m^2/S)	Ds (m^2/S)
I	50	35	5	3.6819	14.4098	59.2778	11.8340	1.6680E-09	1.2217E-09
II	50	45	4	4.6267	18.5070	53.6321	12.5780	1.1099E-09	1.0223E-09
III	50	45	5	4.1762	20.8811	51.1574	12.1501	1.3216E-09	1.1719E-09
IV	50	45	6	5.3693	32.2160	46.3701	12.2551	9.4387E-10	1.0353E-09
V	50	55	5	5.0184	25.0922	30.1820	14.0252	1.0525E-09	1.0909E-09
VI	55	55	4	5.5985	22.3941	10.2298	15.0602	8.3818E-10	6.3085E-10
VII	55	55	6	9.7260	58.3568	11.5099	10.799	9.7044E-10	7.1132E-10
VIII	55	45	5	16.446	82.2318	24.6469	6.6050	9.2965E-10	1.1311E-09
IX	55	35	4	22.647	90.5872	37.9649	4.9309	1.1238E-09	2.2031E-09
X	55	35	6	14.024	84.1471	41.1238	7.1942	1.3709E-09	1.1728E-09
XI	45	45	5	6.9520	34.7602	40.8750	10.2671	1.0244E-09	1.1489E-09
XII	45	55	4	4.7879	19.1515	23.3074	13.8122	9.3112E-10	8.2166E-10
XIII	45	55	6	4.8929	29.3574	20.4524	12.9032	1.0097E-09	7.9251E-10
XIV	45	35	4	16.722	66.8900	33.9647	4.5045	1.1852E-09	1.9682E-09
XV	45	35	6	18.957	113.746	31.3497	5.2604	1.0820E-09	1.0765E-09

The Table 4.5 indicates that for sugar as osmotic agent, the effective diffusivity of water loss and solute gain varied from 8.3818×10^{-10} to 1.6680×10^{-9} m^2/s and 6.3085×10^{-10} to 2.2031×10^{-9} m^2/s respectively, over the temperature range of 35-55°C, concentration from 45–55°B and solution to fruit ratio from 4 to 6. For above range of process conditions, the average values of effective diffusivity for water loss and solute gain were observed as 1.1041×10^{-9} m^2/s and $1.14664 \times 10^{-9} m^2/s$, respectively. These values are comparable to the results of various researchers. Lazarides *et al* (1997) found moisture diffusivity values ranging from 0.142×10^{-9} to 0.469×10^{-9} m^2/s for apple slices at different temperatures (20-50°C) and sucrose solution concentrations (45-65%). Rastogi and Raghavarao (1997) reported values of effective diffusivity of water ranged between 0.311×10^{-9} to 0.734×10^{-9} m^2/s and effective diffusivity of solute ranged between 0.288×10^{-9} to 0.7×10^{-9} m^2/s for carrot rings during osmotic dehydration when 30-50°C and solution to fruit ratio of 20 was used for sugar solution having concentration 40-70°B. Matusek and Meresz (2002) reported that effective diffusivity of sugar ranged from $0.05\text{x}10^{-9}$ to $0.3\text{x}10^{-9}$ m^2/s during osmotic dehydration of carrots in sugar solution. Park *et al* (2002a) reported that effective diffusivities varied from $3.47\text{x}10^{-10}$ to $1.92\text{x}10^{-10}$ m^2/s for water loss and from $1.99\text{x}10^{-10}$ to $3.60\text{x}10^{-10}$ m^2/s for solute gain during osmotic dehydration of pears in sugar syrup having 40-70°B concentration and temperature 40-60°C. Conway *et al* (1983) found diffusion coefficients of water for apples ranged from $15 \text{ x } 10^{-9}$ to $60 \text{ x}10^{-9}$ m^2/s depending on the initial sucrose concentration (50-70°B) and operating temperature (30-50°C). Similarly, Beristain *et al* (1990) reported diffusion coefficients of water ranged between $0.6 \text{ x}10^{-9}$ and $2.5 \text{ x}10^{-9}$ m^2/s for osmotic dehydration of pineapple in sugar solution.

It is clear from the Fig 4.8 that the effective diffusivity for water loss as well as sugar gain decreased with decrease of moisture and increase of solute gain. Highest diffusivity of water was observed for solution of 55°B sugar concentration as compared to 45°B and 50°B sucrose concentration. The values were high for solution to fruit ratio of 5 as compared to ratio of 4 and 6. It was observed that in case of sucrose, the effect of temperature was negative on effective diffusivity of water during the osmotic dehydration process. The values of effective diffusivity were high at 35°C as compared to 45 and 55°C. However, Contrary to the water diffusivity, the solute diffusivity was highest at 55°C solution temperature, 55°B solution concentration and solution to fruit ratio of 6.

Similar behaviours of effective diffusivities for water loss and solute gain were observed during osmotic dehydration of carrot cubes in 45 and 55°Brix sugar solution at solution temperatures 35 and 55°C; and solution to fruit ratios 4 and 6 as indicated by the values tabulated in Appendix-F.

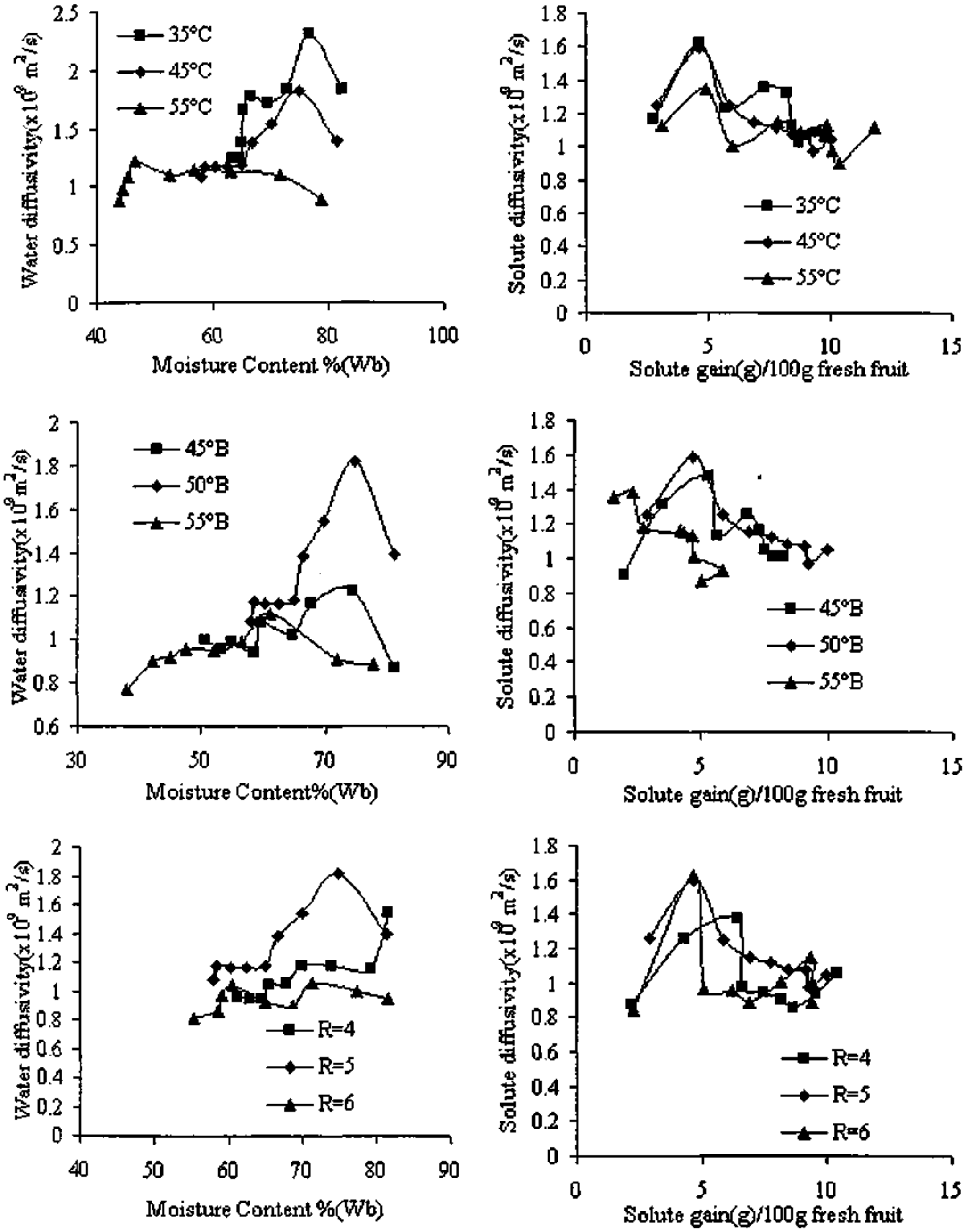


Fig 4.8 Effect of various process parameters on effective diffusivity of water and solute during osmotic dehydration of carrot cubes in osmotic solution of sugar

(C) Solution of sugar-salt mixture

Table 4.6 Effective diffusivity of water and solute for osmotic dehydration of carrot cubes in solution of sugar-salt mixture

No	Conc	Temp	R	m	α	M.C∝	SG∝	D_w (m^2/S)	Ds (m^2/S)
I	10	45	4	5.7678	23.0713	26.6678	13.2101	1.5941E-09	1.2160E-09
II	10	45	5	5.5464	33.2786	24.3318	15.1282	1.7685E-09	1.1747E-09
III	10	35	5	9.0431	45.2153	30.000	11.7641	1.6798E-09	1.6450E-09
IV	10	55	5	8.1116	40.5579	20.5804	14.5772	2.0782E-09	1.5762E-09
V	10	45	6	3.3114	37.8682	19.2023	15.8473	1.6689E-09	1.3077E-09
VI	15	45	5	7.9929	39.9646	19.3462	15.6252	1.9772E-09	1.2610E-09
VII	5	45	5	7.4831	37.4153	29.5913	13.5133	1.7215E-09	1.2172E-09
VIII	15	45	4	6.2003	24.8011	23.3799	15.2201	1.9811E-09	2.3728E-09
IX	15	55	6	6.3612	39.8167	20.0225	15.4792	2.1338E-09	3.2771E-09
X	15	35	4	6.2244	24.8977	27.4629	14.6623	1.9756E-09	1.5394E-09
XI	15	35	6	7.7758	46.6550	27.1663	15.0822	2.3086E-09	1.7707E-09
XII	5	55	4	7.5209	30.1164	19.4811	12.0622	1.6121E-09	1.4486E-09
XIII	5	55	6	6.6405	39.8433	19.4814	13.9471	1.7992E-09	1.4900E-09
XIV	5	35	4	7.4543	31.0173	29.5016	11.2482	1.5447E-09	1.4683E-09
XV	5	35	6	6.3336	39.0018	27.9959	12.8863	1.8039E-09	9.5015E-10

The Table 4.6 indicates that for sugar-salt mixture as osmotic agent, the effective diffusivity of water loss and solute gain varied from 1.5447×10^{-9} to 2.3086×10^{-9} m^2/s and 0.95015×10^{-9} to 3.2771×10^{-9} m^2/s respectively, over the temperature range of 35-55°C, concentration from 45 –55°B and solution to fruit ratio from 4 to 6. For above range of process conditions, the average values of effective diffusivity for water loss and solute gain were 1.8431×10^{-9} m^2/s and 1.5810×10^{-9} m^2/s respectively. The calculated effective diffusion coefficients for solute were analogous to those reported by various researchers. Vivanco *et al* (2002) reported effective diffusivity of solute ranged between 0.12×10^{-9} to 0.06×10^{-9} m^2/s during osmotic dehydration of tilapia fillets in solution of sugar-salt mixture at 20°C temperature and solution to fruit ratio of 4. Azoubel and Murr (2004) reported the effective diffusion coefficients ranged from 0.43×10^{-9} to 1.77×10^{-9} m^2/s for water loss and from 0.04×10^{-9} to 0.54×10^{-9} m^2/s for solute gain during osmotic dehydration of Cherry tomato in solution sucrose-salt mixture. Telis *et al* (2004) reported apparent diffusion coefficients for water loss and solute between 3.35 $\times 10^{-10}$ to 8.58 $\times 10^{-10}$ m^2/s during osmotic dehydration of tomatoes in solution of sugar-salt mixture.

It is clear from the Fig 4.9 that the effective diffusivity for water as well as sugar decreases with decrease of moisture and increase of solute gain. Highest diffusivity of water during osmotic dehydration of carrot cubes was observed for solution of sugar-salt mixture having concentration 50°B +15% as compared to 50°B +5% and 50°B +10% salt. The values were high for solution to fruit ratio of 5 as compared to ratio of 4 and 6. It was observed that in case of osmotic dehydration in salt solution, the effect of temperature was negative on effective diffusivity of water. The values of effective diffusivity were high at temperature of 55°C as compared to 35 and 45°C. Similarly, the solute diffusivity was also highest at 55°C, 50°B sugar +15% salt concentration and solution to fruit ratio of 6. The effective diffusivity increased for water loss with the increase in temperature, concentration and solution to fruit ratio. The similar results were observed for solute diffusion.

Similar behaviours of effective diffusivities for water loss and solute gain were observed during osmotic dehydration of carrot cubes in 50°B+5% and 50°B+15% in sugar-salt mixture solution at solution temperatures 35 and 55°C; and solution to fruit ratios 4 and 6 as indicated by the values tabulated in Appendix-F.

Apparent water diffusivity of various products during osmotic dehydration in different osmotic solutions at different process temperatures during osmotic dehydration are summarized in the following Table 4.7.

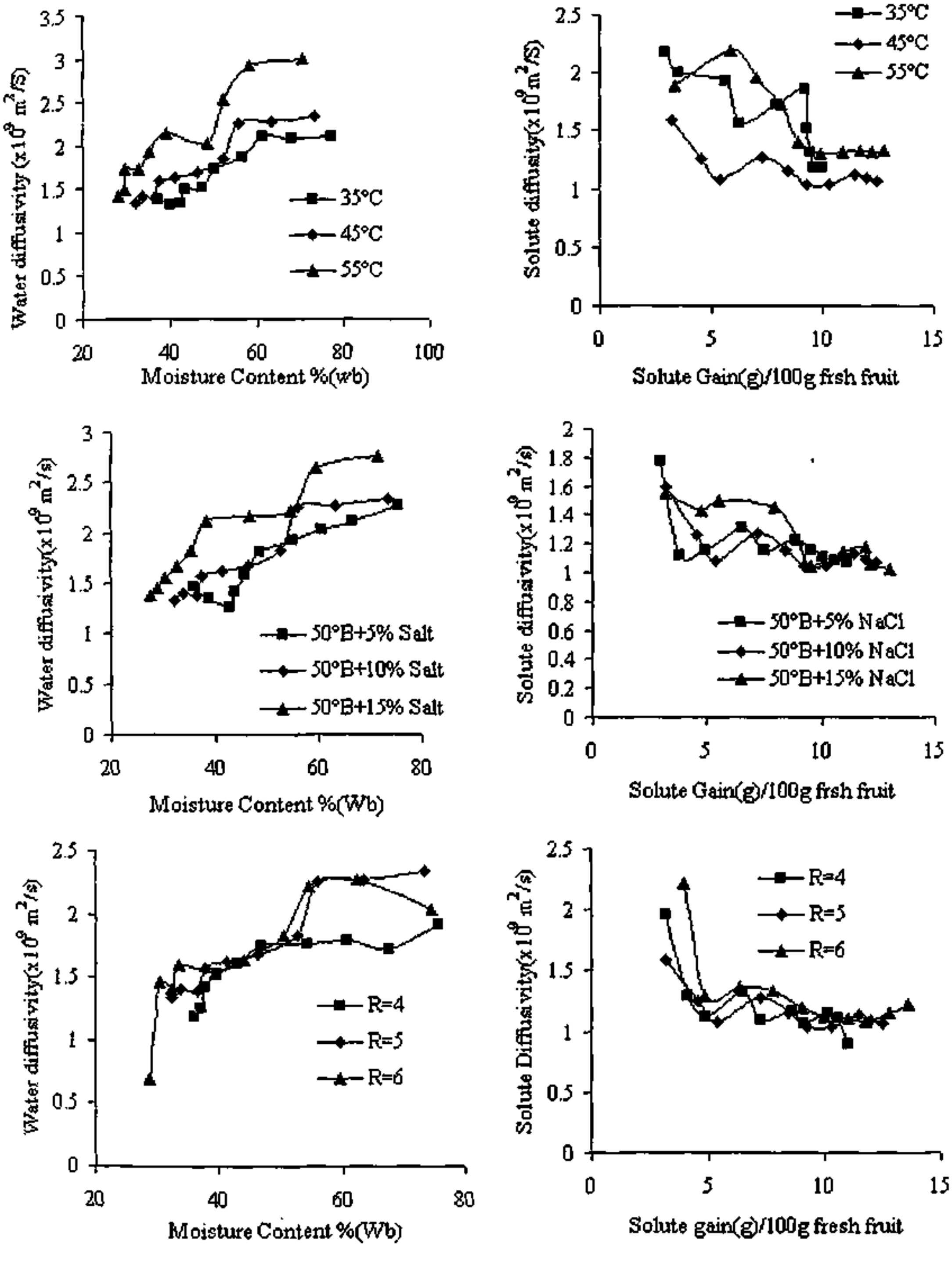


Fig 4.9 Effect of various process parameters on effective diffusivity of water and solute during osmotic dehydration of carrot cubes in osmotic solution of sugar-salt mixture

Table 4.7 Effective diffusivity of water loss during osmotic dehydration of selected fruits and vegetables in different osmotic solutions

Product	**Conc %**	**Temp**	**D_{water} $m^2/sX10^{-10}$**	**Reference**
Pine Apple	50	30-40	7.26-26.38	Beristain *et al* (1990)
Pine Apple	50	30-40	7.45-26.13	Azuara *et al* (1992)
Coconut	40-70	25-45	17.6-39.2	Rastogi and Raghavarao (1994)
Potato	Corn Syrup	25-50	0.88-2.14	Lazarides and Mavroudis (1996)
Pear	40-70°B	40-60	3.47-19	Park K J *et al* (2002a)
Banana	40-70°B	25-35°C	8.5-24.3	Rastogi *et al* (1997)
Apple cubes	70°B	50°C	5.13-5.65	Simal *et al* (1997a and b)
Red Paprika	5-45%sugar +0-15% salt		>=8.0	Ade-Omowaye *et al* (2002a)
Banana chips	50-70°B	50-70°C	27.7-26.6	Waliszewki *et al* (1997)
Pears			1.87-8.12	Park *et al* (2002b)
Apple	40-60°B	20-50°C	0.3323-2.1335	Ertekin and Sultanoglu (2000)
Apple	45-65% Sugar	20-50°C	1.42-3.38	Lazarides *et al* (1997)
Apple	Corn Syrup of DE 18-50	50°C	3.49-5.54	Lazarides *et al* (1997)

4.1.4 Validation of empirical models for osmotic dehydration of carrot cubes

The validity of Power, Page, Newton (Lewis) and Generalized exponential model was checked for moisture ratio and solute gain ratio. For water loss and solute gain, the validity of Penetration, Magee and Azuara model was checked.

In all the experiments of osmotic dehydration in solutions having different composition, concentrations, temperatures and solution to fruit ratio, the values of R^2 were low in case of Newton, Power and Penetration model. It was observed that for both moisture ratio (MR) and solute gain ratio (SGR) the Page model was best-fitted model as compared to GEM, Newton and Power model. As out of these models, Newton model was fitted least; therefore parameters pertaining to this model were not included in this chapter.

Best model chosen was one having the highest coefficient of correlation (R^2) and the least RMSE, Chi-square and E (%). Therefore, the Magee and Azuara model represented the experimental data of osmotic dehydration with more accuracy. Further, for water loss and solute gain, Azuara model had an excellent fit as compared to Magee model due to lower values of E (%). Similar results were reported by Rahman and Lamb (1990), Azoubel and Murr (2000), Kar and Gupta (2001). However, Lazarides and Mavroudis (1996), Pokharkar and Prasad (1998) reported that Penetration model was a universal model for osmotic dehydration, but this model did not fit to the experimental data in the present study. The values of various statistical parameters of these models were given in Appendix-H.

For checking the validity of empirical models for all the osmotic dehydration processes, regression analysis was performed for the entire duration of 4 hours. In case of osmotic dehydration in salt solution, the goodness of fit of for these models was least in comparison to osmotic dehydration in sugar and sugar-salt mixture solutions. The poor fit of models might be due to a sudden fall in the curvilinear part of curve after duration of 90-120 minutes. In some experiments of osmotic dehydration with salt, the values of R^2 were recorded nil, which indicate zero correlation between experimental data and the empirical models. However, Azuara and Page models were found to be fitted in few experiments during osmotic dehydration of carrot cubes in salt solution, particularly at low process temperature. The goodness of fit of models could be improved by performing regression analysis only for curvilinear portion of kinetics curves i.e. for osmotic dehydration of fruit only up to 90-120 minutes in salt solution.

The values of model constants along with statistical parameters for various models are given in Appendix-H. The comparison of experimental and predicted values of various osmotic dehydration models could be analyzed visually in the plots (Fig 4.10 to 4.12)

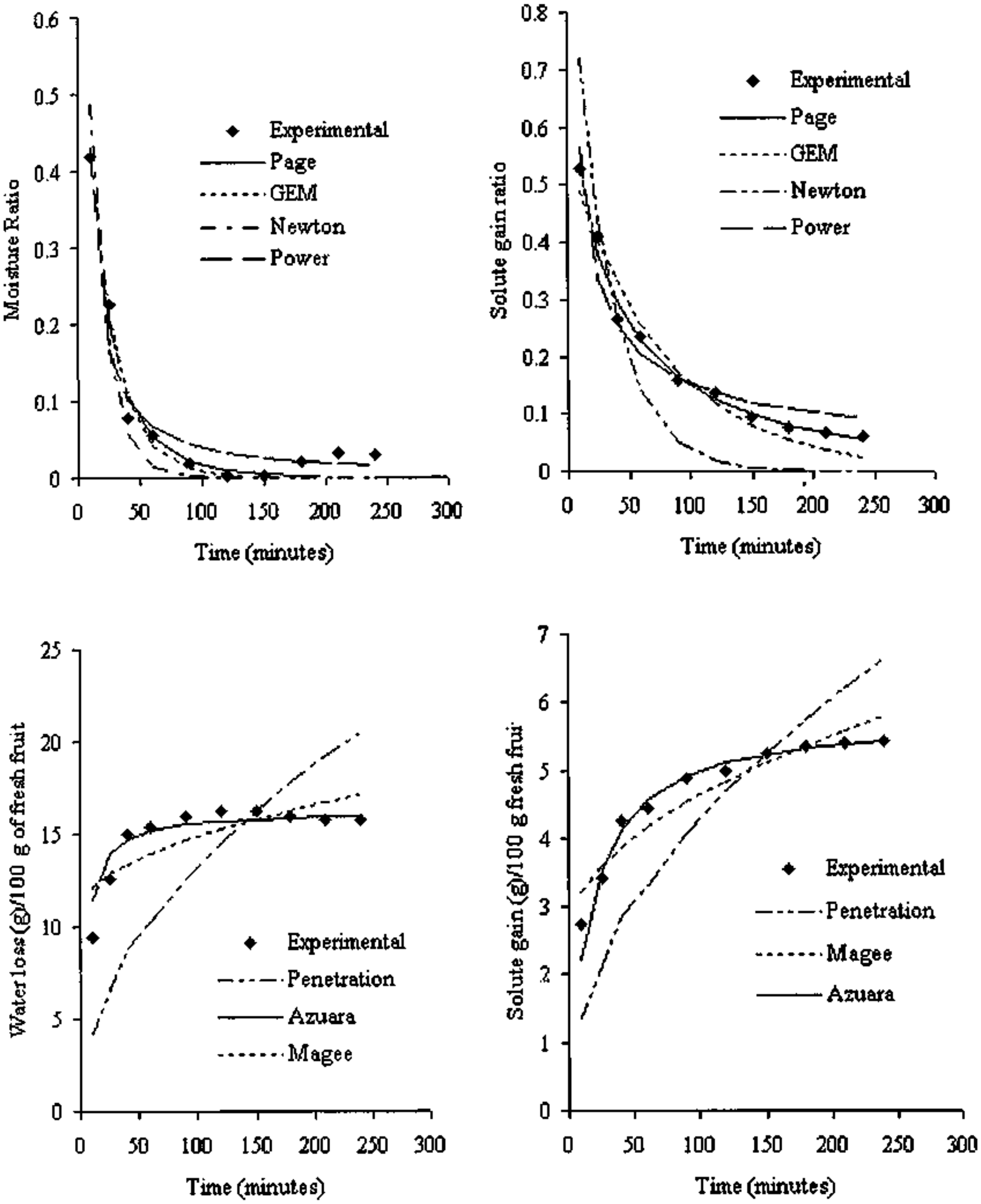


Fig 4.10 Comparison of experimental and predicted values of various models for osmotic dehydration of carrot cubes in solution of 10% salt concentration at 45°C and solution to fruit ratio of 5

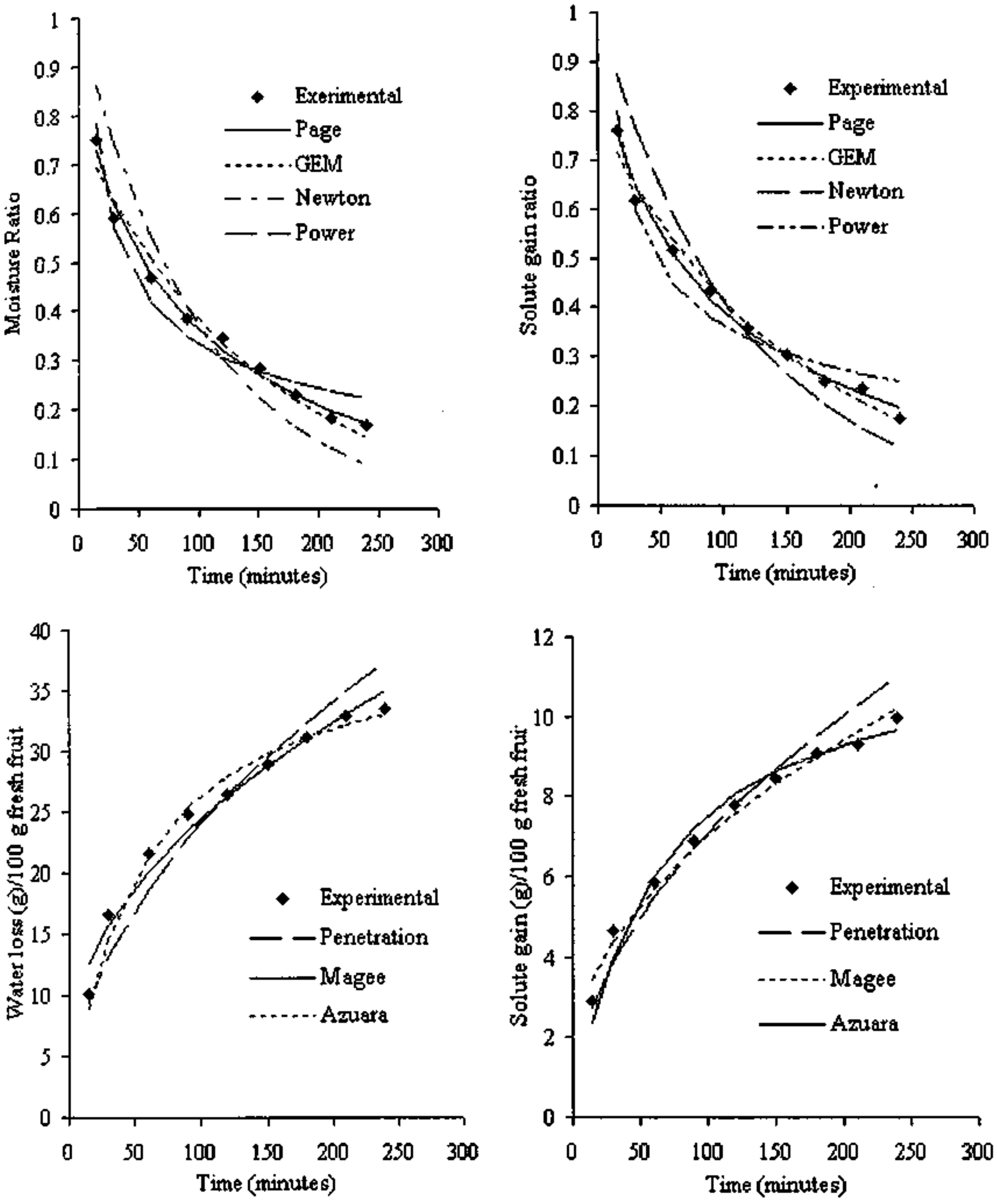


Fig 4.11 Comparison of Experimental and Predicted values of various models for osmotic dehydration of carrot cubes in sugar solution of 50°B concentration at 45°C and solution to fruit ratio of 5

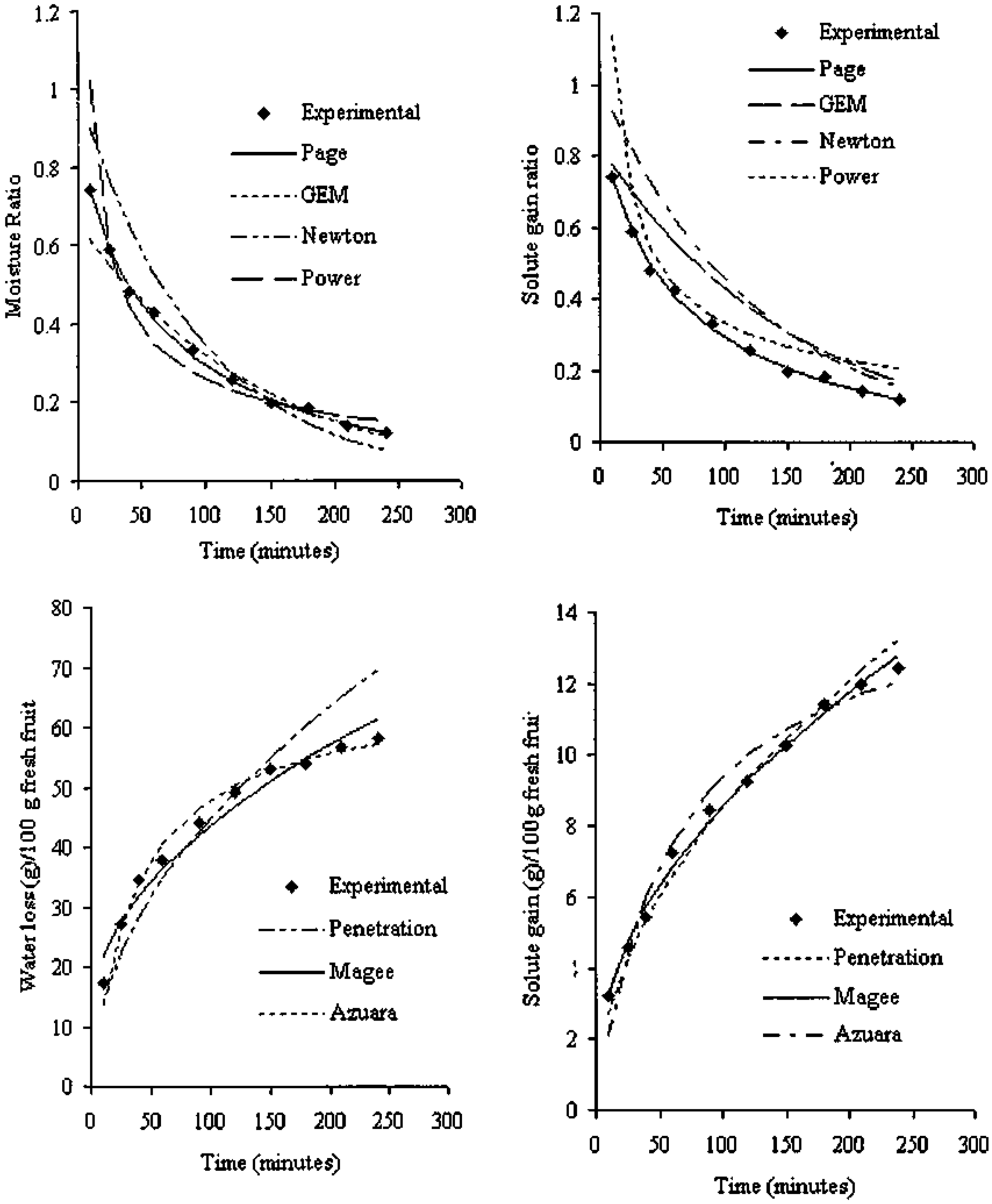


Fig 4.12 Comparison of Experimental and Predicted values of various models for osmotic dehydration of carrot cubes in solution of 50°B+10% salt concentration at 45°C and solution to fruit ratio of 5

4.2 Optimization of osmotic dehydration process by response surface methodology

In order to optimize the process parameters viz. osmotic solution concentration, temperature and process duration for osmotic dehydration of 1 cm x 1 cm x 1 cm carrot cubes in solutions of salt, sugar and sugar-salt mixture central composite rotatable design (CCRD) was adopted (Khuri and Cornell 1987). The data of the experimental studies i.e. the responses measured for each treatment combination was as shown in Appendix-I.

The second order polynomial equation was fitted to the experimental data of each dependent variable as given below

$$Y_{ku} = B_{k0} + \sum_{i=1}^{n} B_{ki} x_{iu} + \sum_{i=1}^{n} B_{kii} x_{iu}^{2} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} B_{kij} x_{iu} x_{ju} + e_{ku}$$

Where Y_{ku}= Response variable (Y_{1u}=Water Loss g/100g Fresh fruit, Y_{2u}= Solute gain g/100 f fresh fruit, Y_{3u}= rehydration ratio, y_{4u}= % shrinkage of rehydrated product, y_{5u}= % Overall acceptability of rehydrated product), x_{iu}'s represent the coded independent variables (x_{1u}= process duration, x_{2u}= process temperature, x_{3u} = solution concentration). Where B_{ko} was the value of fitted response at the centre point of design, i.e. point (0,0,0), B_{ki}, B_{kij} were the linear, quadratic and cross-product regression coefficients, respectively. The subscript 'u' (1 to 3) refers to the treatments. i.e. u=1 for salt solution, u=2 for sugar solution and u=3 for combination of sugar and salt.

The optimization of the osmotic dehydration process was aimed at finding the levels of independent variables viz. osmotic solution concentration, temperature and process duration, which would give maximum water loss, rehydration ratio, overall acceptability and minimum solute gain and shrinkage (%) of rehydrated carrot cubes.

The statistical analysis of the experimental data was performed to observe the effect of various process parameters on measured responses. The results indicate the adequacy of quadratic models for all responses because of high R^2, very low value of p-level and non-significant lack of fit at 5% level of significance. The relative effect of each process parameter on individual response was compared from the β values corresponding to that parameter. The relative effect of each process parameter was compared from the β values corresponding to that parameter. The β coefficients were the regression coefficients obtained by first standardizing the process variables to a mean of zero and standard deviation to one. Thus, the advantage of using β coefficient (as compared to B coefficients which are not standardized) was that the magnitudes of these values allow us to compare the relative contribution of each independent variable in the prediction of the dependent variable (Statistica manual 1995). Higher the positive value of β of a parameter; higher would be the effect of that parameter and vice versa. The negative value of β indicates the negative effect of that parameter on measured response.

Further statistical analysis for overall effect of the process variables on all the responses was performed as presented in Appendix-J. This was a joint test on all parameters involving one particular factor. For example, test for time (x_1) tests the hypothesis that the parameters of x_1, $(x_1)^2$, x_1x_2, x_1x_3 etc are equal to zero. In simple terms, the values in Appendix-J give factor wise analysis of variance i.e. the contribution of each independent variable to the total sum of squares are separated. These results revealed that the process variables time, temperature and concentration have significant overall effect on the five responses. Process time and solution temperature have most significant effect (significant at 1% level) on all the responses for all the osmotic agents. However non-significant effect of sugar solution concentration was observed on solute gain, rehydration ratio and shrinkage, and that of salt solution concentration on overall acceptability of rehydrated product. It could be due to very small difference of concentration between two successive osmotic solutions.

The response surface and contour plots were generated for different interaction of any two independent variables, while holding the value of third variable as constant. Such three-dimensional surfaces could give accurate geometrical representation and provide useful information about the behaviour of the system within the experimental design.

The detailed analysis of various responses for the osmotic dehydration of carrot cubes in salt, sugar and mixture of sugar-salt solutions having different solution concentrations and temperatures are described as under:

4.2.1 Diagnostic checking of fitting mode and surface plots for various responses

4.2.1.1 Diagnostic checking of fitted model and surface plots for water loss during osmotic dehydration

(a) Salt solution

The magnitude of p and β values in Table 4.8 indicates the maximum positive contribution of osmotic solution concentration followed by solution temperature, and negligible contribution of process duration effect on the water loss during osmotic dehydration in salt solution. It implies increase in water loss with increase of osmotic concentration and temperature. The quadratic terms of process parameters have negative and significant effect on water loss. Further, the interactions of 'time and temperature', and 'temperature and concentration' have negative, and that of 'time and concentration, positive effect on water loss having negligible magnitude as compared to linear terms of process variables. The Fig 4.13 also indicates an increase in water loss with increase in osmotic solution concentration and temperature. However, no significant change in water loss was observed with the increase in process time after 90 minutes. No significant rise in water loss was observed beyond concentration of 10% and temperature of 40°C.

(b) Sugar solution

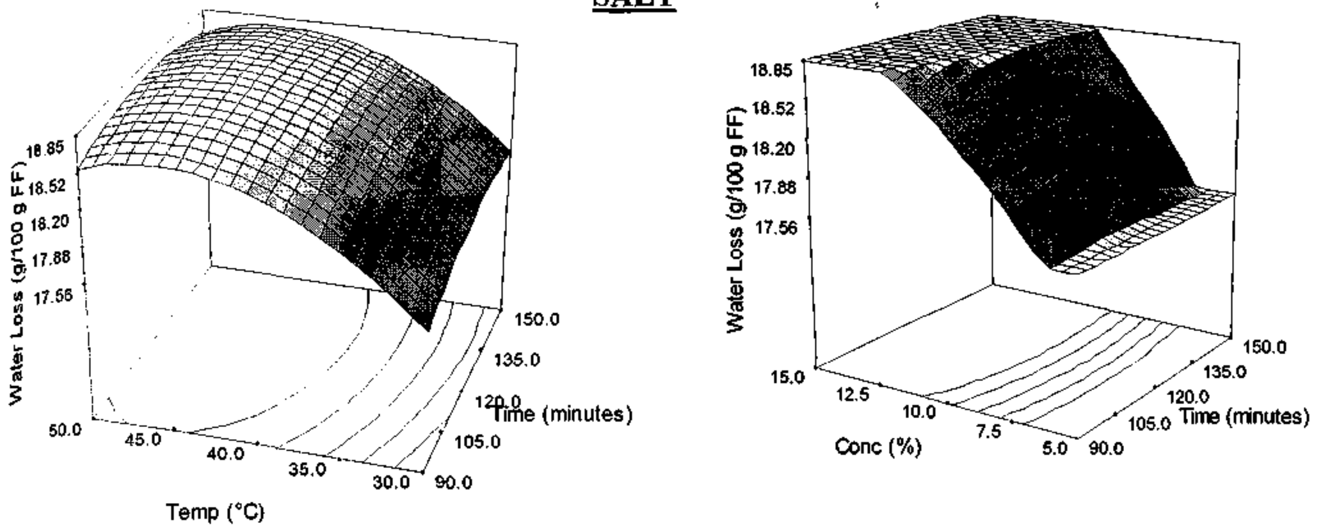
The magnitude of p and β values in Table 4.8 indicates the maximum contribution of solution temperature followed by process duration, and negligible but significant contribution of solution concentration on water loss during osmotic dehydration in sugar

Table 4.8 Regression summary and ANOVA for for <u>water loss</u> for osmo-convective dehydration in solutions of salt, sugar and sugar-salt mixture

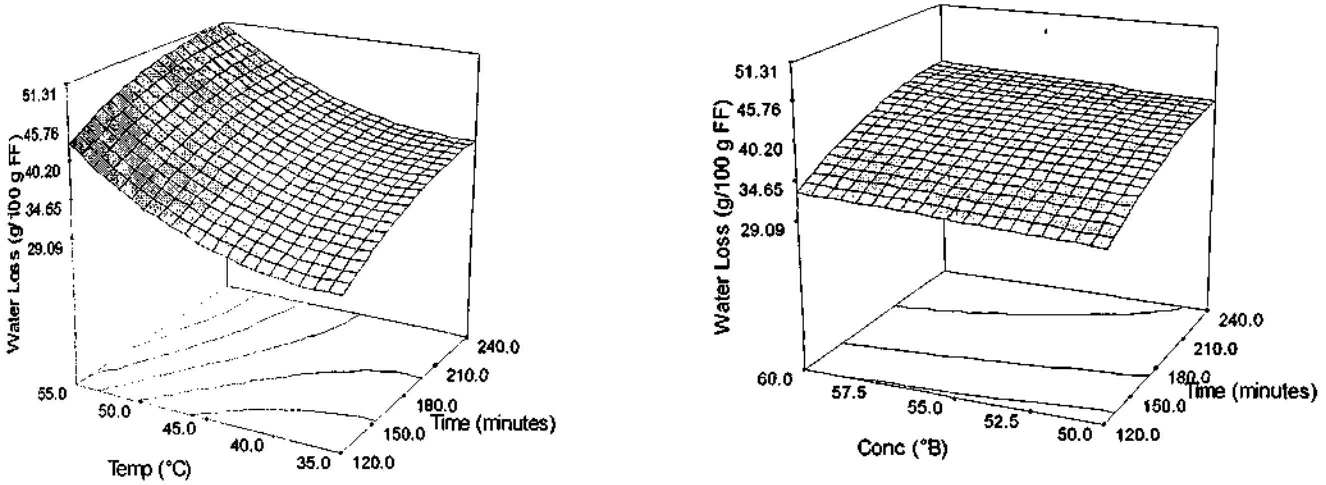
		Salt				Sugar				Sugar-salt			
Source	df	β	B	Sum of squares	p-level	β	B	Sum of squares	p-level	β	B	Sum of squares	p-level
Model	9	-	-	26.4366	9E-22	-	-	1165.08	9E-11	-	-	639.169	1.37E-23
Constant	1	-	18.724	-	8E-34	-	38.547	-	1E-17	-	45.186	-	1.51E-32
Time	1	0.0635	0.0883	0.10656	2.4E-12	0.4715	4.4099	265.588	4E-10	0.4824	3.3	148.721	5.77E-23
Temp	1	0.3212	0.4469	2.72775	2.2E-19	0.7227	6.6864	610.571	6E-12	0.5212	3.5654	173.607	2.66E-23
Conc	1	0.8493	1.1816	19.0677	1.3E-23	0.1056	0.9253	11.6939	0.0004	0.1973	1.3499	24.8874	4.39E-19
Time*Time	1	-0.1	-0.134	0.26028	2.8E-14	-0.217	-1.913	52.722	9E-07	-0.2354	-1.554	34.7808	8.24E-20
Temp*Temp	1	-0.325	-0.436	2.74076	2.2E-19	0.4205	3.7305	200.553	1E-09	0.4914	3.2434	151.603	5.24E-23
Conc*Conc	1	-0.217	-0.291	1.21961	1.2E-17	0.0017	-0.034	0.01671	0.9363*	-0.1294	-0.854	10.5126	3.26E-17
Time*Temp	1	-0.031	-0.057	0.02581	2.6E-09	-0.012	-0.15	0.1788	0.5555*	0.0517	0.4621	1.70834	2.83E-13
Time*Conc	1	0.1025	0.1864	0.27783	2E-14	0.0053	0.0644	0.03315	0.7982*	-0.0409	-0.365	1.06712	2.94E-12
Temp*Conc	1	-0.141	-0.257	0.52855	8.1E-16	0.0034	0.0411	0.0135	0.8703*	-0.3345	-2.99	71.5015	2.25E-21
Residual	10	-	-	0.00067	-	-	-	3.41148	-	-	-	0.00702	-
Lack of Fit	5	-	-	0.00047	0.1922	-	-	2.62611	0.1056	-	-	0.00525	0.1292
Pure Error	5	-	-	0.0002	-	-	-	0.78537	-	-	-	0.00177	-
Corrected Total	19	-	-	26.4373	-	-	-	1168.49	-	-	-	639.176	-
R^2	0.9997					0.9959				0.9999			
Adj R^2	0.9995					0.9924				0.9999			

* Non-significant at 5%level of confidence interval.

SALT



SUGAR



SUGAR-SALT MIXTURE

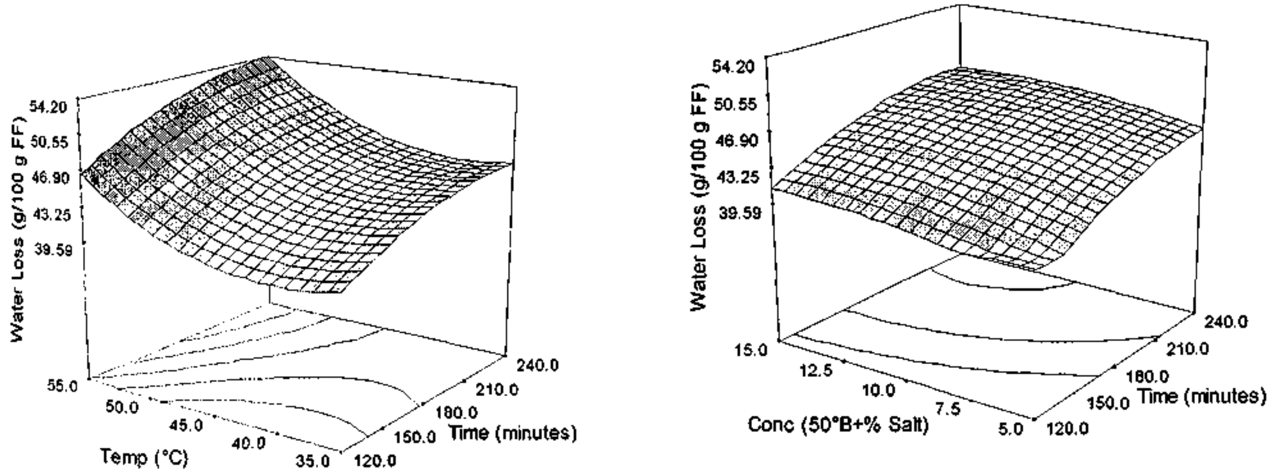


Fig 4.13 Effect of process variables on water loss during osmotic dehydration of carrot cubes in solutions of salt, sugar and sugar-salt mixture

solution. It implies increased water loss with increase of solution temperature and process duration. The quadratic terms of temperature have positive effect and time has negative effect on water loss. The maximum contribution of quadratic term was of osmotic solution temperature followed by time; whereas quadratic term of concentration has non-significant effect on water loss. The interactions of all the process parameters have non-significant effect on water loss. Fig 4.13 indicates an increase in water loss with increase of process duration and osmotic solution temperature and non-significant increase in water loss with increase of osmotic solution concentration ranged between 50 to 60°B. This might be due to the small difference of 5°B concentration between two successive osmotic solution concentrations.

(c) Solution of sugar-salt mixture

The magnitude of p and β values in Table 4.8 indicates the maximum positive contribution of osmotic solution temperature followed by process duration and solution concentration on the water loss during osmotic dehydration in solution of sugar-salt mixture. It implies increased water loss with increase of solution temperature and process time. The quadratic terms of time and concentration have negative, and that of temperature have positive effect on water loss. Further, interactions of 'time and temperature', 'temperature and concentration' have negative but significant effect, whereas the interaction of 'time and concentration' has positive, but significant effect on water loss. However, the interaction terms of all terms have negligible effect on water loss except interaction of 'temperature and concentration'. Fig 4.13 also indicates an increase in water loss with increase of process duration and osmotic solution temperature and non-significant increase in water loss with increase of osmotic solution concentration between ranged 5 to 15% salt in 50°B sucrose solution

The equations of models fitted for water loss during osmotic dehydration in the actual form of process variables after elimination of non-significant terms at 5% level of significance are shown as under;

For salt solution

Water Loss(g)/100 g fresh fruit = 2.45435+0.033932 * Time + 0.46770 * Temp + 0.52560 * Conc - 493 $x10^{-4}$ * Time^2 - 4.36098 $x10^{-3}$ * Temp^2 - 0.011636 * Conc^2 - 1.8933 $x10^{-4}$ * Time * Temp + 1.2424 $x10^{-3}$ * Time * Conc - 5.1407 $x10^{-3}$ * Temp * Conc

For sugar solution

Water Loss(g)/100 g fresh fruit = 43.44828 + 0.26443 * Time - 2.69182 * Temp + 0.18507 * Conc - 5.30363 $x10^{-4}$ * Time^2 + 0.037338 *Temp^2

For sugar-salt mixture solution

Water Loss(g)/100 g fresh fruit = 41.96419 + 0.18787*Time - 2.10325*Temp + 3.86303 * Conc - 4.31535$x10^{-4}$ * Time^2 + 0.032434 * Temp^2 - 0.034164 * Conc^2 + 7.7017 $x10^{-4}$ * Time * Temp - 1.21742$x10^{-3}$ * Time * Conc - 0.05979 * Temp * Conc

4.2.1.2 Diagnostic checking of fitted model and surface plots for solute gain during osmotic dehydration

(a) Salt solution

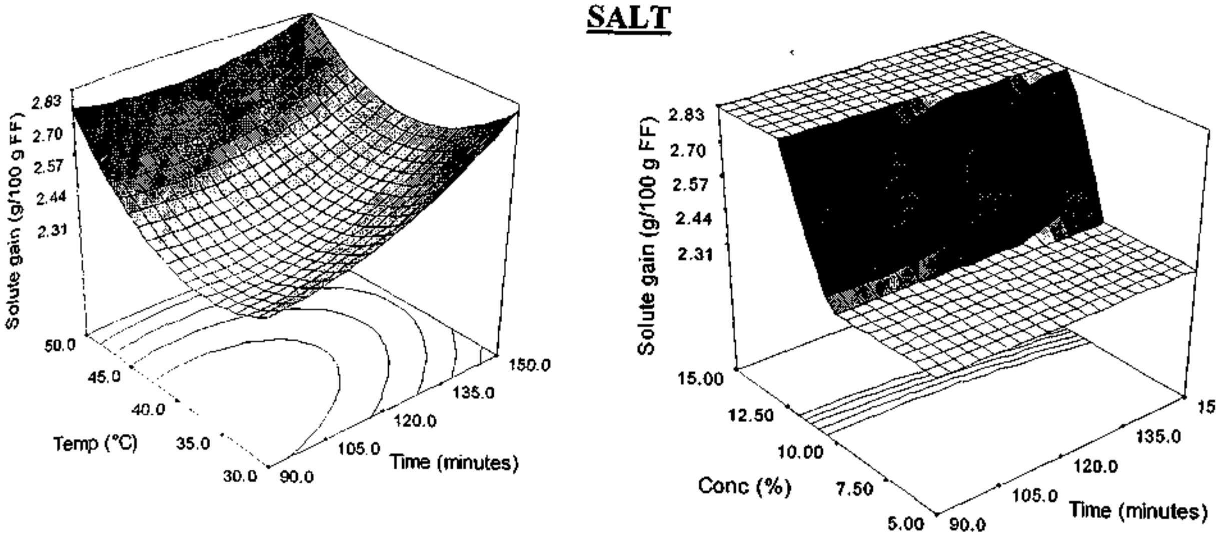
The magnitude of p and β values in Table 4.9 indicates maximum contribution of solution concentration, and the negligible but significant contribution of time and temperature on the solute gain during osmotic dehydration in salt solution. It implies the increased solute gain with increase of osmotic solution concentration. The quadratic terms of solution concentration and temperature have maximum positive effect on solute gain. Further, the interaction of 'time and temperature', 'temperature and concentration' have negative effect, whereas, the interaction of 'time and concentration, has positive effect on solute gain. However, the interaction terms have negligible effect on solute gain except the interaction of 'temperature and concentration' as compared to the impact of linear and quadratic terms. Fig 4.14 also indicates a significant increase in solute gain with the increase of osmotic solution concentration, temperature and process time. The solute gain

Table 4.9 Regression summary and ANOVA for <u>solute gain</u> during osmo-convective dehydration in solutions of salt, sugar, and sugar-salt mixture

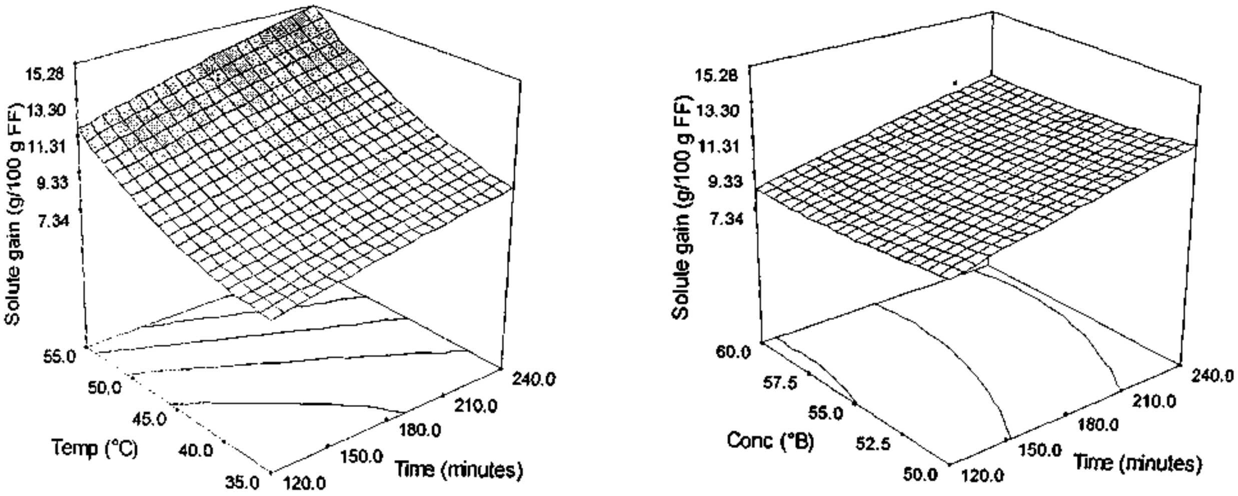
Source	df	Salt				Sugar				Sugar-salt			
		β	B	Sum of squares	p-level	β	B	Sum of squares	p-level	β	B	Sum of squares	p-level
Model	9	-	-	29.6597	2.1E-20	-	-	131.747	6E-06	-	-	63.1774	2.41E-18
Constant	1	-	2.3836	-	3E-23	-	10.133	-	9E-12	-	13.466	-	4.54E-27
Time	1	0.083	0.1223	0.20419	3.8E-12	0.4556	1.4421	28.4031	2E-05	0.6096	1.3112	23.4787	9.77E-19
Temp	1	0.0672	0.0991	0.13403	3.1E-11	0.7978	2.5255	87.1047	1E-07	0.7014	1.5087	31.0872	2.4E-19
Conc	1	0.8825	1.3006	23.1009	2.1E-22	-0.101	-0.32	1.3963	0.1294*	0.3406	0.7326	7.3297	3.28E-16
Time*Time	1	0.0578	0.0822	0.09727	1.5E-10	-0.025	-0.075	0.08117	0.6987*	0.0717	0.1488	0.31895	1.89E-09
Temp*Temp	1	0.1595	0.2268	0.74125	6.2E-15	0.3096	0.9455	12.8823	0.0005	0.086	0.1784	0.45891	3.18E-10
Conc*Conc	1	0.2317	0.3295	1.56432	1.5E-16	0.0845	0.2581	0.96005	0.2005*	0.0225	0.0467	0.03145	8.23E-05
Time*Temp	1	-0.044	-0.085	0.05807	1.9E-09	0.0744	0.3077	0.75749	0.2515*	0.0004	0.0012	1.2E-05	0.9046*
Time*Conc	1	0.099	0.1906	0.29066	6.6E-13	0.014	0.0578	0.02674	0.8237*	-0.0021	-0.006	0.00028	0.5604*
Temp*Conc	1	-0.355	-0.684	3.7443	1.9E-18	0.0459	0.1898	0.28815	0.4701*	-0.0948	-0.267	0.56834	1.11E-10
Residual	10	-	-	0.00141	-	-	-	5.11221	-	-	-	0.00777	-
Lack of Fit	5	-	-	0.00106	0.1259	-	-	3.16045	0.3049	-	-	0.00611	0.0902
Pure Error	5	-	-	0.00035	-	-	-	1.95175	-	-	-	0.00167	-
Corrected Total	19	-	-	29.6611	-	-	-	136.859	-	-	-	63.1852	-
R^2		0.9999				0.9626				0.9998			
Adj R^2		0.9999				0.9290				0.9997			

* Non-significant at 5%level of confidence interval.

SALT



SUGAR



SUGAR-SALT MIXTURE

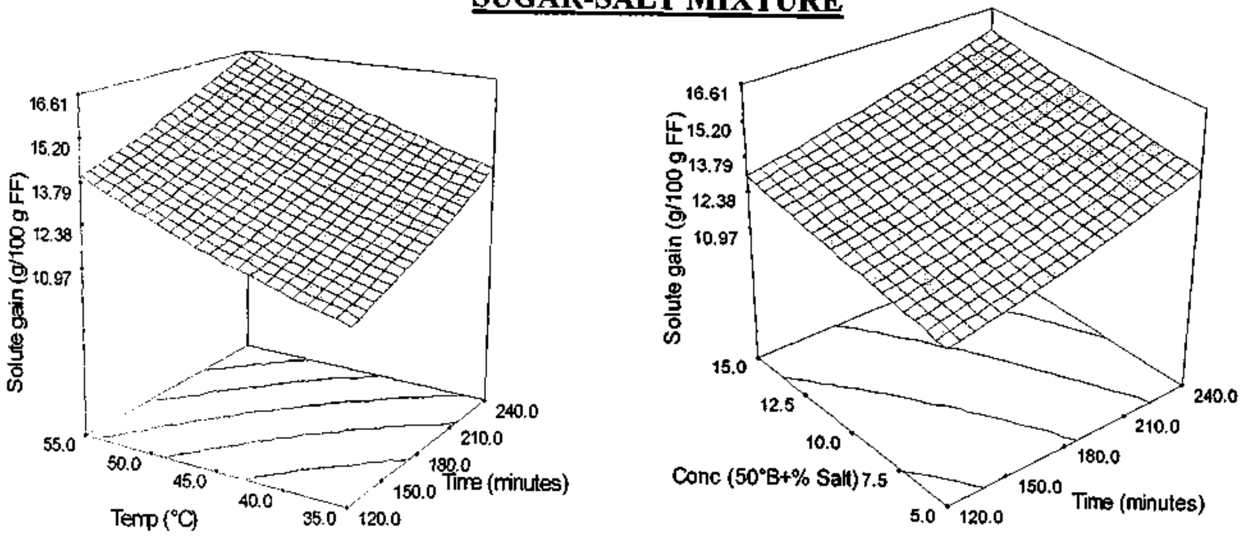


Fig 4.14 Effect of process variables on solute gain during osmotic dehydration of carrot cubes in solutions of salt, sugar and sugar-salt mixture.

was lowest for 90 minutes duration at 5-10 % salt concentration and 35°C osmotic solution temperature.

(b) Sugar solution

The magnitude of p and β values in Table 4.9 indicates the maximum positive contribution of osmotic solution temperature followed by process duration on solute gain during osmotic dehydration in sugar solution. The osmotic solution concentration has non-significant effect on the solute gain. It implies increased solute gain with increase of osmotic solution temperature and process duration. The quadratic term of temperature has positive and significant effect and that of time and concentration have non-significant effect on solute gain. Further, the interactions of all the variables have non-significant effect on solute gain. Fig 4.14 also indicates a linear increase in solute gain with increase of process duration and osmotic solution temperature and non-significant increase in solute gain with increase of osmotic solution concentration ranged between 50 to 60°B.

(c) Solution of sugar-salt mixture

The magnitude of p and β values in Table 4.9 indicates the maximum contribution of osmotic solution temperature followed by process duration, whereas, the solution concentration has least but significant effect on the solute gain during osmotic dehydration in solution of sugar-salt mixture. It implies increased solute gain with increase of process duration, osmotic solution temperature and concentration.

The quadratic terms of time, temperature and concentration have positive and significant effect on solute gain, but effects of the quadratic terms were negligible in comparison to effect of linear terms of process parameters. Further, only the interaction of 'time and concentration' has significant but negative effect on solute gain, however, the effect was negligible in comparison to effect of linear terms of process parameters. The Fig 4.14 also indicates an increase in solute gain with increase of process duration and osmotic solution temperature. Slight increase in solute gain was observed with increase of osmotic solution concentration between 5 to 15% salt in 50°B sucrose solution.

The equations of models fitted for solute gain during osmotic dehydration in the actual form of process variables after elimination of non-significant terms at 5% level of significance are shown below;

For salt solution

$$\text{Solute Gain(g)/100 g fresh fruit} = -0.15316 - 0.01918 * \text{Time} - 6.2363\text{x}10^{-4} * \text{Temp} + 0.39136 * \text{Conc} + 9.1284\text{x}10^{-5} * \text{Time}^2 + 2.2679\text{x}10^{-3} * \text{Temp}^2 + 0.013179 * \text{Conc}^2 - 2.8399\text{x}10^{-4} * \text{Time} * \text{Temp} + 1.2707\text{x}10^{-3} * \text{Time} * \text{Conc} - 0.013683 * \text{Temp} * \text{Conc}$$

For sugar solution

$$\text{Solute Gain (g)/100 g fresh fruit} = +13.38943 + 0.024036 * \text{Time} - 0.58349 * \text{Temp} + 9.289\text{x}10^{-3} * \text{Temp}^2$$

For sugar-salt mixture solution

$$\text{Solute Gain(g)/100 g fresh fruit} = +4.01829 + 6.976\text{x}10^{-3} * \text{Time} + 0.043579 * \text{Temp} + 0.34903 * \text{Conc} + 4.1325\text{x}10^{-5} * \text{Time}^2 + 1.7845\text{x}10^{-3} * \text{Temp}^2 + 1.8686\text{x}10^{-3} * \text{Conc}^2 - 5.3308\text{x}10^{-3} * \text{Temp} * \text{Conc}$$

4.2.1.3 Diagnostic checking of fitted model and surface plots for rehydration ratio

(a) Salt solution

The magnitude of p and β values in Table 4.10 indicates the maximum negative contribution of solution concentration, whereas, the solution temperature and time have least, negative and significant effect on the rehydration ratio. It implies the decrease of rehydration ratio with increase of osmotic solution concentration. The quadratic terms of time and concentration have positive, whereas the solution temperature has negative effect on rehydration ratio. The relative magnitude of β values indicated that, the effect of quadratic term of concentration was pronounced than that of other two factors on rehydration ratio. Further, the interaction of 'time and temperature', 'temperature and concentration' have positive effect, whereas, that of 'time and concentration, has negative

Table 4.10 Regression summary and ANOVA for rehydration ratio after osmo-convective dehydration in solutions of salt, sugar and sugar-salt mixture

Source	df	Salt				Sugar				Sugar-SALT			
		β	B	Sum of squares	p-level	β	B	Sum of squares	p-level	β	B	Sum of squares	p-level
Model	9	-	-	9.86306	1.9E-23	-	-	0.98574	6E-08	-	-	0.58596	4.31E-09
Constant	1	-	3.1457	-	6.8E-30	-	3.2808	-	2E-19	-	2.952	-	2.33E-21
Time	1	-0.196	-0.166	0.3785	6.5E-19	-0.464	-0.126	0.21544	3E-07	-0.724	-0.151	0.30989	2.98E-10
Temp	1	-0.188	-0.16	0.34884	9.8E-19	-0.824	-0.223	0.6791	1E-09	-0.569	-0.118	0.1914	3.16E-09
Conc	1	-0.863	-0.733	7.33812	2.4E-25	0.1026	0.0278	0.01053	0.0238	-0.3758	-0.078	0.0835	1.72E-07
Time*Time	1	0.0201	0.0165	0.00392	4.8E-09	-0.054	-0.014	0.00291	0.1917*	-0.0019	-4E-04	2.1E-06	0.9504*
Temp*Temp	1	-0.011	-0.009	0.0012	1.3E-06	-0.235	-0.061	0.05414	0.0001	-0.0242	-0.005	0.00034	0.4365*
Conc*Conc	1	0.4234	0.3471	1.73671	3.2E-22	-0.041	-0.011	0.00167	0.3145*	-0.0331	-0.007	0.00063	0.2944*
Time*Temp	1	0.0534	0.0593	0.0281	2.8E-13	0.1464	0.0518	0.02145	0.0035	0.0148	0.004	0.00013	0.6286*
Time*Conc	1	0.0018	0.0019	3E-05	0.1367*	0.0037	0.0013	1.4E-05	0.9259*	-0.0145	-0.004	0.00012	0.6350*
Temp*Conc	1	-0.015	-0.017	0.00221	7.7E-08	-0.062	-0.022	0.00389	0.1367*	0.004	0.0011	9.5E-06	0.8947*
Residual	10	-	-	0.00012	-	-	-	0.01485	-	-	-	0.00518	-
Lack of Fit	5	-	-	8.9E-05	0.1078	-	-	0.00395	0.8551	-	-	0.0039	0.1234
Pure Error	5	-	-	2.7E-05	-	-	-	0.0109	-	-	-	0.00128	-
Corrected Total	19	-	-	9.86318	-	-	-	1.0006	-	-	-	0.59114	-
R^2		0.9999				0.9851				0.9912			
Adj R^2		0.9999				0.9717				0.9833			

* Non-significant at 5%level of confidence interval.

effect on rehydration ratio. However, all the interaction terms have negligible but significant effect on rehydration ratio. Fig 4.15 also indicates non-significant variation of rehydration ratio with the increase of process duration and decrease in rehydration ratio is more dependent on osmotic solution concentration and temperature. The rehydration ratio is maximum for 90 minutes duration at 5% salt concentration and 30°C osmotic solution temperature.

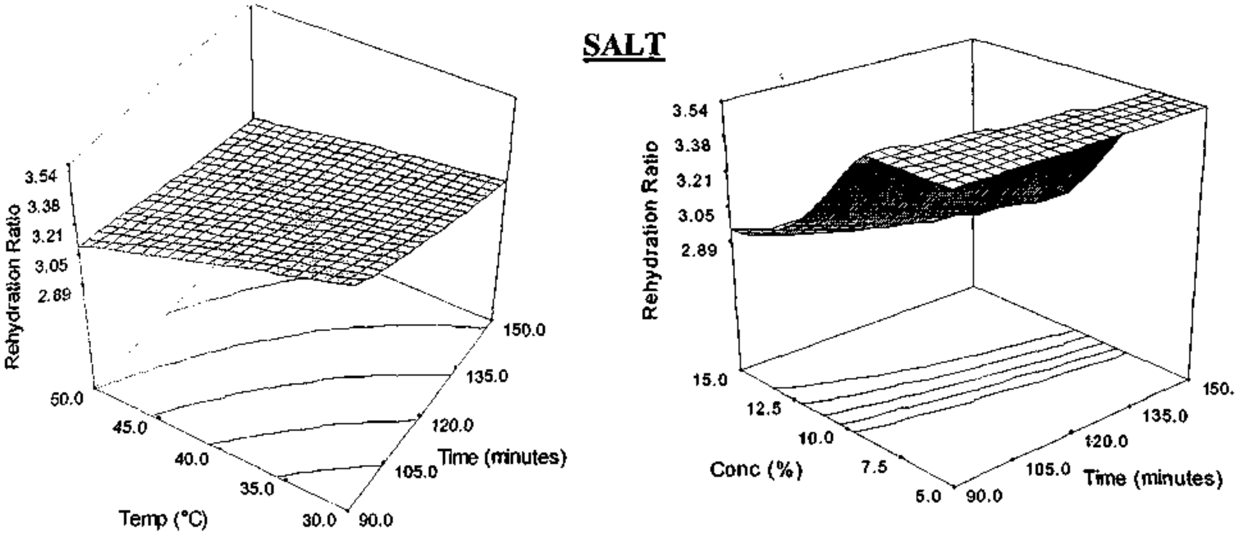
(b) Sugar solution

The magnitude of p and β values in Table 4.10 indicates the maximum negative contribution of osmotic solution temperature on rehydration ratio followed by process duration. The concentration has least significant and positive effect on rehydration ratio. It implies decrease in rehydration ratio with increase of solution temperature and process duration. The quadratic terms of time and concentration have non-significant effect on rehydration ratio. Further, only the interaction of 'time and temperature' has positive and significant effect on rehydration ratio. Fig 4.15 also indicates a linear decrease in rehydration ratio with increase of process duration and osmotic solution temperature. However, no significant change in rehydration ratio was observed with increase of osmotic solution concentration ranged between 50 to 60°B.

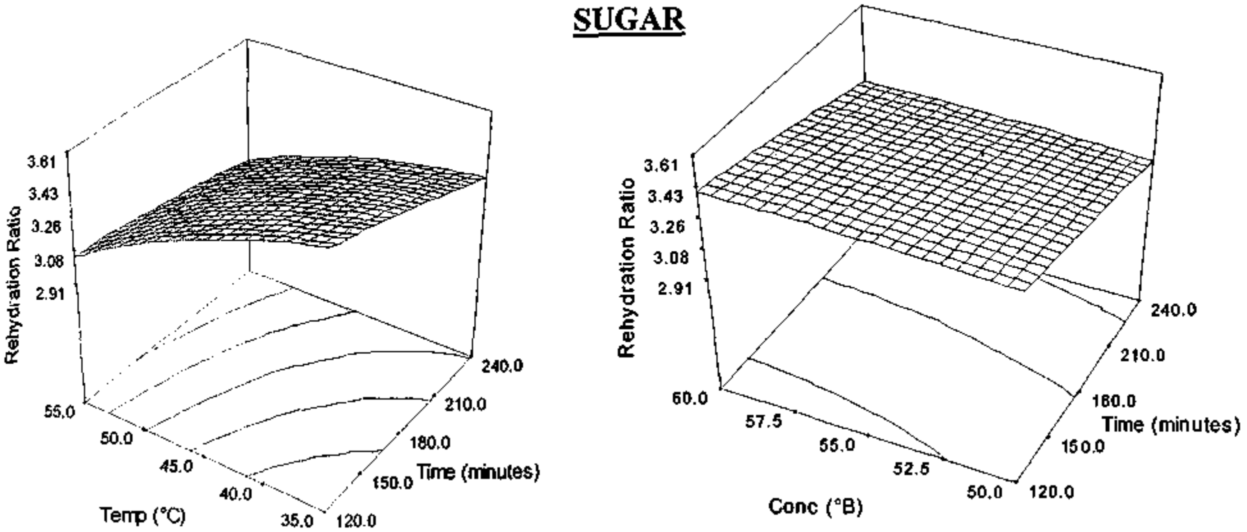
(c) Solution of sugar-salt mixture

The magnitude of p and β values in Table 4.10 indicates the maximum negative contribution of process duration followed by solution temperature, whereas the solution concentration has least but significant effect on the rehydration ratio. It implies the decrease in rehydration ratio with increase of process duration and osmotic solution temperature and concentration. The effects of all the quadratic and interaction terms were non-significant on rehydration ratio. Fig 4.15 indicates a linear decrease in rehydration ratio with increase of process duration, osmotic solution concentration and osmotic

SALT



SUGAR



SUGAR-SALT MIXTURE

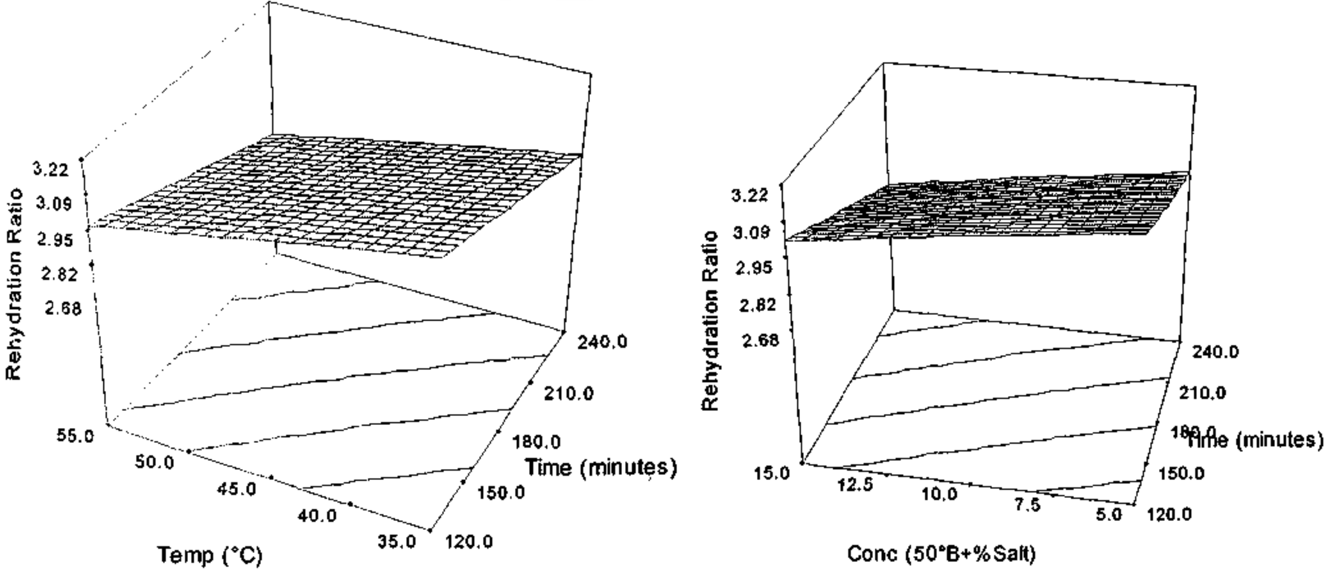


Fig 4.15 Effect of process variables on rehydration ratio of osmo-convectively dehydrated carrot cubes in solutions of salt, sugar and sugar-salt mixture.

solution temperature.

The equations of models fitted for rehydration ratio during osmotic dehydration in the actual form of process variables after elimination of non-significant terms at 5% level of significance are as shown below:

For salt solution

$$\text{Rehydration Ratio} = +8.23891 - 0.017853 * \text{Time} - 0.029065 * \text{Temp} - 0.41103 * \text{Conc} + 1.8336\times10^{-5} * \text{Time}^2 - 9.1297\times10^{-5} * \text{Temp}^2 + 0.0139 * \text{Conc}^2 + 1.976\times10^{-4} * \text{Time} * \text{Temp} - 3.322\times10^{-4} * \text{Temp} * \text{Conc}$$

For sugar solution

$$\text{Rehydration Ratio} = +3.84053 - 5.9764\times10^{-3} * \text{Time} + 0.015301 * \text{Temp} + 5.553\times10^{-3} * \text{Conc} - 5.9037\times10^{-4} * \text{Temp}^2 + 8.6291\times10^{-5} * \text{Time} * \text{Temp}$$

For sugar-salt mixture solution

$$\text{Rehydration Ratio} = +4.0849 - 2.5106\times10^{-3} * \text{Time} - 0.011839 * \text{Temp} - 0.015639 * \text{Conc}$$

4.2.1.4 Diagnostic checking of fitted model and surface plots for shrinkage of rehydrated carrot cubes

(a) Salt solution

The magnitude of p and β values in Table 4.11 indicates the maximum positive contribution of solution temperature followed by process duration whereas; the concentration has least but significant and negative effect on the shrinkage (%) of rehydrated product. It implies increase in shrinkage of rehydrated product to large extent with increase in process duration and solution temperature. The quadratic term of solution temperature has significant but negative effect having negligible magnitude as compared to the linear terms of process parameters. The maximum positive contribution towards shrinkage of rehydrated product was of quadratic term of concentration followed by process duration. The quadratic term of solution temperature has significant but negative effect on shrinkage of rehydrated product. The interaction of 'temperature and concentration' has significant positive effect, whereas, the effects of other interactions are

Table 4.11 Regression summary and ANOVA for <u>shrinkage</u> (%) after rehydration of osmo-convective dehydration in solutions of salt, sugar and sugar-salt mixture

Source	df	Salt				Sugar				Sugar-salt			
		β	B	Sum of squares	p- level	β	B	Sum of squares	p-level	β	B	Sum of squares	p-level
Model	9	-	-	1299.69	5.6E-06	-	-	383.615	2E-08	-	-	26.8113	3.42E-06
Constant	1	-	20.52	-	7.1E-10	-	5.1928	-	4E-09	-	-0.002	-	0.987062
Time	1	0.4659	4.633	293.141	1.8E-05	-0.807	-4.287	250.975	5E-10	-0.516	-0.736	7.38894	4.7E-06
Temp	1	0.7163	7.1226	692.831	3.7E-07	-0.525	-2.792	106.493	3E-08	-0.1378	-0.196	0.52662	0.039369
Conc	1	-0.18	-1.791	43.7886	0.01467	0.0921	0.6124	5.12194	0.0249	-0.1541	-0.22	0.65901	0.024327
Time*Time	1	0.1889	1.8116	47.294	0.01204	0.0858	0.4774	3.28409	0.0351	0.3955	0.5439	4.26337	5.11E-05
Temp*Temp	1	-0.18	-1.724	42.8318	0.01551	0.1203	0.6541	6.16673	0.0066	0.3955	0.5439	4.26337	5.11E-05
Conc*Conc	1	0.2626	2.5187	91.4203	0.00168	0.0514	0.1238	0.22094	0.1756*	0.0099	0.0136	0.00266	0.8697*
Time*Temp	1	0.1251	1.625	21.125	0.0681*	0.162	1.125	10.125	0.0009	0.3356	0.625	3.125	0.00018
Time*Conc	1	0.0289	0.375	1.125	0.6471*	-0.054	-0.375	1.125	0.1529*	0.4698	0.875	6.125	1.08E-05
Temp*Conc	1	0.2021	2.625	55.125	0.00796	-0.054	-0.375	1.125	0.1529*	0.2013	0.375	1.125	0.006103
Residual	10	-	-	50.5079	-	-	-	3.3355	-	-	-	0.93865	-
Lack of Fit	5	-	-	41.0079	0.0672	-	-	2.50216	0.1264	-	-	0.93865	-
Pure Error	5	-	-	9.5	-	-	-	0.83333	-	-	-	0	-
Corrected Total	19	-	-	1350.2	-	-	-	386.95	-	-	-	27.75	-
R^2		0.9625				0.9878				0.9662			
Adj R^2		0.9289				0.9768				0.9357			

* Non-significant at 5%level of confidence interval.

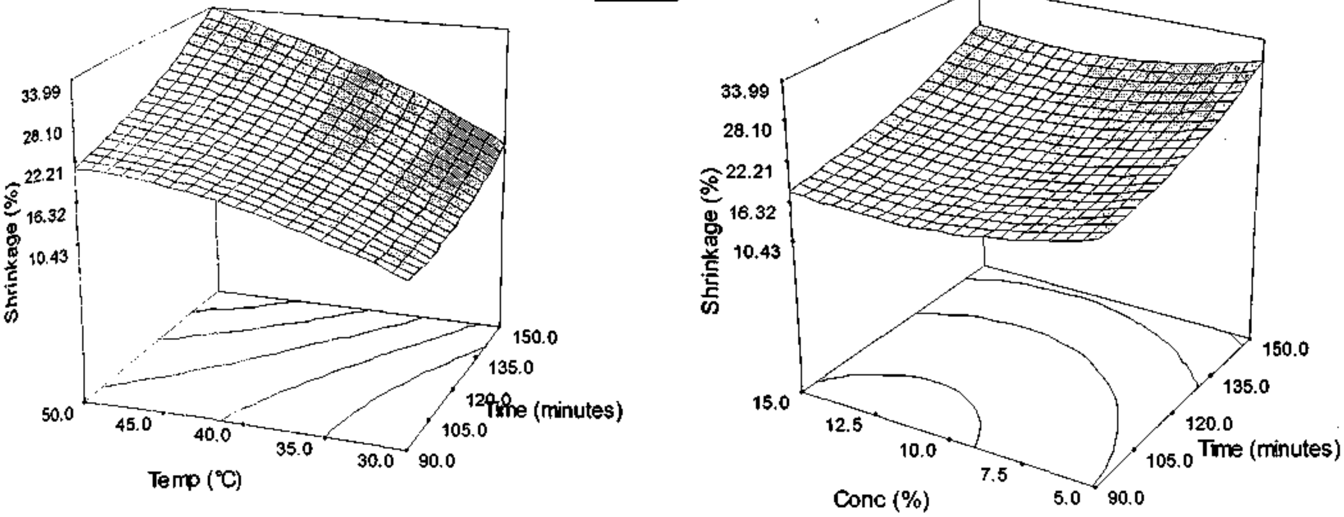
found to be non-significant on shrinkage of rehydrated product. In case of shrinkage of rehydrated product, negative significant effect of any process parameter is more desirable. Fig 4.16 also indicates non-significant variation of shrinkage with the increase of osmotic solution concentration; whereas, an increase in shrinkage of rehydrated product was observed with increase of osmotic solution temperature and process duration. The shrinkage is lowest for 90 minutes duration at 10% salt concentration and 30°C osmotic solution temperature.

(b) Sugar solution

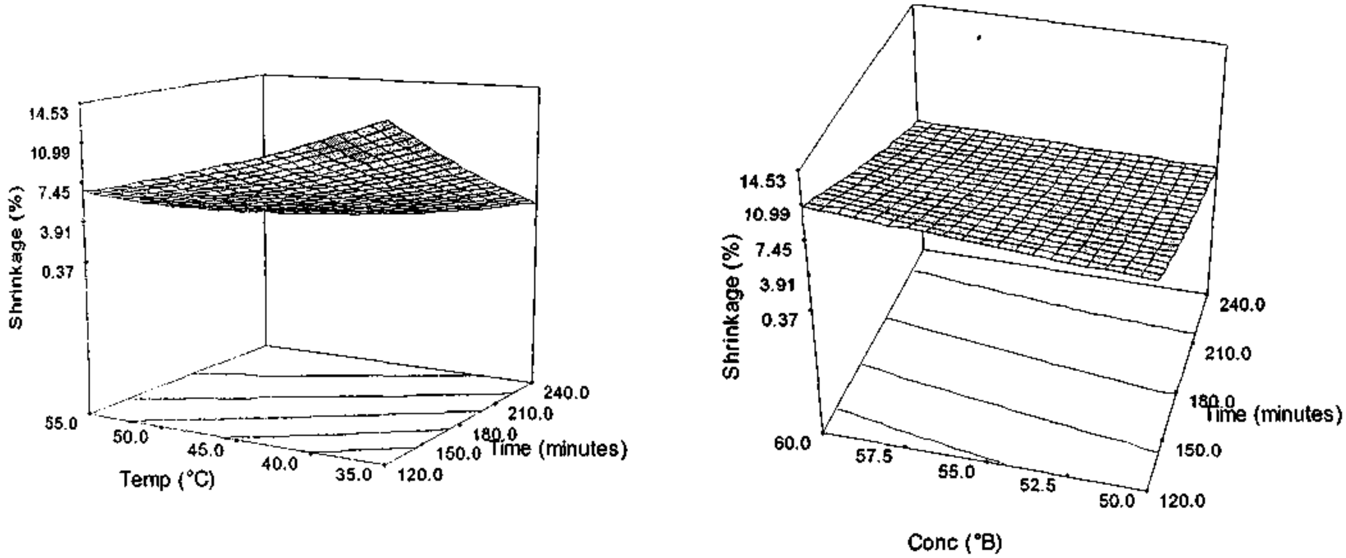
The magnitude of p and β values in Table 4.11 indicates the maximum negative contribution of process duration followed by osmotic solution temperature on shrinkage of rehydrated product. The solution concentration showed minimum but significant and positive effect on the shrinkage of rehydrated product. It implies decrease in shrinkage with advancement of process duration and increase in solution temperature, whereas increase of solution concentration resulted into negligible increase in shrinkage of rehydrated product.

The quadratic terms of temperature has maximum positive effect followed by process duration, and that of solution concentration has non-significant effect on shrinkage of rehydrated product. Further, only the interaction of 'time and temperature' has positive and significant effect on shrinkage of rehydrated product. Fig 4.16 also indicates slight increase in shrinkage of rehydrated carrot cubes with increase of osmotic solution concentration, and significant decrease in shrinkage with increase of osmotic solution temperature and process duration. Minimum shrinkage of rehydrated carrot cubes was observed for 50°B osmotic solution concentration at 55°C temperature and process duration of 240 minutes.

SALT



SUGAR



SUGAR-SALT MIXTURE

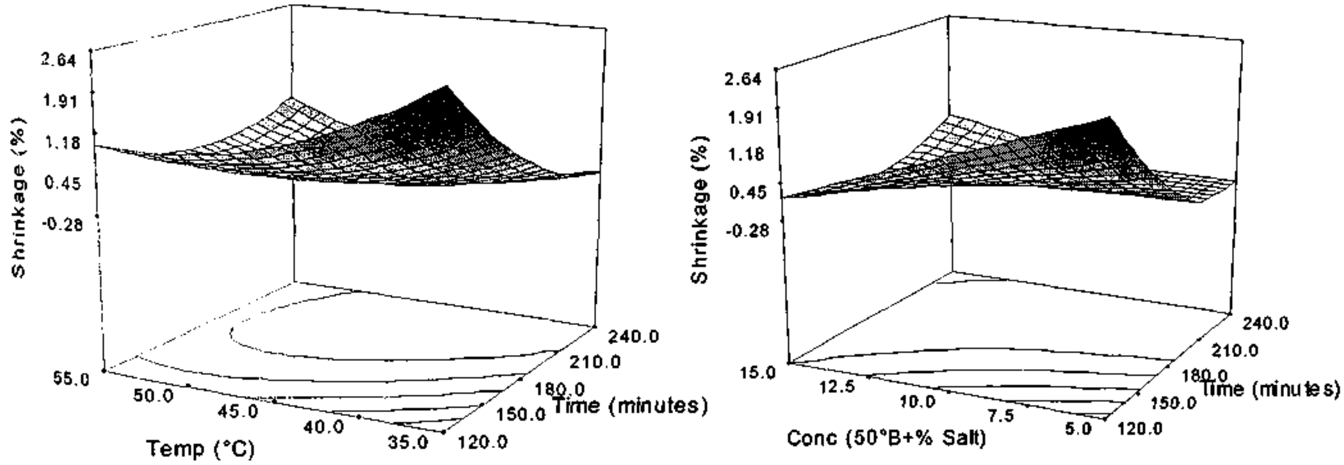


Fig 4.16 Effect of process variables on shrinkage (%) after rehydration of osmo-convectively dehydrated carrot cubes

(c) Solution of sugar-salt mixture

The magnitude of p and β values in Table 4.11 indicated the maximum negative contribution of process duration, and least contribution of solution concentration and temperature on the shrinkage (%) of rehydrated product. It implies decrease in shrinkage of rehydrated product with the advancement of process duration. The quadratic terms of time and temperature have positive and significant effect, whereas that of concentration has non-significant effect on shrinkage (%) of rehydrated product. Further, all the interaction terms of all process parameters has positive and significant effect on shrinkage (%) of rehydrated product. The maximum positive contribution was of interaction of 'time and concentration' followed by 'time and temperature' and 'temperature and concentration.' Fig 4.16 also indicates a non-linear decrease in shrinkage with increase of process duration, osmotic solution temperature and concentration.

The equations of models fitted for shrinkage (%) of rehydrated product during osmotic dehydration in the actual form of process variables after elimination of non-significant terms at 5% level of significance are as shown below;

For salt solution

Shrikage (%) of rehydrated product = + 9.55508 - 0.32865* Time + 1.56644* Temp - 4.47306 * Conc + 2.0128x10^{-3} * Time^{2} - 0.017240 * Temp^{2} + 0.10075* Conc^{2} + 0.0525 * Temp * Conc

For sugar solution

Shrinkage (%)of rehydrated product = + 56.35500 - 0.20233 * Time - 1.19441* Temp + 0.12248* Conc + 1.2919 x10^{-4}* Time^{2} + 6.4185 x10^{-3}* Temp^{2} + 1.875 x10^{-3}* Time * Temp

For sugar-salt mixture solution

Shrinkage(%)of rehydrated product = +36.471 - 0.14256* Time - 0.7704* Temp -0.9064* Conc + 1.5071 x10^{-4}* Time^{2} + 5.4256 x10^{-3}* Temp^{2} + 1.0417x10^{-3}* Time * Temp + 2.9167 x10^{-3}* Time * Conc + 7.5 x10^{-3}* Temp * Conc

4.2.1.5 Checking of fitted model and surface plots for overall acceptability of rehydrated carrot cubes

(a) Salt solution

The magnitude of p and β values in Table 4.12 indicates the maximum negative contribution of solution temperature followed by process duration on the overall acceptability (%) of rehydrated product. The concentration has positive and significant effect on the overall acceptability (%) of rehydrated product. It implies that both time and solution temperature have adverse effect, whereas the solution concentration contributes to overall acceptability of the rehydrated product. Only the quadratic term of solution concentration has significant but negative effect on overall acceptability. The interaction of 'temperature and concentration' has negative and significant but negligible effect as compared to linear terms of process parameters on the overall acceptability (%) of rehydrated product. Fig 4.17 also indicates slight variation of overall acceptability of rehydrated product with the increase of process duration and osmotic solution concentration. However, a linear decrease in overall acceptability of rehydrated product was observed with increase of osmotic solution temperature. The highest overall acceptability is observed for 90 minutes duration at 10% salt concentration and 30°C osmotic solution temperature.

(b) Sugar solution

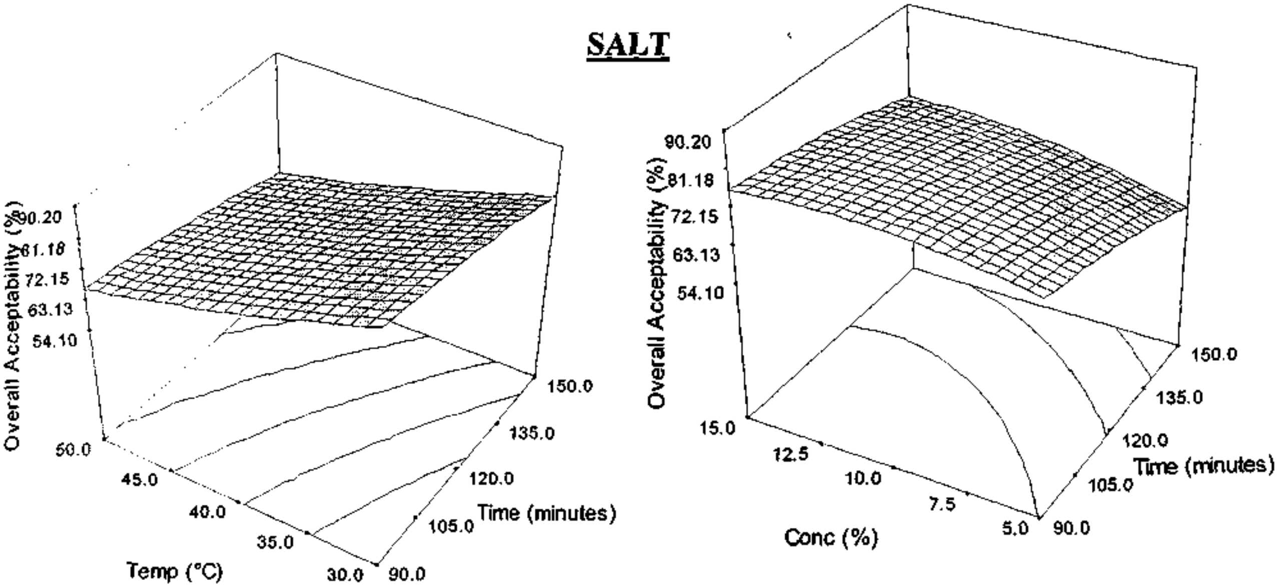
The magnitude of p and β values in Table 4.12 indicates the maximum positive contribution of process duration followed by solution temperature and concentration on overall acceptability of rehydrated product. The quadratic terms of time, temperature and concentration have negative and significant effect on overall acceptability (%) of rehydrated product. Only the interaction of 'time and concentration' has positive and significant effect on overall acceptability (%) of rehydrated product. Fig 4.17 also indicates a non-linear increase in overall acceptability of rehydrated product with increase

Table 4.12 Regression summary and ANOVA for overall acceptability (%) of rehydrated product after osmo-convective dehydration in solutions of sugar, salt and sugar-salt mixture

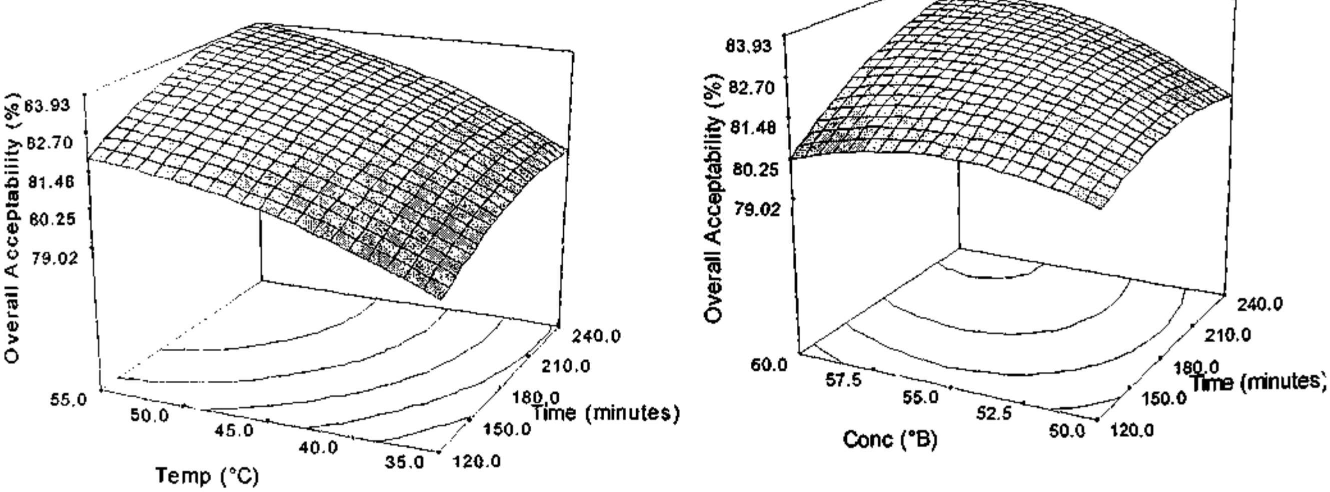
Source	df	Salt				Sugar				Sugar-salt			
		β	B	Sum of squares	p-level	β	B	Sum of squares	p-level	β	B	Sum of squares	p-level
Model	9	-	-	2907.66	8.5E-05	-	-	68.0605	1E-05	-		537.108	8.35E-08
Constant	1	-	72.087	-	2.8E-12	-	82.478	-	7E-22	-	98.333	-	1.84E-20
Time	1	-0.439	-6.62	598.504	0.0003	0.3863	0.882	10.6241	0.0002	0.438	2.7692	104.724	6.72E-07
Temp	1	-0.757	-11.43	1784.02	2.9E-06	0.6866	1.5676	33.5614	1E-06	0.2285	1.4445	28.4957	0.000191
Conc	1	0.2569	3.8775	205.328	0.00996	0.2682	0.6124	5.12194	0.0024	0.2322	1.4678	29.4224	0.000169
Time*Time	1	-0.102	-1.48	31.5603	0.2421*	-0.257	-0.565	4.60154	0.0033	-0.4832	-2.947	125.159	2.92E-07
Temp*Temp	1	0.0805	1.1718	19.7882	0.3481*	-0.257	-0.565	4.60154	0.0033	-0.3673	-2.24	72.3027	3.67E-06
Conc*Conc	1	-0.199	-2.894	120.704	0.03535	-0.337	-0.742	7.931	0.0005	-0.4542	-2.77	110.594	5.22E-07
Time*Temp	1	0.019	0.375	1.125	0.8191*	0.0419	0.125	0.125	0.5422*	-0.4389	-3.625	105.125	6.61E-07
Time*Conc	1	0.0824	1.625	21.125	0.3330*	0.2095	0.625	3.125	0.0102	-0.0454	-0.375	1.125	0.2818*
Temp*Conc	1	-0.196	-3.875	120.125	0.03571	0.1257	0.375	1.125	0.0876*	0.1362	1.125	10.125	0.006624
Residual	10	-	-	204.141	-	-	-	3.13952	-	-	-	8.69166	-
Lack of Fit	5	-	-	165.308	0.0689	-		1.63952	0.4623	-	-	5.35832	0.3076
Pure Error	5	-	-	38.8333	-	-	-	1.5	-	-	-	3.33333	-
Corrected Total	19	-	-	3111.8	-	-	-	71.2	-	-	-	545.8	-
R^2		0.9343				0.9559				0.9840			
Adj R^2		0.8753				0.9162				0.9697			

* Non-significant at 5%level of confidence interval.

SALT



SUGAR



SUGAR-SALT MIXTURE

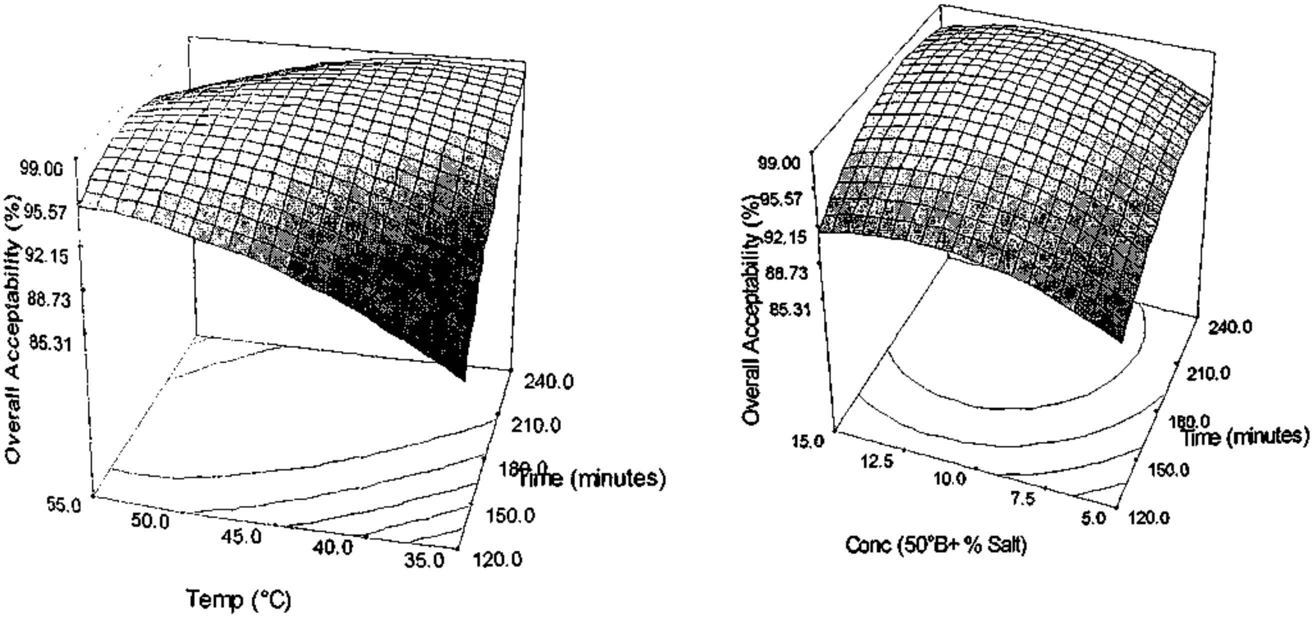


Fig 4.17 Effect of process variables on <u>overall acceptability</u> (%) of rehydrated carrot cubes after osmo-convective dehydration in solutions of salt, sugar and sugar-salt mixture

of process duration and osmotic solution temperature and very slight increase with increase of osmotic solution concentration between 50 to 60°B. Highest overall acceptability of rehydrated product is observed for 55°B sucrose solution.

(c) Solution of sugar-salt mixture

The magnitude of p and β values in Table 4.12 indicates the maximum positive, significant contribution of process duration, followed by solution concentration and temperature on the overall acceptability (%) of rehydrated product. The quadratic terms of the entire process variable have negative and significant effect on overall acceptability of rehydrated product. The quadratic terms of time has maximum negative effect followed by solution concentration and temperature on overall acceptability (%) of rehydrated product. The interaction term of 'time and temperature, has maximum negative effect followed by positive effect of 'temperature and concentration' on overall acceptability of rehydrated product, while, interaction of' 'time and concentration' has non-significant effect. Fig 4.17 also indicates a non-linear increase in overall acceptability with increase of process duration and osmotic solution temperature and concentration. However a slight increase in overall acceptability has been observed with increase of osmotic solution concentration between 10 to 15% salt in 50°B sucrose solution.

The equations of models fitted for overall acceptability (%) of rehydrated product during osmotic dehydration in the actual form of process variables after elimination of non-significant terms at 5% level of significance are given below;

For salt solution

Acceptability (%)of rehydrated product = + 93.835 - 0.2207 * Time - 0.3679* Temp +6.1685* Conc - 11465* Conc^2 - 0.0775 * Temp * Conc

For sugar solution

Acceptance (%) of rehydrated product = - 19.6249 - 0.0434* Time + 0.6653* Temp + 3.0116* Conc - 1.5696 $\times 10^{-4}$* Time^2 - 5.6507 $\times 10^{-3}$* Temp^2 - 0.0297* Conc^2 + 2.0833 $\times 10^{-3}$* Time * Conc

For sugar-salt mixture solution

Acceptance (%)of rehydrated product = $- 41.1838 + 0.6127 * \text{Time} + 3.0228* \text{Temp} + 1.4972* \text{Conc} - 0.1861 \times 10^{-4}* \text{Time}^2 - 0.0224* \text{Temp}^2 - 0.11081* \text{Conc}^2 - 6.0417 \times 10^{-3}* \text{Time} * \text{Temp} + 0.0225* \text{Temp} * \text{Conc}$

4.2.2 Optimization of osmo-convective dehydration process for carrot cubes

Graphical multi-response optimization technique was adopted to determine the workable optimum conditions for the osmotic dehydration of carrot cubes. The contour plots for all responses were superimposed and regions that best satisfy all the constraints were selected as optimum conditions. The main criterion for constraints optimization was maximum possible water loss, rehydration ratio, overall acceptability, and lower solute gain, shrinkage as low as possible (Themelin *et al* 1997; Ade-Omowaye *et al* 2002a). These constraints resulted in "feasible zone" of the optimum solutions (shaded area in the superimposed contour plots). Superimposed contour plots having common superimposed area for all responses for osmo-convective dehydration in solutions of salt, sugar, and sugar-salt mixture are as shown in Fig 4.18 to 4.20.The points in the following ranges of process parameters were found to be optimum for osmo-convective dehydration.

Table 4.13 Range of process parameters for optimum conditions

Solution	Time (minutes)	Temp. (°C)	Concentration
Salt	90-102	31-33	10-10.5 %
Sugar	185-220	46-52	55-57°B
Sugar-salt	165-185	44-50	50°B+(9-11%)

In order to optimize the process conditions for osmotic dehydration process by numerical optimization technique, equal importance of '3' was given to all the three process parameters (viz. time, temperature and concentration). However, the importance given to different responses was different, based on their relative contribution to quality of

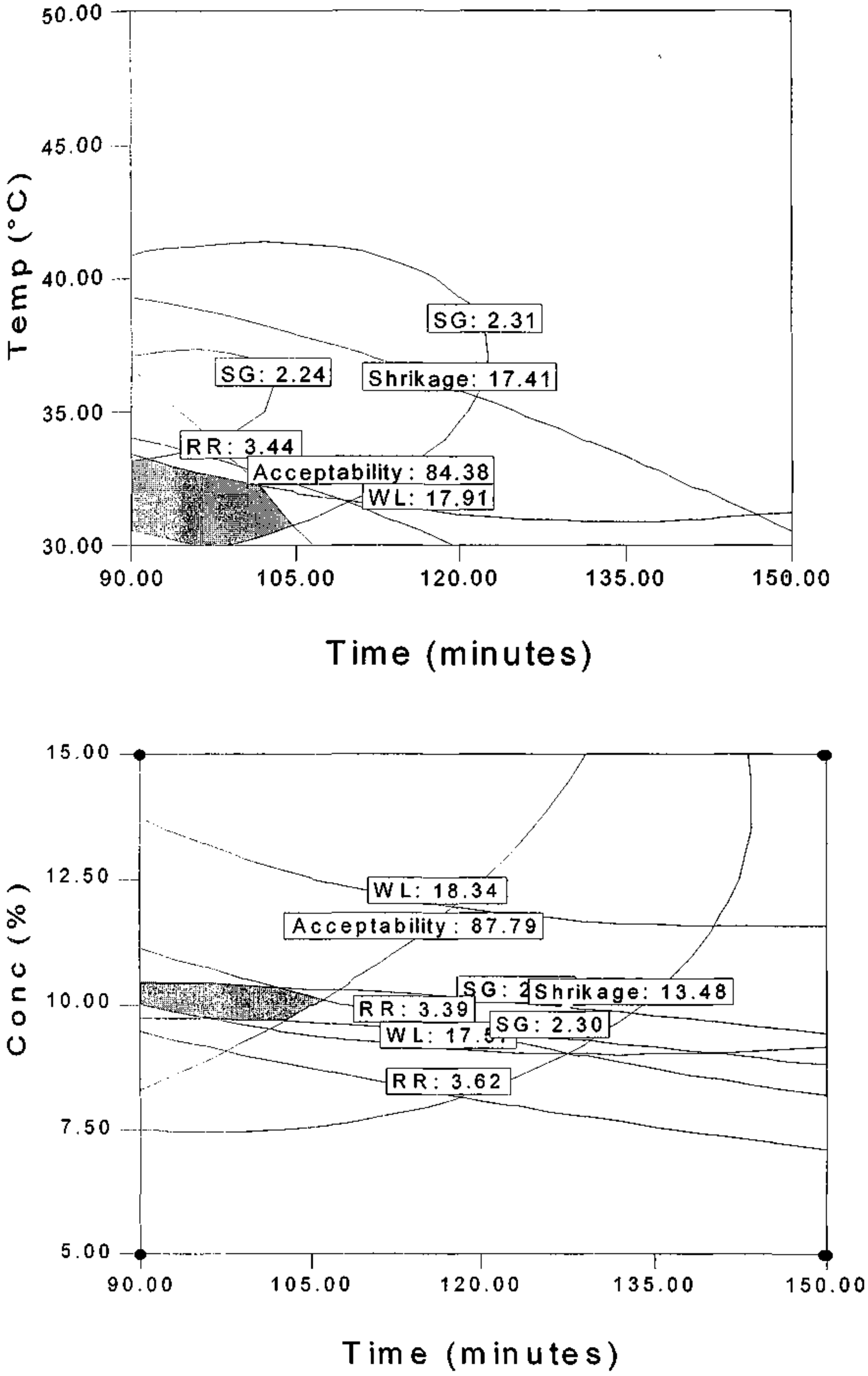


Fig 4.18 Overlaid contours of different responses for optimization of osmotic dehydration process of carrot cubes in salt solution.

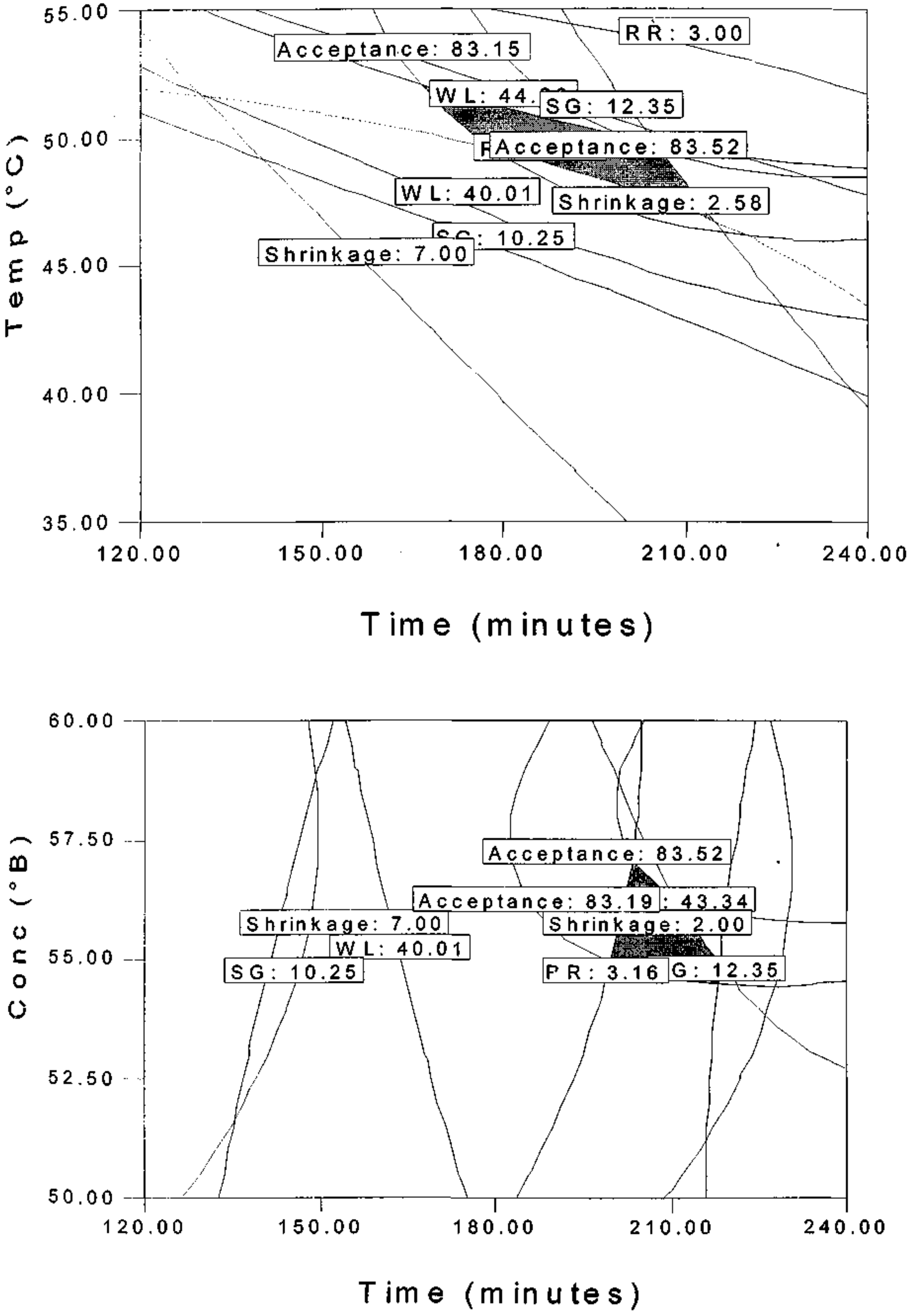


Fig 4.19 Overlaid contours of different responses for optimization of osmotic dehydration process of carrot cubes in sugar solution.

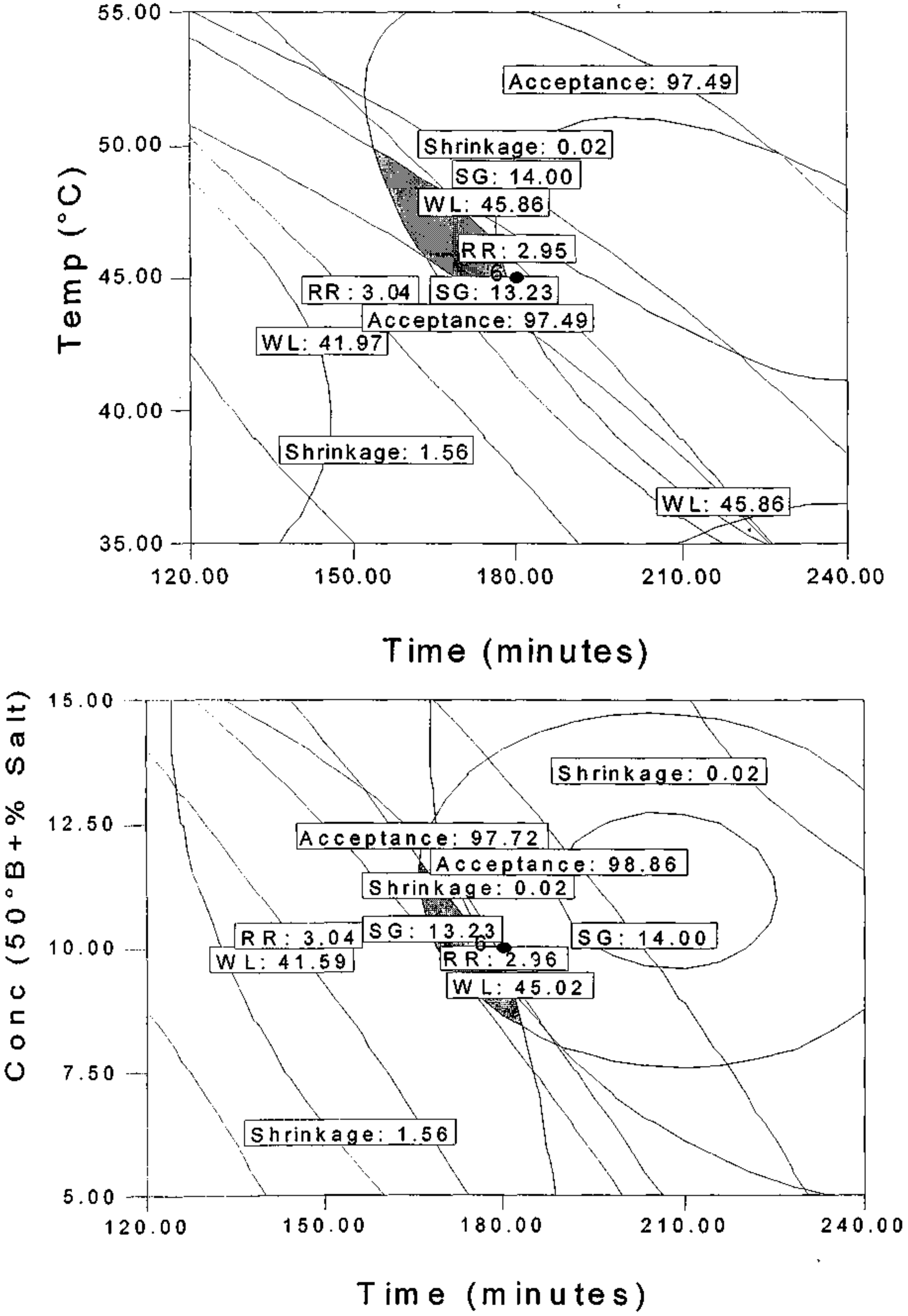


Fig 4.20 Overlaid contours for the optimization of osmotic dehydration process for carrot cubes in solution of sugar and salt mixture.

final product, as given below:

Response	**Importance**
1. Water Loss	4
2. Solute Gain	2
3. Rehydration Ratio	3
4. Shrinkage (%)	4
5. Overall acceptability	5

Maximum importance was given to the overall acceptability (%), because it includes a number of parameters like colour, flavour, firmness and appearance etc.

The optimum operating condition for each process variable viz. concentration, temperature and time for each type of osmotic pretreatment along with the predicted values of responses and overall desirability are given in Table 4.14.

4.3 Mass transfer kinetics of carrot cubes during convective dehydration

In order to study the impact of various pretreatments and process parameters on convective dehydration behaviour, carrot cubes of size 1cm x 1cm x 1cm were osmotically pretreated in solutions of salt (10% salt concentration, at 35°C for 60 minutes), pure sugar (50°B concentration, at 45°C for 180 minutes), and sugar-salt mixture (50°B sugar +10% salt, at 45°C for 180 minutes) along with 0.3% sodium metabisulphite, which resulted into approximated average moisture loss of 8, 15 and 22% respectively. Corresponding to these experimental parameters, the approximated average values of solute gain were 2, 13 and 18% respectively. It has been reported that, up to 70% of the initial water could be removed from a plant tissue by osmotic dehydration depending on raw material properties, osmotic solution characteristics and process parameters (Brennen 1989). The remaining water, however, did not ensure stability of material, as water activity would be generally higher than 0.9. To achieve shelf stability, the interaction of osmotic dehydration with

Table 4.14 Optimum solutions for various process parameters for osmo-convective dehydration of carrot cubes in solutions of salt, sugar and sugar-salt mixture

Solution	Response						Optimum conditions		
	Name	Importance	Range	Target	Predicted	Desirebility	Time	Temp	Conc
Salt	Water loss	4	15.91-19.9	Maximum	17.87	0.635	90	30	11%
	Solute gain	2	0.92-5.49	Minimum	2.88				
	Rehydration Ratio	3	2.49-5.36	Maximum	3.37				
	Shrinkage (%)	4	7-39	Minimum	9.39				
	Overall acceptability(%)	5	50-95	Maximum	91.62				
Sugar	Water loss	4	26.16-60.78	Maximum	44.79	0.634	220	49	58.2°B
	Solute gain	2	6.76-16.39	Minimum	12.46				
	Rehydration Ratio	3	2.72-3.64	Maximum	3.1				
	Shrinkage (%)	4	0-16	Minimum	1.73				
	Overall acceptability(%)	5	75-78	Maximum	83.91				
Sugar-salt	Water loss	4	34.9-60.37	Maximum	45.68	0.671	180	46.5	50°B+10%
	Solute gain	2	10.04-17.10	Minimum	13.63				
	Rehydration Ratio	3	2.61-3.27	Maximum	2.94				
	Shrinkage (%)	4	0-4	Minimum	0				
	Overall acceptability(%)	5	81-99	Maximum	98.32				

further processing would be important for quality assurance (Brennen 1989; Lenart and Cerkowniak 1996). To prepare shelf stable product having final moisture content 4-5% (w.b.), osmotically pretreated carrot cubes were further subjected to convective dehydration at an air temperature of 55, 65 and 75°C and an air velocity of 1.6 m/s with direction of air flow through the product. Similar studies on convective dehydration behaviour of osmotically pretreated products were reported by Park *et al* (2002b) for pears, Kaleemullah *et al* (2002a) for papaya cubes, Pokharkar and Prasad (2002) for pineapple and Nieto *et al* (1998) for apples. The objective of the present work was to study the effect of osmotic pre-treatment and air temperature, on the drying behaviour of the carrot cubes. The data pertaining to the convective dehydration kinetics is given in Appendix-K.

4.3.1 Effect of various process parameters and pretreatment on convective dehydration behaviour of carrot cubes

The effects of various process parameters (like drying air temperature, step drying) and pretreatments (like osmotic pretreatment, blanching, calcium chloride addition) on convective drying characteristics are discussed below:

4.3.1.1 Effect of osmotic pretreatment on convective dehydration kinetics of carrot cubes

A marked difference in the convective drying behaviour of un-osmosed and pre-osmosed carrot cubes in salt, sugar and sugar-salt mixture solution is indicated in Fig 4.21. The data reveals that drying of pre-osmosed carrot cubes is slower than the un-osmosed (blanched) carrot cubes. This might be due to slow-down effect of the infused solute on the air-drying rate. However, the drying of un-osmosed carrot cubes had been started at relatively high moisture content (approximately 89.5-91.5% w.b.) whereas the drying of osmotically pretreated samples began at too low moisture content of about 82% (w.b.) for salt, 78% (w.b.) sugar and 71% (w.b.) sugar-salt osmotic mixture pretreatment. The

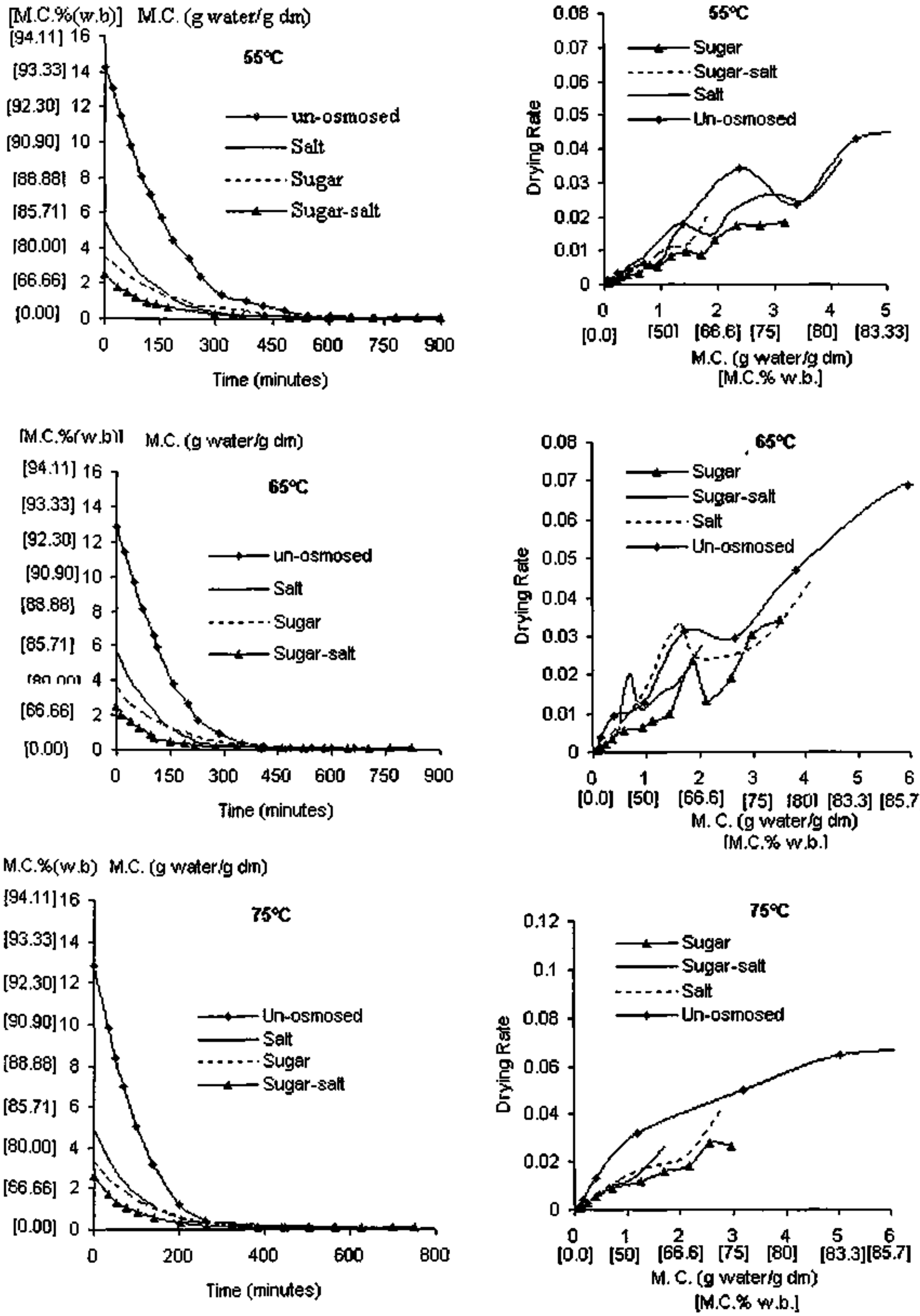


Fig 4.21. Effect of osmotic pretreatment on convective drying characteristics and drying rate of carrot cubes

osmotic pretreatment in salt, sugar and sugar-salt mixture solution added approximately 75,105 and 175 minutes respectively to the convective dehydration time of un-osmosed (blanched) carrot cubes at 55°C drying air temperature. The increase in total convective dehydration might be due to the resistance offered to water removal by the solute gained during osmotic pretreatment. Lenart (1994), Lenart and Cerkowniak (1996), Kaleemullah *et al* (2002a) and Erle and Schubert (2001) reported that, even a simple immersion of raw material into an osmotic solution, caused a substantial decrease of water removal rates in convective dehydration. The decrease in moisture removal rates during complementary convective dehydration might be due to the fact, that the solute uptake "blocks" the surface layers (pores) of the product, posing an additional resistance to mass exchange, which was in close agreement with results of Telis *et al* (2001), Nieto *et al* (1998), Chopra (2001).

Out of osmotically pretreated carrot cubes, the lowest convective dehydration time was observed for the samples osmosed in solution of salt than those osmosed in solutions of pure sugar and sugar-salt mixture. This might be due to different modes and extents of sample impregnation with osmotic solutes of different molecular size during osmotic dehydration process, which is consistent with results of Lazarides *et al* (1995a). Lenart and Flink (1984) reported that, the resistances imparted by infused sugar and salt to moisture out flow during convective dehydration were different, because the sugar (having high molecular weight) accumulates in a thin subsurface layer resulting in surface tissue compaction (an extra mass transfer barrier), while salt (having low molecular weight) penetrates the osmosed tissue to a much greater depth. Mazza (1983) and Chopra (2001) also reported that salt or sugar treatment of carrot pieces before air-drying decreased the rate of moisture transport significantly. It is indicated in Fig 4.21 that the drying behaviour is similar for higher drying air temperatures (65 and 75°C) except the differences of increased drying rates and reduced total convective drying times.

It can be concluded that the osmotic pretreatments, lowered the rates of complementary convective drying process, and increased the total dehydration time as compared to direct convective drying to a final moisture contents of 4-5 % (w.b.) at all the convective drying air temperatures. This contradicted the results of Lenart (1994), Singh (2001), Torringa *et al* (2001) and Matusek and Meresz (2002) according to which osmotic dehydration spectacularly shortened the total convective drying time. The reduction in convective dehydration is only possible if, osmo-convective has to be performed to prepare intermediate moisture foods (IMF) having high final moisture content.

4.3.1.2 Effect of drying air temperature on drying kinetics of carrot cubes

During convective dehydration of un-osmosed and pre-osmosed carrot cubes, it was observed that, the time required to achieve final moisture content of 5 g water/g dm was different at all drying air temperatures. More time was required for the osmotically pretreated samples as compared to un-osmosed carrot cubes. The moisture removal inside the carrot cubes was higher at higher drying air temperatures by virtue of higher thermal energy and mass transfer. As indicated by drying rate curves in Fig 4.22 (a) and (b), the migration of moisture to surface and evaporation (drying) rate from the surface to air decreased with decrease of the moisture in the product. The mean drying rates are 1.762 g water/g dry matter (dm) per minute for un-osmosed carrot cubes at a drying air temperature of 55°C, which increased to 1.962 and 2.285 g water/g dm per minute for an air temperature of 65 and 75°C respectively. The corresponding values were 0.677, 0.745 and 0.780 g water/ g dry matter per minutes for osmotically pretreated with salt solution; 0.421, 0.450 and 0.478 g water/ g dry matter per minutes for sugar; 0. 271, 0.295 and 0.363 g water/ g dry matter per minutes for carrot cubes osmotically pretreated with mixture of sugar-salt solution at an air drying temperature of 55, 65 and 75°C respectively. Similar trends of mean drying rates of various products were reported by Sarsavadia *et al*

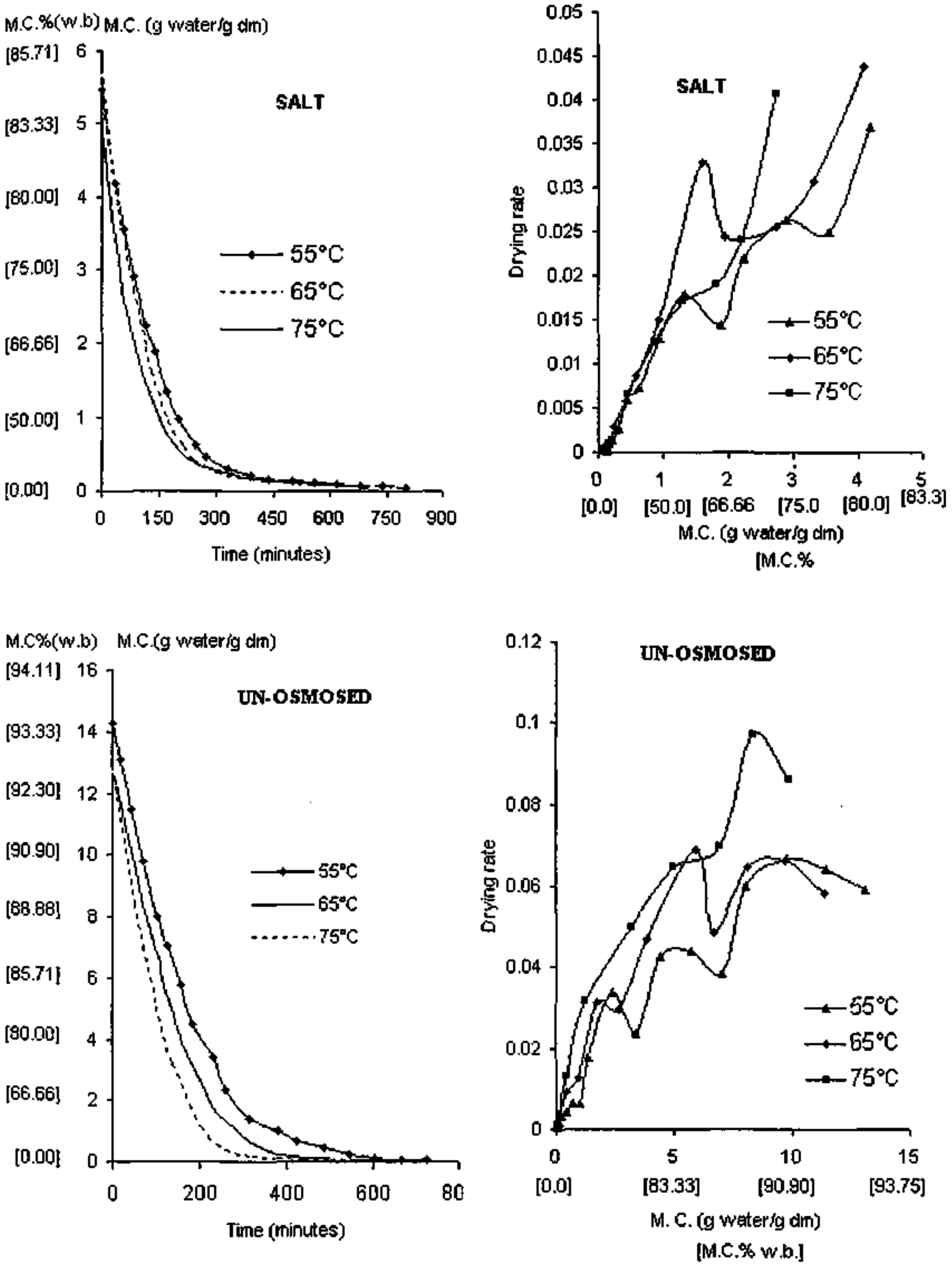


Fig 4.22 (a) Effect of air temperature on drying characteristics and drying rate of un-osmosed and pre-osmosed carrot cubes.

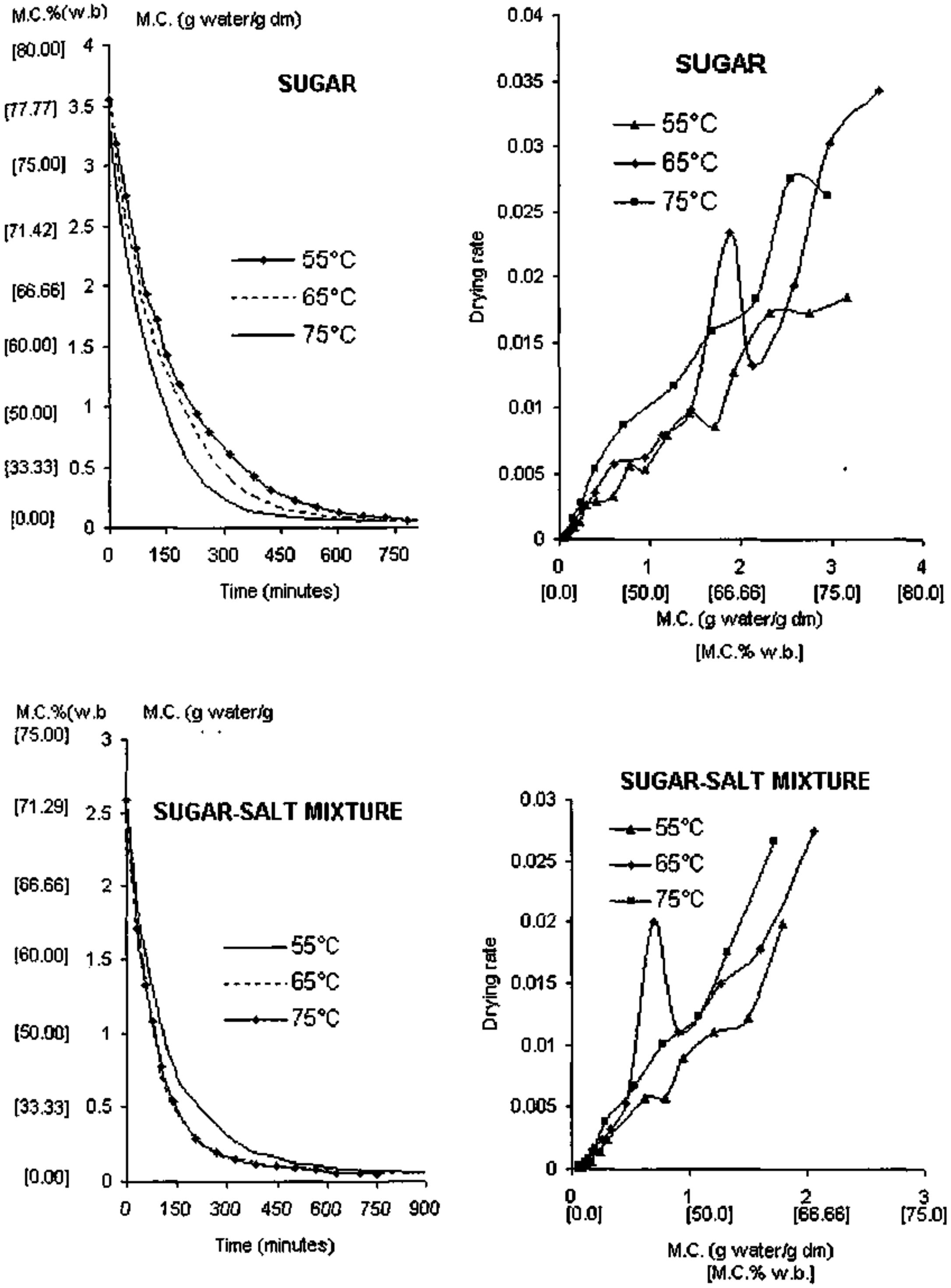


Fig 4.22 (b) Effect of air temperature on drying characteristics and drying rate of un-osmosed and pre-osmosed carrot cubes.

(1999); Maskan (2000); Ertekin and Yaldiz (2004).

The drying rates are higher in the beginning of the drying process and later decreased with decrease of moisture for un-osmosed and osmotically pretreated samples under all the conditions of convective dehydration (Fig 4.21 and 4.22 a and b) and drying air temperature. The drying and drying rate curves indicate that drying of carrot cubes took place only in falling rate period. This was because the drying process would have been governed by moisture diffusion process, which is consistent with the results reported for convectively dehydrated carrots by Mulet *et al* (1989a and b), Prabhanjan *et al* (1995), Litvin *et al* (1998), Prakash *et al* (2004), Doymaz (2004a). Similar findings were also reported for other products by Diamante and Munro (1993) for sweet potato slices and Doymaz (2004b) for white mulberry. The reason for reduction of drying rate might also be due to reduction in porosity of the material due to shrinkage with the advancement of drying process, which increased the resistance to movement of water leading to further fall in drying rates. The effect of shrinkage on drying behaviour had also been reported by Reppa *et al* (1999); Gabas *et al* (1999), Hatamipour and Mowla (2002), Johnson *et al* (1998), Pabis (1999) and Davidson *et al* (2004).

Although, it was expected that a vegetable like carrot having high moisture (92% w.b.) should have constant rate of drying, because initially evaporation took place at the surface or near the surface; when drying proceeds evaporation occurs from inside the solid and water vapour had to be transported to the surface by diffusion. But, the drying rate curves for convective dehydration temperatures of 55, 65 and 75°C as shown in Fig 4.22 (a) and (b) indicate that, the drying process occurred mainly in falling rate drying period, starting from the approximated initial moisture content of 1284% d.b. (~91.5% w.b.), 565% d.b. (~85% w.b.), 320% d.b. (~75.5% w.b.) and 249% d.b. (~71% w.b.) for un-osmosed, osmosed with salt, sugar and mixture of sugar-salt solutions respectively; to a final moisture content of 5% (d.b.). The existence of falling rate period indicated a diffusional-controlled type mechanism of drying in accordance to the results of Maskan and Gogus (1998); Tulasidas *et al* (1993); Yaldiz *et al* (2001); Doymaz (2004a and b) and Ertekin and Yaldiz (2004). The absence of constant rate period might also be due to the reason that the product could not provide a constant supply of water for an appreciable period of time because of rapid thin layer drying of the product at initial stages of drying. Similar reasons were also reported by Prabhanjan *et al* (1995), Sabarez *et al* (1997); Maskan *et al* (2002); Prakash *et al* (2004), Lahsasni *et al* (2004) and Togrul and Pehlivan (2003).

Drying curves show very low drying rates, when the average moisture content of the product approached to 2 to 1 g water/ g dm. Drying times from 2 to 1 g water/ g dm accounted for 30-40% of total drying time depending up on the temperature of drying air. Therefore, a considerably long drying period would be necessary to achieve a final moisture content lower than 1 g water/ g dm. To reach safe final moisture content of 4-5% (w.b.), the total average duration for convective dehydration at different drying air temperatures at an air velocity of 1.6 m/s and osmotic pretreatments is summarized below in Table 4.15.

Table 4.15 Total convective drying time for osmotically pretreated and un-osmosed carrot cubes at different air temperatures.

	Average drying time in minutes			
Temperature	**Un-osmosed**	**Salt**	**Sugar**	**Sugar-salt**
55°C	725	800	830	900
65°C	650	765	795	815
75°C	560	620	690	700

The analysis of variance (ANOVA) of total convective dehydration time revealed that, both the osmotic pretreatment and drying air temperature have significant effect at 5% level of confidence interval (Appendix-L).

4.3.1.3 Effect of osmotic pretreatment and air temperature on shrinkage during osmo-convective dehydration

The quality of dried product changes during the drying process, depending on pretreatment, drying method and conditions (Krokida and Maroulis 1997). In present study, the shrinkage of the carrot cubes during convective dehydration process of carrot cubes was measured by toluene displacement method. After osmotic dehydration, the shrinkage of product was measured by water displacement method. No significant shrinkage was observed during osmotic dehydration, however an increase in the density of the product was observed due to penetration of solute into the product.

It was indicated by Fig 4.23 that the shrinkage of the product increased linearly with decrease of moisture during convective dehydration. The shrinkage was least for the samples osmotically pretreated in solution of sugar-salt mixture. The maximum shrinkage was observed in the un-osmosed (blanched) samples during convective dehydration. Further, during convective dehydration the shrinkage was more in samples osmotically pretreated with salt solution as compared to osmotic pretreatment with sugar syrup, which was consistent with the results of Torringa *et al* (2001). Therefore, the shrinkage of the dehydrated product was directly related to both the moisture content and the amount of solute infused into the product during the osmotic pretreatment. The samples osmoticlly dehydrated with salt were fluffy as compared to other samples after convective dehydration i.e. their density was less as compared to other samples after convective dehydration. The shrinkage of carrot cubes after osmo-convective dehydration can be visually seen by Fig 4.24.

It was found that the apparent density increased, while the porosity of final product decreased due to the solute gain. The shrinkage behaviour of various products during convective dehydration was investigated by various researchers, e.g. plantain (Johnson *et al* 1998); vegetables and mushrooms (Pabis 1999) and carrots (Hatamipour and Mowla

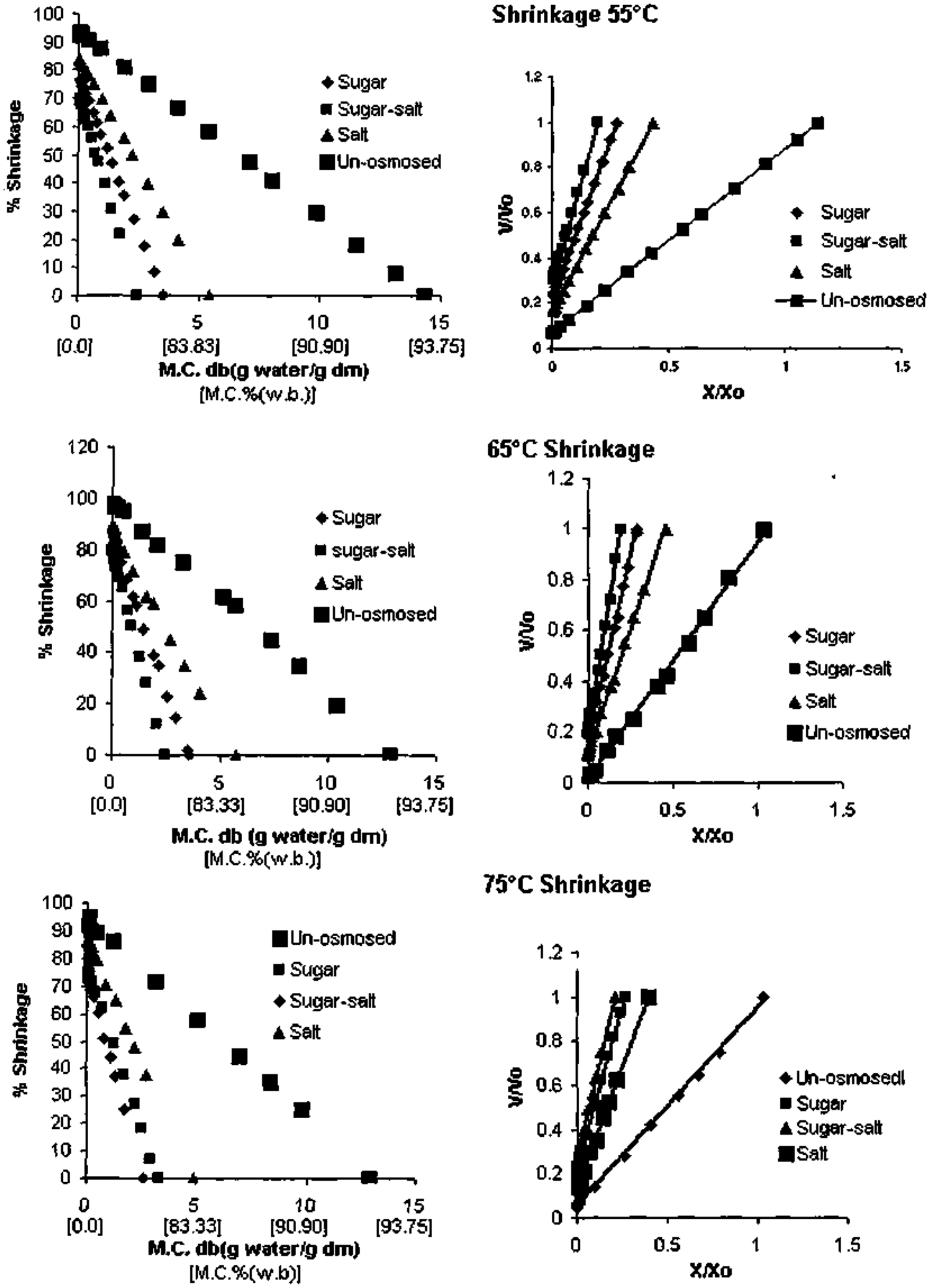


Fig 4.23. Effect of osmotic pretreatment on shrinkage behaviour of carrot cubes during convective dehydration at different drying air temperatures.

2002). Similar results had also been reported by Krokida and Maroulis (1997); Viberg *et al* (1998); Prado *et al* (2000); Erle and Schubert (2001) and Ochoa *et al* (2002).

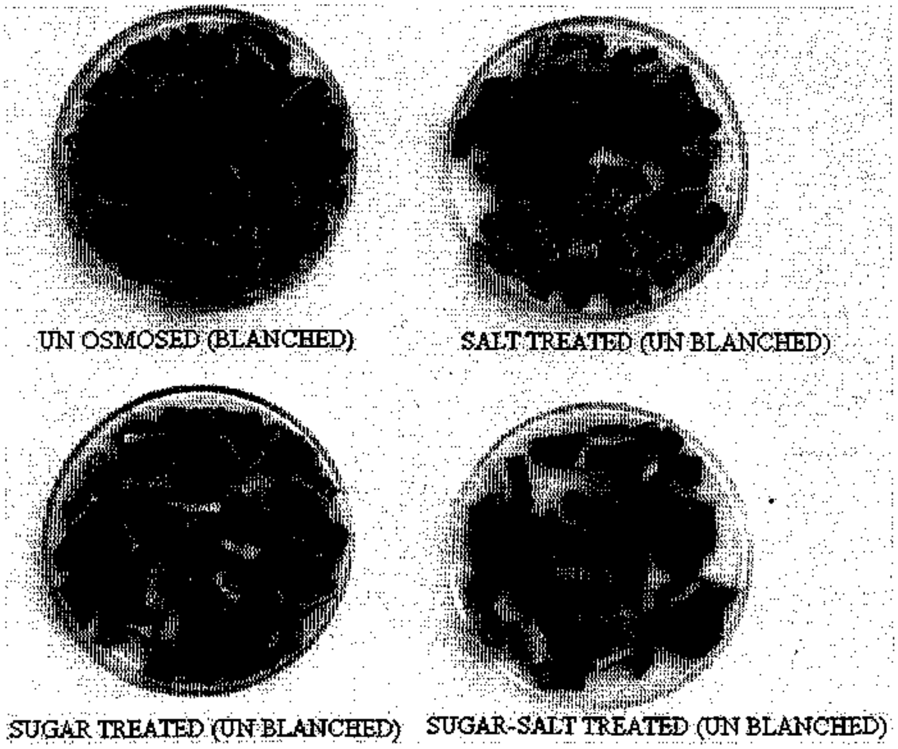


Fig 4.24 Effect of osmotic pretreatment on shrinkage of dehydrated carrot cubes

The relationship between shrinkage and moisture content was established by regression analysis of the data to the equation with high value of correlation coefficient ($R^2 > 0.98$).

$V/Vo = A+B*(X/Xo)$

Table 4.16 Values of various coefficients for shrinkage equation at different temperature and osmotic pre-treatments.

Pre-treatments	55°C			65°C			75°C		
	B	A	R^2	B	A	R^2	B	A	R^2
Un-osmosed	0.819	0.0655	0.999	0.9313	0.0194	0.998	0.8917	0.0622	0.998
Salt	1.9313	0.1545	0.989	1.9496	0.1186	0.997	2.2206	0.1296	0.999
Sugar	2.7502	0.2201	0.997	2.8697	0.1689	0.999	2.9720	0.2143	0.997
Sugar-salt mixture	3.5763	0.2861	0.999	4.1166	0.1984	0.999	3.5573	0.2586	0.999

The analysis of variance (ANOVA) of shrinkage constants reveals that, both the osmotic pretreatment and drying air temperature have significant effect on 'A' at 5% level of confidence interval, whereas the effect of temperature on 'B' was non-significant (Appendix-M).

4.3.1.4 Effect of osmotic pretreatment on dehydration ratio

After convective dehydration of carrot cubes up to 4-5% moisture content (w.b), dehydration ratio was calculated to find the recovery of final product based on amount of fresh product used. It was observed that dehydration ratio is directly related to the amount of solute infused during osmotic dehydration. The infused solute resulted into increased density and decreased porosity of osmo-convectively dehydrated product. The un-osmosed and pre-osmosed carrot cubes were convectively dried up to final moisture content of 5% (w.b). The dehydration ratio was maximum for the un-osmosed samples and lowest for the osmotic pretreatment with solution of sugar-salt mixture. Further, the dehydration ratio was found to be less for the osmotically pretreated samples with sugar solution as compared to salt solution. The dehydration ratio varied from 14.57 to 14.80 (for un-osmosed, blanched); 6.35 to 6.75 (pre-osmosed in solution of 10% salt at 30°C for 90 minutes); 4.95 to 5.76 (pre-osmosed in solution of 55°B sugar solution at 45°C for 180 minutes) and 3.35 to 4.72 (pre-osmosed in solution of 50°B sugar +10% salt at 45°C for 180 minutes). However, dehydration ratio was reported as 9.57 by Banga and Bawa (2002) during convective dehydration of carrots.

4.3.1.5 Effect of blanching on convective drying behaviour of carrot cubes

The blanching of un-osmosed carrot cubes before convective dehydration was performed to minimize the enzymatic degradation. During blanching, loss in total solids was observed which might be due to leaching of soluble solids from carrot cubes. For carrot cubes of dimensions 1 cm x 1 cm x 1 cm, the maximum total solid losses were observed during first minute blanching as compared to next two minutes as indicated by Fig 4.25. The blanching for specified time of 3 minutes resulted in average total solid loss 16.66%, whereas, the losses were observed as 13.58% after blanching for one minute. Thus the un-blanched osmotically pretreated samples have more retention of vitamins, flavour and colour as compared to the blanched samples dehydrated by convective dehydration process alone. Loss of carotenoids and texture of carrots due to blanching had also been reported by Roy *et al* (2001). The convective drying behaviour of blanched and un-blanched carrot cubes osmotically pretreated with various osmotic agents is as shown in Fig 4.26.

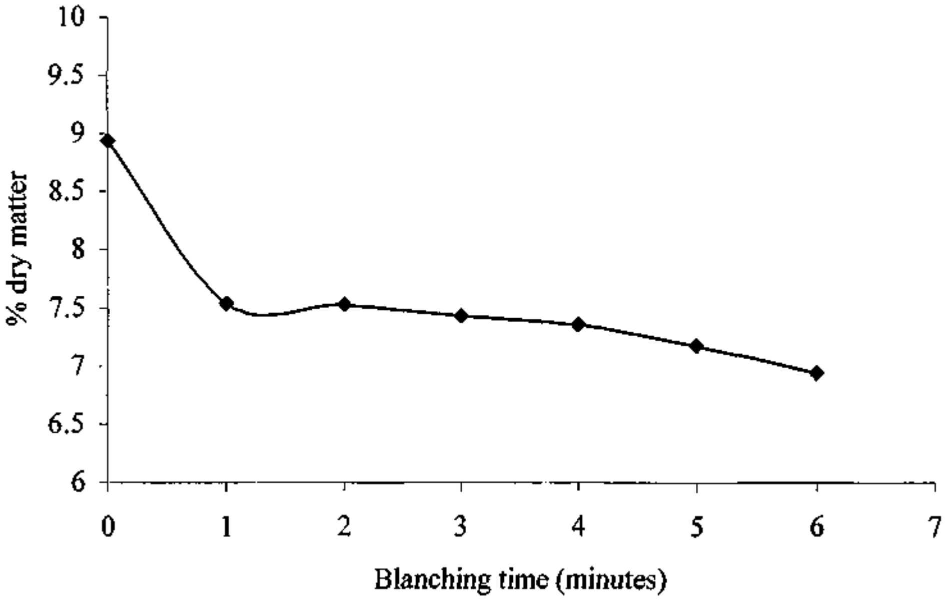


Fig 4.25 Loss of total solids with blanching time at 100°C

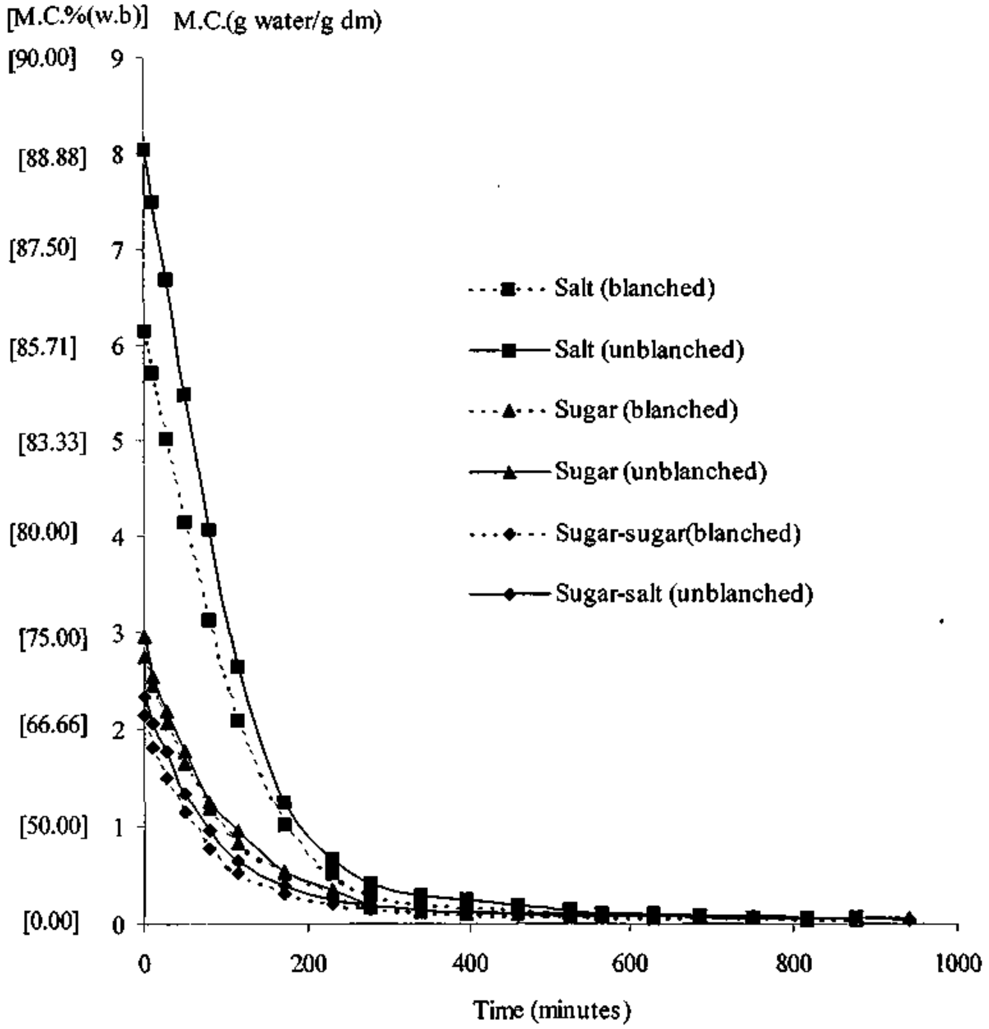


Fig 4.26 Drying behavior of blanched and un-blanched pre-osmosed carrot cubes at 65°C.

4.3.1.6 Effect of calcium chloride addition on convective drying behaviour of carrot cubes

Experiments were conducted to observe the effect of $CaCl_2$ on drying behavior and firmness of the carrot cubes. The drying behaviour of carrot cubes with and without $CaCl_2$ treatment at an air temperature of 70°C and air velocity of 1.6 m/s is given in Fig 4.27. The firmness was measured after rehydration of carrot cubes. In present study no significant effect of $CaCl_2$ addition on texture and convective drying behaviour was observed. However, (Lenart 1996) reported that addition of $CaCl_2$ increased the textural strength of the food material.

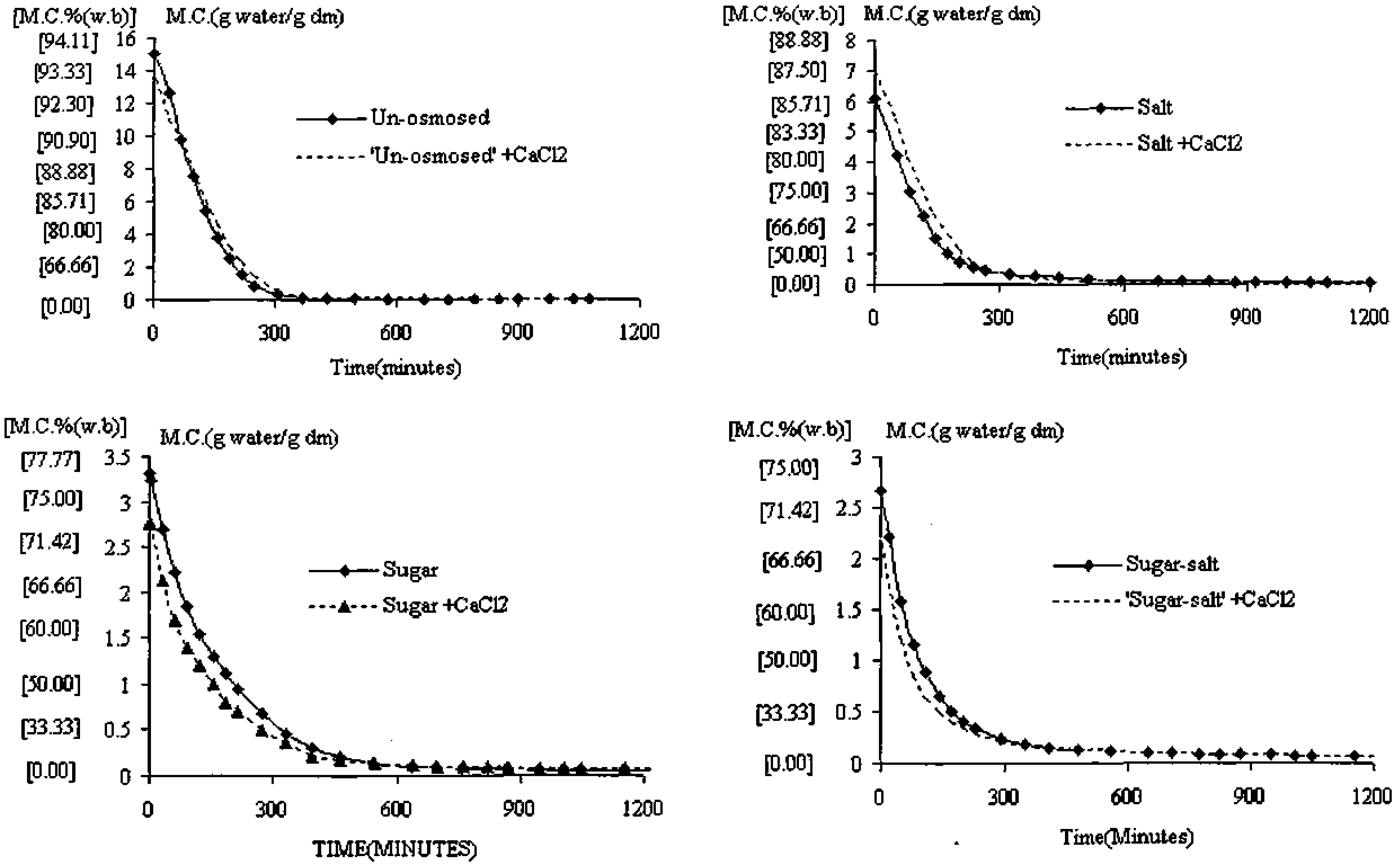


Fig 4.27 Effect of Calcium Chloride addition on convective drying behaviour of un-osmosed and osmotically pretreated carrot cubes at 70°C .

4.3.1.7 Effect of step drying on convective drying behaviour of carrot cubes

The step drying was carried out for the purpose of reduction of total convective dehydration time without affecting the quality of finished product. Step drying of carrot cubes was performed at the temperatures 82°C for first 90 minutes followed by drying at 66°C up to final moisture content of 4-5% as suggested by Dauthy (1995). The convective drying behaviour of un-osmosed and pre-osmosed carrot cubes is as shown in Fig 4.28. The drying rates were faster in the initial stages, which might be due high thermal energy of air having temperature of 82°C for first 90 minutes and availability of free water for evaporation. The drying took place in the falling rate period and no constant drying rate was observed. The step drying resulted in reduction of total convective drying time by 30-40% without any adverse effect on the quality of final dehydrated and rehydrated product. However this type of drying is only possible, if all the material to be dehydrated are placed and taken out at one time.

4.3.2 Effective moisture diffusivity for convective dehydration process

Convective drying in the falling rate period is being postulated to depend on internal mass transfer resistance. Although moisture and the solid are independent phases and do not constitute a single phase, but for the purpose of quick engineering design, the food material properties and the material-solvent interactions are usually lumped into an empirical single effective diffusivity. This parameter is obtained experimentally by applying the Fick's second law for species diffusion in a single phase and takes in to account the internal porosity,ε, and tortuosity,τ, of the sample ($D_{eff} = D_{solution} * \varepsilon/\tau$) (Achanta and Okos 1996; Nieto *et al* 1998). In addition, drying is a simultaneous heat and mass transfer process and correlations of moisture changes must involve solution of coupled differential equations. However, the internal fruit temperature during drying may be considered uniform due to the low Biot number for heat transfer usually found for

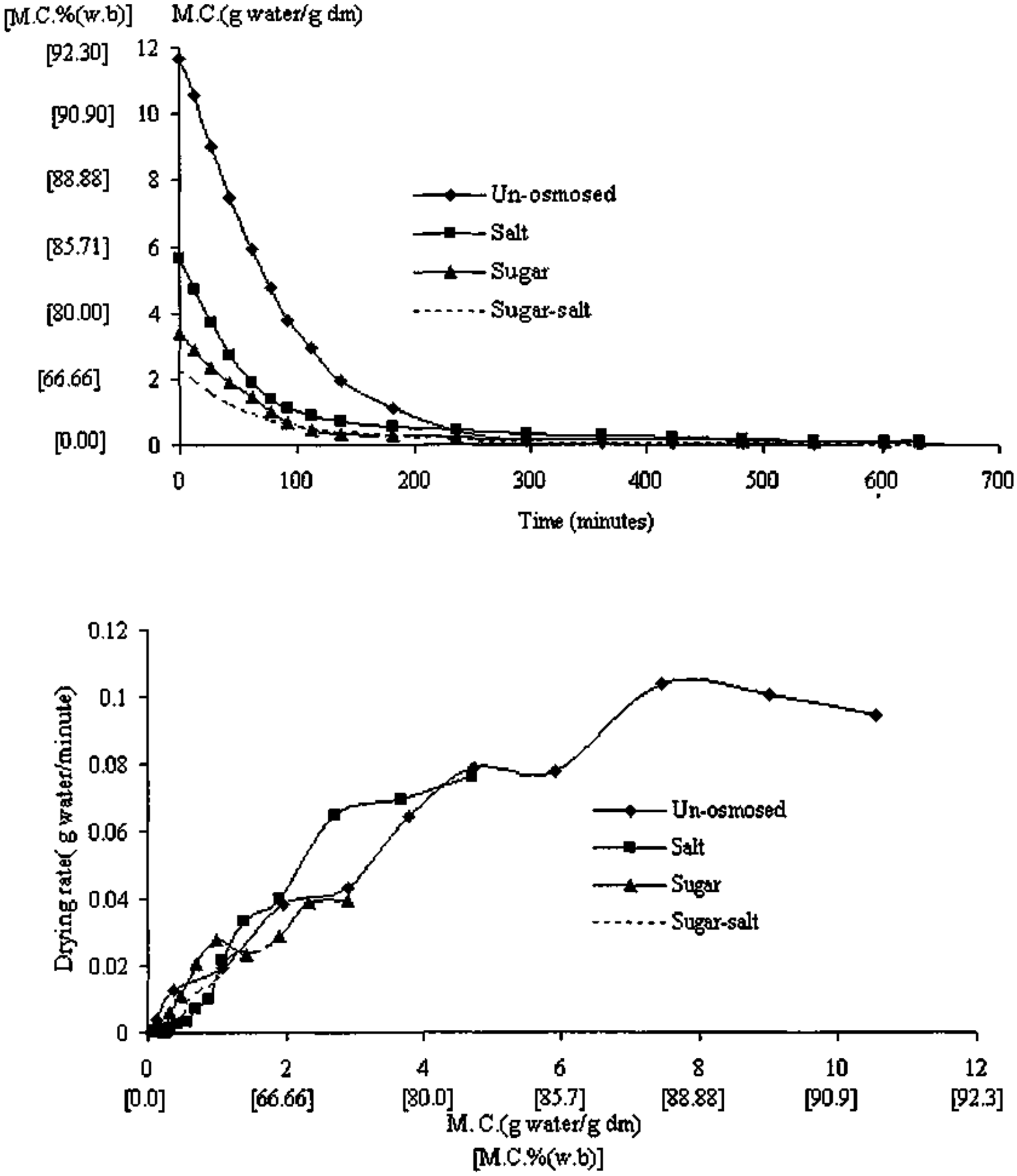


Fig 4.28 Drying behaviour and drying rate of un-osmosed and pre-osmosed carrot cubes for step drying

convectional air-drying of foods (Alzamora *et al* 1979). Negligible external heat transfer effects (i.e. isothermal process) were also assumed in this work to establish a simplified model and Fick's second law was then used for describing the rate of moisture movement during the first falling rate period of drying. The expression of Fick's law for diffusion out of an infinite slab given by Crank (1975), with boundary conditions of internal resistance controlling and initial uniform moisture content, integrated over the volume of slab is as follow:

$$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\exp\left[\frac{-(2n+1)^2\pi^2 D_e t}{4L^2}\right] \qquad (4.25)$$

The variation in moisture diffusivity with moisture content is a complex and system specific function. Karathanos *et al* (1990) and Nieto (1998) reported that the effective moisture diffusivity (D_{eff}) of a food material characterizes its intrinsic mass transport property of moisture, which includes its molecular diffusion, liquid diffusion, vapour diffusion, thermodynamic flow and other possible mass transport mechanisms.

For long drying periods, Moisture ratio (MR) was further simplified to M/Mo instead of $(M_t-M_e)/(M_o-M_e)$ (Thakor *et al* 1999; Ramesh *et al* 2001; Pokharar and Prasad 2002; Doymaz 2004a). The effective moisture diffusivity (D_{eff}) values of carrot cubes during convective dehydration were calculated by iteration technique using computer program in C++ language (Appendix-N), which was developed to solve the equation 4.25. The program was executed only for positive values of Fourier number ($F_o= D_{eff}*t/L^2$) (Sharma *et al* 2003). The values of Fourier No. becomes negative at a value of moisture ratio greater than 0.810619. The computer program could be executed for any positive value of n, but in present case the value of 'n' was fixed as 25, because the series might converge after first 3-10 terms (Simal *et al* 1997a; Toledo 2000; Vivanco *et al* 2002; Park *et al* 2002b). The average effective moisture diffusivity $(D_{eff})_{avg}$, was calculated by taking arithmetic mean of the positive values of effective diffusivities that were estimated at various levels of moisture content in the convective drying process.

It was indicated by Fig 4.29, that effective moisture diffusivity (D_{eff}) in air-drying process was considerably affected by previous application of osmotic pretreatments. The reduction of effective moisture diffusivity (D_{eff}) with osmotic pretreatment can be attributed to lower moisture diffusion due to infusion of solute in the pores (blocking) of the fruit i.e. lowering of porosity, which was similar to the results of Reppa *et al* (1999). Further, infused solute acting as water-binding agent (i.e. hygroscopic) might also provide increased internal resistance to moisture movement as reported by Rahman and Lamb (1991); Pokharar and Prasad (2002). The lowering of effective moisture diffusivity might be due to the resistance to moisture out flow, which was imparted by the solute layer in the subsurface of the fruit. Further, this solute layer got hardened during the progression of fruit drying which imparted more resistance to water out flow. Johnson *et al* (1998) reported that the sample shrinkage and super facial hardening impede the moisture transfer from sample to air, introducing additional resistance and resulting a low effective diffusivity value. But contrary to this, in present study of osmo-convective dehydration, the values of effective moisture diffusivity of pre-osmosed samples were low, even though the shrinkage of these samples was too less as compared to un-osmosed ones. This might be due to decrease of porosity due to solute infusion in pre-osmosed samples, which in turn resulted in the lowering of effective moisture diffusivity $\left(\because \; D_{eff} = \frac{D_{solution} * porosity}{tortuosity} \right)$. During convective drying, shrinkage was maximum for un-osmosed carrot cubes and was minimum for samples pre-osmosed with mixture of sugar-salt solution followed by pure sugar and salt. That is the reason that the effective moisture diffusivity (D_{eff}) values are lowest for samples pre-osmosed with solution of

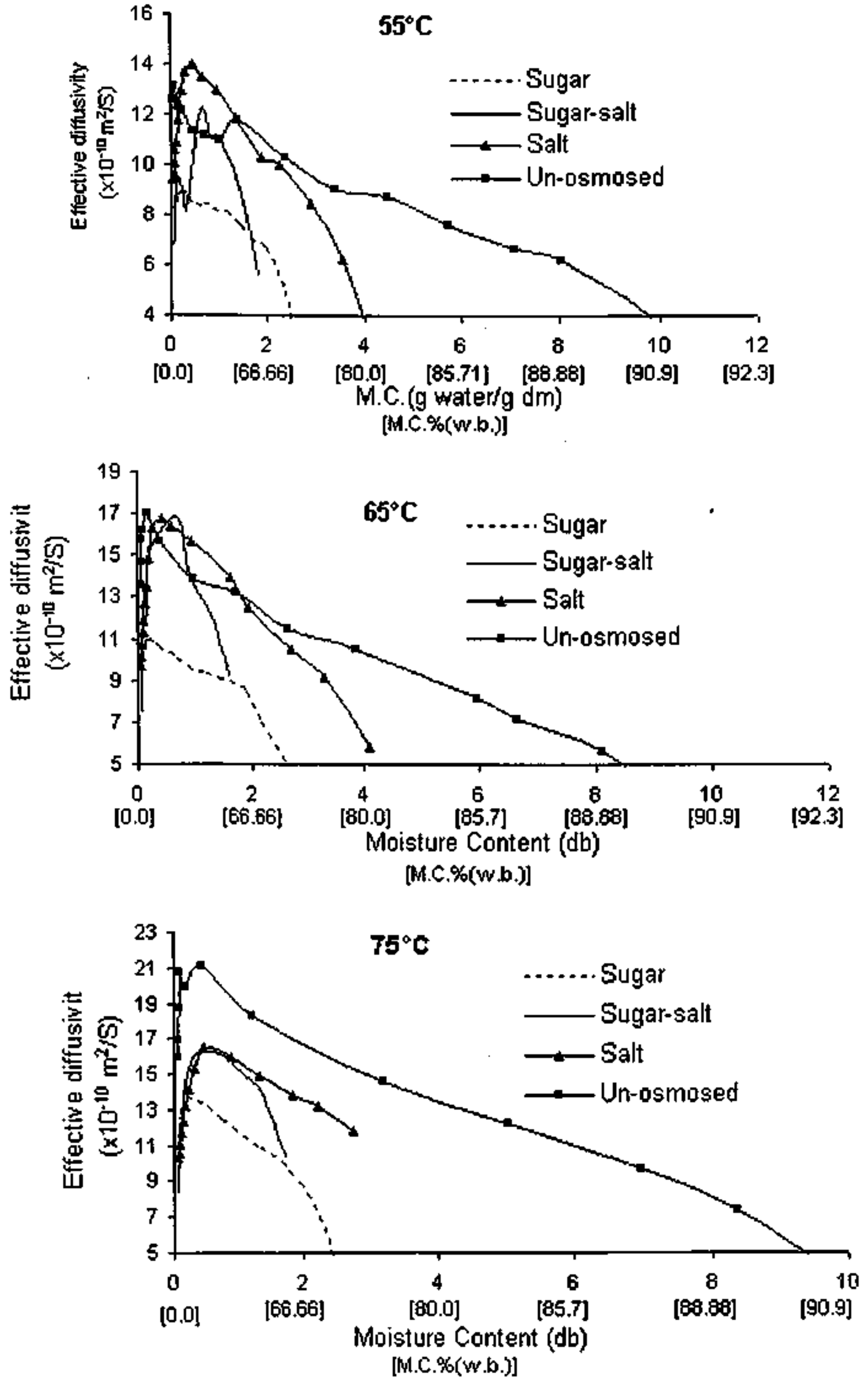


Fig 4.29. Effect of osmotic pretreatment on effective moisture diffusivity during convective dehydration of carrot cubes at different drying air temperatures

sugar-salt mixture followed by sugar, and salt for convective dehydration before 0.2 to 0.3 g water/g dm. The increase in D_{eff} in un-osmosed samples might also be due to the blanching and shortening of diffusional path for moisture movement due to shrinkage (Ruiz-Cabrera *et al* 1997). The high diffusivity in un-osmosed fruit samples might also be due to availability of initial high moisture (approximately 92% w.b.) as compared to 45-75% (w.b.) in pre-osmosed samples, which was consistent with the results of Rahman and Lamb (1991) and Simal *et al* (1997a and b). Karathanos *et al* (1995) also found that D_{eff} was $16x10^{-10}m^2/s$ in apples air-dried at 55°C, while this parameter decreased to $5x10^{-10}$ m^2/s, when samples were osmotically pre-treated in 45°B sucrose solution.

The effective moisture diffusivity (D_{eff}) increased with increase of drying air temperature as indicated in Fig 4.30. The increase in average effective moisture diffusivity with increase in temperature might be because of increase in the vapour pressure inside the carrot cubes, which was consistent with results of Sablani *et al* (2003). Effective moisture diffusivity identified through air-drying experiments carried out with un-osmosed and pre-osmosed carrot cubes, ranged from $7.81x10^{-10}$ to $10.6x10^{-10}$ m^2/s at 55°C. These values are lower than the corresponding values for the experiments carried out at 65 and 75°C.

It is also evident from Figs 4.29 and 4.30 that effective moisture diffusivity (D_{eff}) increased with decrease in the moisture content at all drying air temperatures and osmotic pretreatments only up to a moisture level of 0.2-0.3 g water/g dm (16.6 to 23.0% m.c. on w.b). This behavior might be due to the fact, that however, the initial temperature of the sample being less than drying air temperature in the beginning of the drying process, but with reduction in moisture content, the sample got heated up and subsequently the moisture diffusivity got increased. This is in accordance with the study of Adu and Otten (1996). They also concluded that the diffusion coefficient decreases with decreasing moisture content, but is more dependent on product temperature than moisture content.

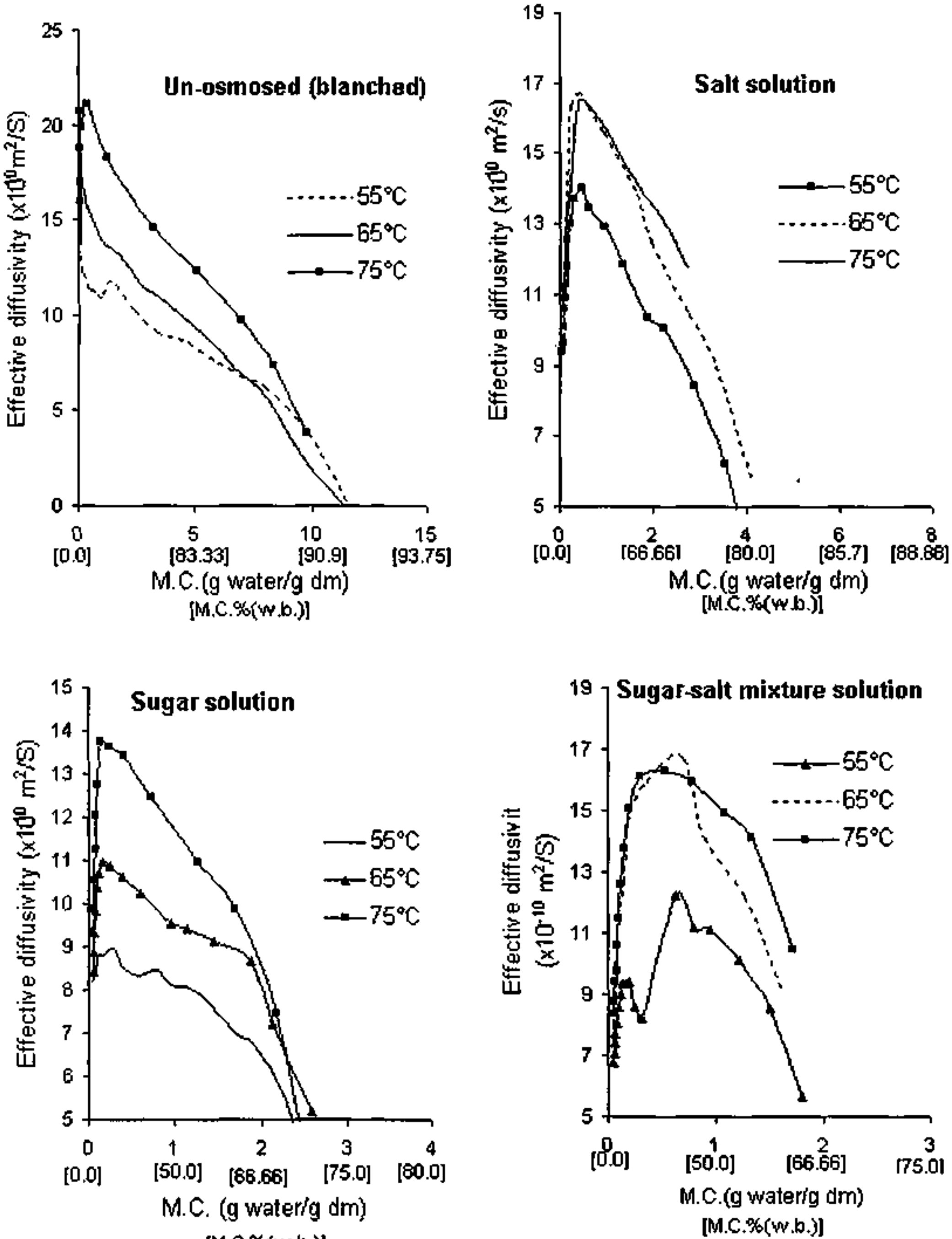


Fig 4.30. Effect of drying air temperature on effective moisture diffusivity during convective dehydration of carrot cubes osmotically pretreated with different solutions

Similar trends were also reported for convective drying of garlic slices by Vazquez *et al* (1999b), Sharma *et al* (2003) and (Raghavan *et al* 1995). Further, in the last phase of each experiment below moisture content approximately 0.2 to 0.3 g water/g dm, there was a sharp decrease of moisture diffusivity, although the product temperatures were high. This might be because; even though the diffusion coefficient was more dependent on temperature than moisture content, but at a constant product temperature (not air temperature), it decreased with decrease of moisture content (Adu and Otten 1996). The decrease of average effective moisture diffusivity $(D_{eff})_{avg}$ in later stages may be due to non-availability of free water for diffusion at finishing stage of convective dehydration. In later stage of drying, high shrinkage and superficial hardening of the product might also impede the moisture transfer from sample to the air, thus introducing additional resistance, which resulted in low average effective moisture diffusivity.

The values of average moisture diffusivity $(D_{eff})_{avg}$ for all drying conditions are presented in Table 4.17. In convective drying of carrot cubes at drying air temperatures ranging from 55 to 75°C, average effective moisture diffusivity $(D_{eff})_{avg}$ varied between 0.9259×10^{-9} and 1.4955×10^{-9} m^2/s, between 1.0646×10^{-9} and 1.3214×10^{-9} m^2/s, between 0.7811×10^{-9} and 1.0779×10^{-9} m^2/s, and between 0.8060×10^{-9} and 1.2509×10^{-9} m^2/s for un-osmosed and pre-osmosed samples with salt, sugar, and sugar-salt mixture respectively. At 65°C drying air temperature, average effective moisture diffusivity $(D_{eff})_{avg}$ was 1.20738×10^{-9}, 1.19643×10^{-9}, 0.933356×10^{-9} and 1.08436×10^{-9} m^2/s for un-osmosed, and pre-osmosed with salt, sugar, and sugar-salt mixture respectively. The corresponding values of average effective moisture diffusivities were higher at 75°C temperature and lower at 55°C.

Table 4.17 Average effective moisture diffusivity for un-osmosed and pre-osmosed carrot cubes during convective dehydration.

Temp	Un-osmosed	Salt	Sugar	Sugar-salt
55°C	9.26E-10	1.06E-09	7.81E-10	8.81E-10
65°C	1.21E-09	1.20E-09	9.33E-10	1.08E-09
75°C	1.50E-09	1.32E-09	1.08E-09	1.25E-09

Comparison of moisture diffusivities during dehydration is difficult to compare with the literature values because of variation in food composition and physical structure and different methods and models employed to estimate diffusivity (Shi and Maguer 2002; Sablani *et al* 2000). Mulet *et al* (1989b) reported average effective diffusivity values $19.3\text{x}10^{-10}\text{m}^2/\text{s}$ at 60° for carrots and $2.3\text{x}10^{-10}$ m^2/s at 60°C in potatoes was reported by Gekas and Lamberg (1991). The average effective moisture diffusivity found by Karathanos *et al* (1995), varied from 4 to $21\text{x}10^{-10}\text{m}^2/\text{s}$ for apples. The average effective moisture diffusivity for moisture during convective dehydration of pears by Park *et al* (2002b) was found to be 2.06 to $6.37\text{x}10^{-10}$ m^2/s for un-osmosed pears and 1.87 to 8.12 $\text{x}10^{-10}$ m^2/s for pre-osmosed pears in sugar syrup. The effective moisture diffusivity of potatoes varied from $1.225\text{x}10^{-9}$ to $3.278\text{x}10^{-9}$ m^2/s (Akpinar *et al* 2003)

ANOVA was used to study the effect of hot air temperature on average effective moisture diffusivities $(D_{eff})_{avg}$ for convective drying process (Appendix-N). It shows that both drying air temperature and osmotic pre-treatment have significant effect on average effective moisture diffusivity at 5% level of significance.

4.3.3 Activation energy for convective dehydration

The dependence of average moisture diffusivity $(D_{eff})_{avg}$ on drying air temperature was obtained by Arrhenius relation presented as below

$$(D_{eff})_{avg} = D_o e^{-\left(\frac{E_a}{RT_{abs}}\right)}$$

Where T_{abs} is the absolute temperature (K); R is the Gas constant having a constant value of 8.134 KJ/mole K; D_o is the effective moisture diffusivity at 273K temperature; and E_a is the activation energy. Thermodynamically, activation energy is the relative ease with which the water molecules pass the energy hurdle when migrating within the product.

The temperature dependency of average effective moisture diffusivity $(D_{eff})_{avg}$ for convective drying for all the osmotic pretreatments is shown in Fig 4.31. The average effective moisture diffusivity $(D_{eff})_{avg}$ is plotted against reciprocal of absolute temperature, and a straight line relation with negative slope is obtained, which implies that the $(D_{eff})_{avg}$ of carrot cubes decreases linearly with increase in $1/T_{abs}$ during convective dehydration.

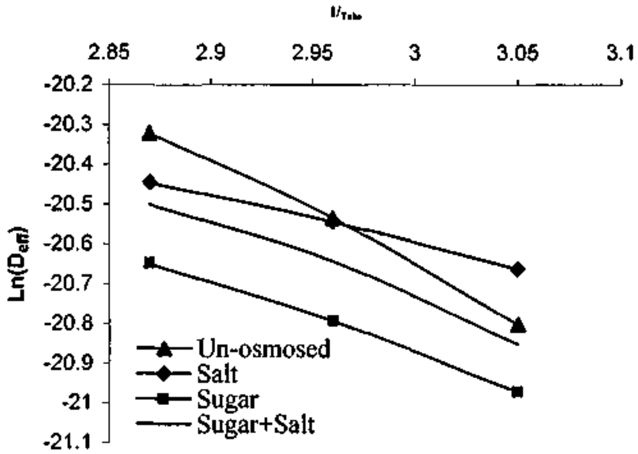


Fig 4.31 Effect of drying air temperature on effective diffusivity during convective dehydration of carrot cubes osmotically pretreated in different solutions

Following equations with high correlation coefficients ($R^2>0.99$), were obtained for these linear plots under different drying conditions.

For un-osmosed

$$(D_{eff})_{avg} = 3.0\times10^{-6} \exp(-2.6633/T_{abs}) \qquad (R^2=0.9962)$$

For salt

$$(D_{eff})_{avg} = 4.0\times10^{-8} \exp(-1.2003/T_{abs}) \qquad (R^2=0.9978)$$

For sugar

$$(D_{eff})_{avg} = 2.0\times10^{-7} \exp(-1.7889/T_{abs}) \qquad (R^2=0.9963)$$

For mixture of sugar and salt

$$(D_{eff})_{avg} = 3.0\text{x}10^{-7} \exp(-1.9501/T_{abs}) \quad (R^2=0.9886)$$

The activation energy for the convective drying of carrot cubes is 21.6633 KJ/mole K for un-osmosed samples, which was 9.7632, 14.5509, 15.8621 KJ/mole K in case of salt, sugar, and mixture of sugar-salt, respectively.

Table 4.18 Activation Energy and effective moisture diffusivity at 273k (0°C)

Treatment	D_o (m2/s)	E_a (KJ/moleK)
Un-osmosed	3.00E-06	21.6633
Salt	4.00E-08	9.7632
Sugar	2.00E-07	14.5509
Sugar-salt mixture	3.00E-07	15.8621

It is observed that activation energy (E_a) decreases with the osmotic pretreatment. The activation energy of un-osmosed (blanched) samples might be high due to the destruction of cell structure (pores) of carrot cubes as blanching was done only for the un-osmosed samples. The high value of activation energy (E_a) for un-osmosed samples might also be due to presence of high initial moisture content of 92% (w.b.) as compared to 45-72% (w.b.) for pre-osmosed samples. Therefore more thermal energy would be required to remove high amount of water from un-osmosed carrot cubes. The activation energy is lowest for samples pre-osmosed with salt solution, and is highest for samples pre-osmosed with sugar-salt mixture solution. The relative activation energy of carrot cubes pre-osmosed with solutions of salt, sugar and sugar-salt mixture might be explained on the basis of relative porosity of fruit depending up on the amount and molecular weight of salt and sugar infused into carrot cubes. Similar results were reported by Reppa *et al* (1999).

During conventional dehydration, the activation energy values for diffusivity of vegetables may be as low as 9 KJ/mole K (Yusheng and Poulsen 1988) and as high as 280 KJ/mole K (Feng and Tang 1999). The values estimated in the present study of carrot cubes dehydration are within the range expected for convective drying process. The activation energy values calculated in present study exhibited a magnitude close to the values proposed for biological materials ranging between 26.46 to 31.21 KJ/mole for Pears without osmotic dehydration, 24.34 to 28.20 KJ/mole for pears with osmotic dehydration (Park 2002b); 39.7 KJ/mole and 24.0 KJ/mole for fresh and osmotically pretreated apple cubes respectively (Simal *et al* 1997b); 24.788 to 28.031 KJ/mole for osmotically pretreated pineapple (Pokharkar and Prasad 2002) and 24.6 KJ/mole at 60°C air temperature for carrot slices (Mulet 1989a). The lower activation energy translates to higher moisture diffusivity in the drying process.

4.3.4 Validity of various empirical models for convective drying kinetics

The following empirical models have been used to describe convective drying kinetics of thin layer drying of grapes (Tulasidas *et al* 1993), carrots (Prabhanjan *et al* 1995), egg plant (Ertekin and Yaldiz 2004) and for garlic cloves (Sharma *et al* 2003).

Page Model	$MR = Exp(-K*t^N)$
GEM	$MR = A*Exp(-K*t)$
Logarithmic Model	$MR = A*Exp(-K*t)+C$
Two Term	$MR = A*Exp(-K_0*t)+B*Exp(-K_1*t)$
Midilli *et al* (2002)	$MR = A*Exp(-K*t^N)+C*t$

Where K, N, A, B and C are model constants.

Drying curves were fitted to the experimental data using these moisture ratio equations. However moisture ratio (MR) was simplified to M/Mo instead of (M-Me)/(Mo-Me) due to long drying periods as suggested by Thakor *et al* (1999), Diamente and Munro (1993), Togrul and Pehlivan (2002), Midilli *et al* (2003), Yaldiz *et al* (2001) and Doymaz (2004a). The low R^2 and high RMSE values for GEM, two-term exponential model and Logarithmic model leads to their rejection. The high R^2 values for the Page and Middili model were acceptable to characterize the convective drying behaviour of un-osmosed and pre-osmosed carrot cubes. Further, R^2 was highest and RMSE and χ^2 were least for the Middilli model as compared to Page model.

During the analysis of experimental data, it was observed that none of the above said models except Midilli model (except in few experiments) could represent the actual data. Middili models was modified and tried to fit the data as below:

$MR= A*Exp(-K*t^N)+C$

The modification in Midilli model was made assuming that, towards the finish stage of the convective drying process, the value of moisture ratio had become almost constant. It is clear from Appendix-O that R^2 is highest and RMSE, χ^2 and E values are least for modified Middili model, which indicated that this is the best model for predicting the convective dehydration behaviour of un-osmosed and pre-osmosed carrot cubes at drying air temperature of 55, 65 and 75°C.

The values of various coefficients of models and various statistical parameters for these models are also presented in Appendix -O.

4.4 Effect of osmo-convective dehydration on quality parameters of product

The purpose of the present work was to study the effect of osmotic pretreatments on the quality parameters of dehydrated and rehydrated carrot cubes. It was observed that, osmotic pretreatment affected various thermo-physical and quality parameters of the product, such as colour, flavour, density and porosity, water sorption properties and textural characteristics. Similar results were reported by Ertekin and Cakaloz (1996b), Singh *et al* (1999) and Bidaisee and Badrie (2001). In the present study, rehydrated carrot cubes, osmotically pretreated with mixture of sugar-salt followed by convective dehydration, showed organoleptic properties (texture, taste, colour and overall acceptability) comparable with freshly harvested carrots. The difference in quality of dehydrated and rehydrated carrot cubes, osmotically pretreated in solutions of different osmotic agents, can be visually compared from the Fig 4.32 and 4.33.

The effects of various osmotic pretreatments on various quality parameters are as discussed below.

4.4.1 Effect of osmotic pretreatments on colour of rehydrated carrot cubes

The colour was measured in terms of 'L', 'a' and 'b' values after proper grinding and mixing of rehydrated carrot cubes. The average 'L', 'a' and 'b' values of fresh carrots varied between 33.28-33.46, 25.56-25.90 and 13.29-13.51 respectively. It was observed that, blanching of un-osmosed carrots improved the colour of the rehydrated product, which was consistent with the results of Chua *et al* (2000). The comparison of average values of 'L', 'a' and 'b' for rehydrated carrot cubes osmotically pretreated with different osmotic agents before convective dehydration is given in Fig 4.34. It is indicated in Fig 4.34, that blanching decreases the 'L' and 'b' values non-significantly, whereas it significantly increases the 'a' value. Degradation of appearance and colour bleaching observed for the carrot cubes pre-treated with salt solution, may be due to the bleaching action of chlorine gas produced from the osmotic solution of sodium chloride which increased the 'a' value of rehydrated carrots. The appearance and colour of rehydrated carrot samples osmotically pre-treated with solution of sugar-salt mixture is comparable to those of fresh carrots. The variation of 'L' and 'a' value may be due the relative proportion of central portion of carrot (xylem) and outer portion (phloem) in the sample. Pereira *et al* (2004) for processed guavas, Tedjo *et al* (2002) for mangoes; Waliszewski *et al* (1999) for banana; Krokida *et al* (2001) for french fries and Venkatachalapathy and Raghavan (1999) for strawberries also reported the improvement in colour due to osmotic pretreatment and blanching.

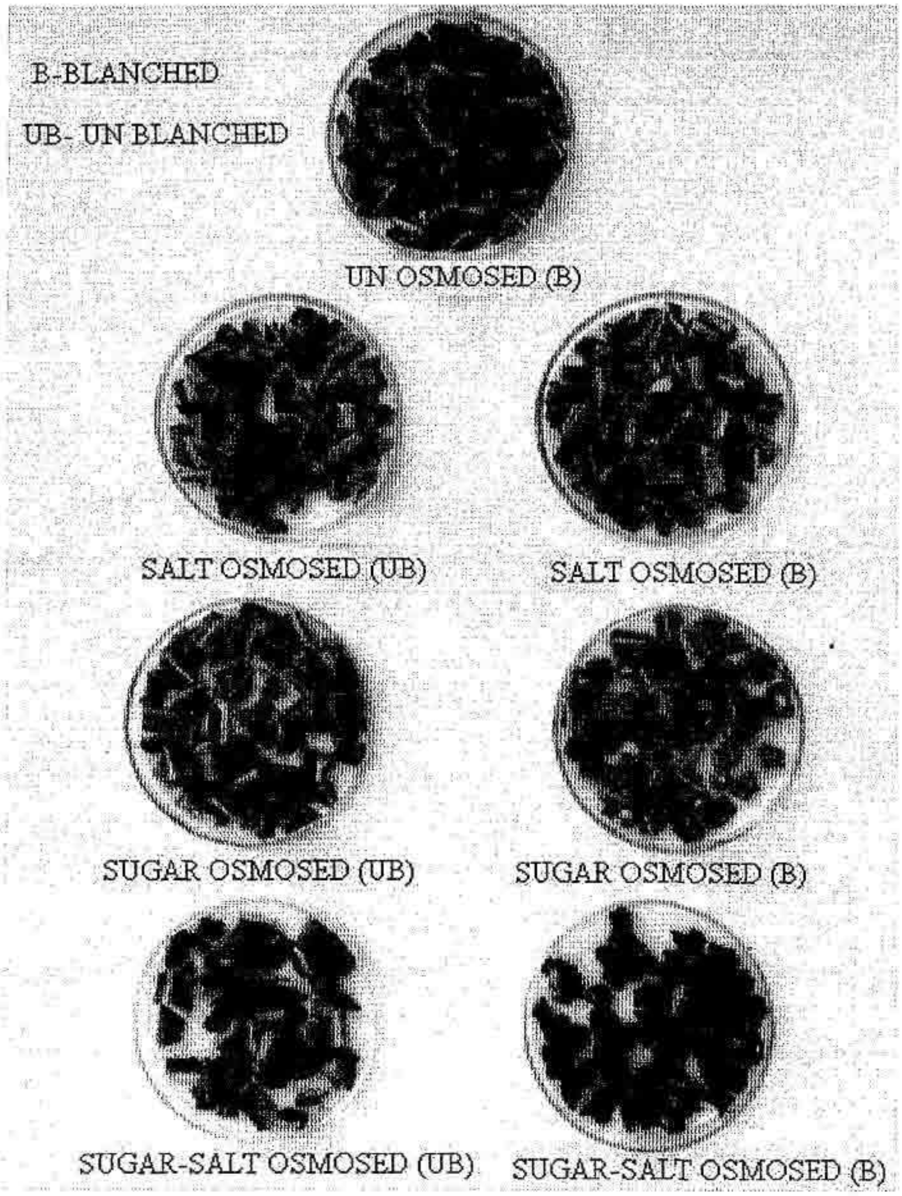


Fig 4.32 Osmo-convectively dehydrated blanched and un-blanched carrot cubes.

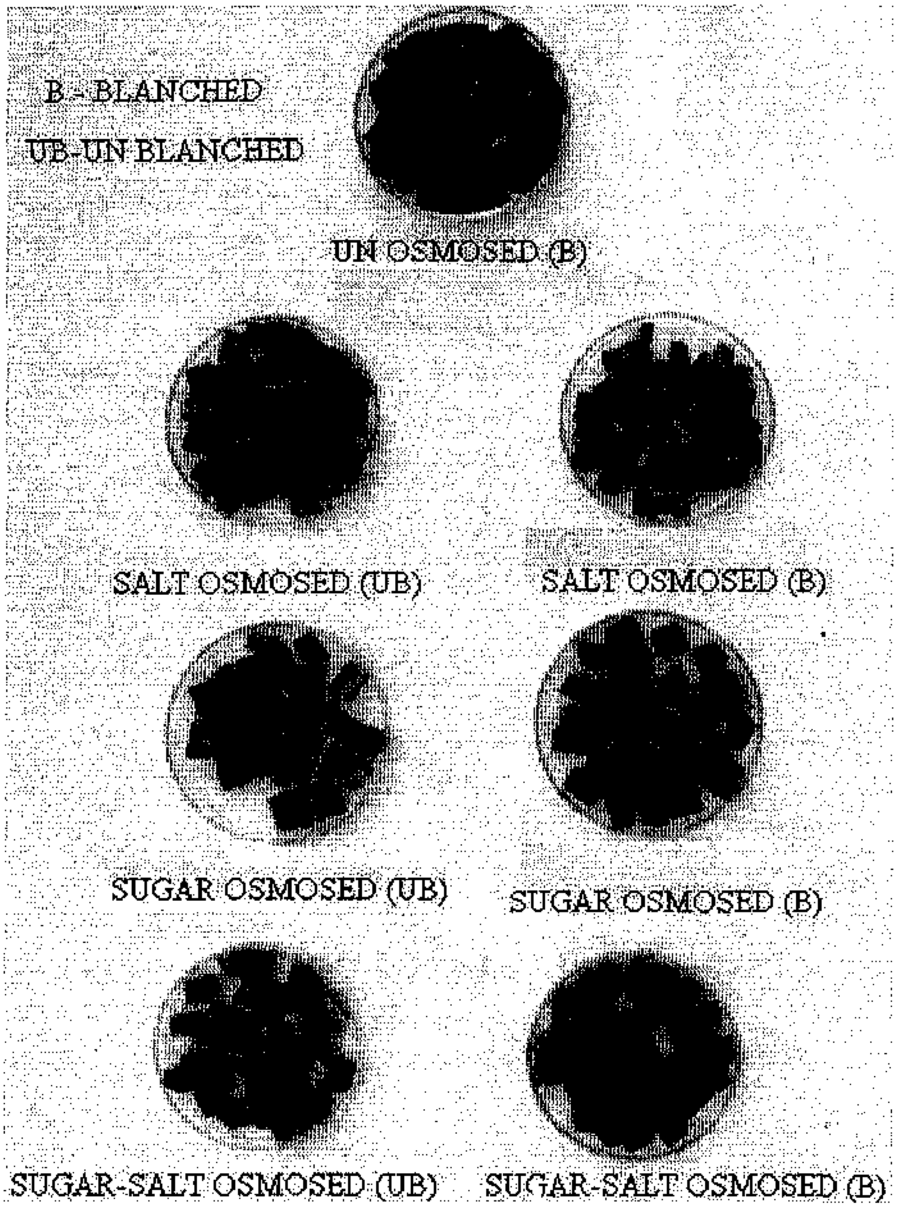


Fig 4.33 Rehydrated carrot cubes after osmo-convective dehydration.

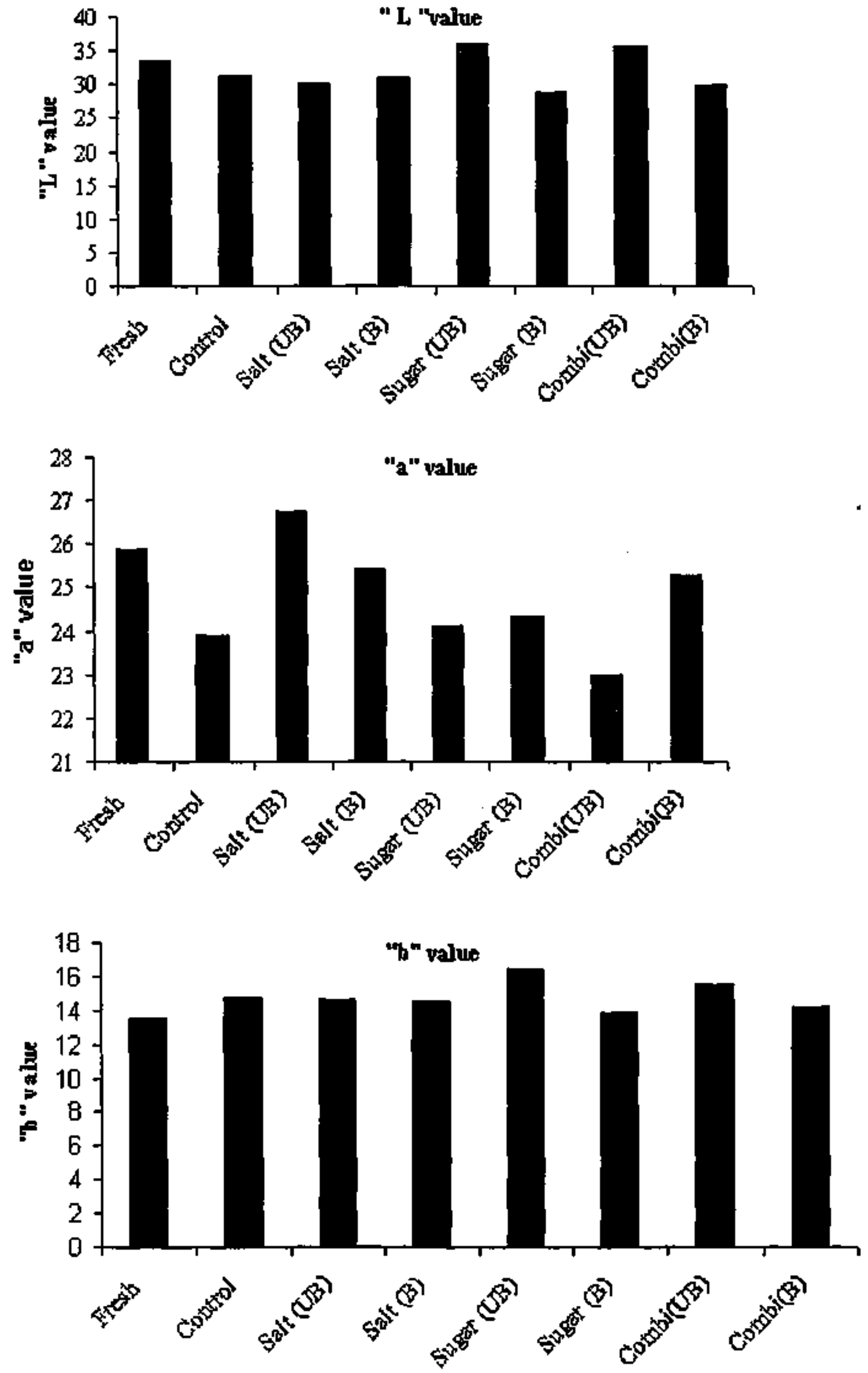


Fig 4.34. Effect of blanching and osmotic pretreatment on colour ('L', 'a' and 'b' value) of rehydrated product.

4.4.2 Effect of osmotic pretreatments on Texture/firmness of rehydrated carrot cubes

The force required to compress 25% of the dimension of fully rehydrated carrot cubes measured the firmness as suggested by Roy *et al* (2001). It is indicated in Fig 4.35 that the highest force for 25% compression of rehydrated carrot cubes is for the samples osmotically pre-treated in solution of sugar-salt mixture and is least for un-osmosed (blanched) samples. Further, the compression force is more in rehydrated carrot cubes which were osmotically pretreated in sugar solution as compared to pretreatment in salt solution. The average force required for 25% compression were 285, 362, 1285 and 3200 g/cm^2 for un-osmosed (blanched), pre-osmosed with salt, sugar and mixture of sugar-salt respectively as compared to 4200 g/cm^2 for fresh carrot cubes.

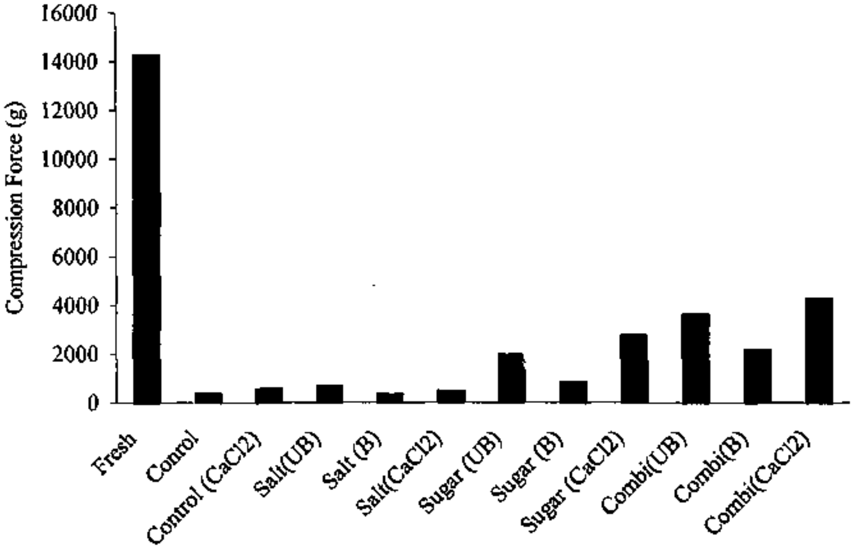


Fig 4.35 Effect of blanching and $CaCl_2$ addition on firmness of carrot cubes

Blanching of un-osmosed carrot cubes resulted in reduction of total compression force, which is consistent with the results of Ramos *et al* (1992), Lee *et al* (1979). The reduction in firmness by blanching of carrot cubes may be due to the fact that, the blanching is an important factor affecting texture due to changes in pectic substances. The increase in firmness of osmotically pretreated samples is in close agreement with Krokida *et al* (1999, 2000), Tedjo *et al* (2002), Gonzalez *et al* (1993) and Pereira *et al* (2004). Variation observed in the compression force of rehydrated carrot cubes was high, which may be due to the different responses of dehydrated carrot cubes towards the rehydration and shape regain behaviour at ambient temperature of water. The regain of shape was found to be maximum in case of carrot cubes osmotically pretreated with mixture of sugar and salt followed by sugar, salt and un-osmosed samples.

Texture was being reported a highly important structural quality parameter (Barat *et al* 2001), and the consumers tend to prefer processed fruits and vegetables with firm texture than that of conventional processed products. Lenart (1996), Lee *et al* (1979) and Alvarez *et al* (2001) reported an increased firmness of fruits and vegetables due to binding of pectic substances with Ca^{++} or Mg^{++} ions. To increase the firmness of carrot cubes, 0.5% $CaCl_2$ was incorporated to osmotic or blanching solution. This pretreatment resulted in increase of firmness for all the pretreatments, except the samples pretreated with salt and $CaCl_2$ solution. The exception might be due to some chemical changes in pectic substances due to the combined action of Sodium chloride and $CaCl_2$. However, in the present study, the effects of $CaCl_2$ addition on the firmness of the carrot cubes were found to be non-significant. Textural improvement can also be done by using additives such as glycerol, sucrose and salt (Jayaraman *et al* 1988).

4.4.3 Effect of osmotic dehydration on water sorption isotherms (EMC) of dehydrated product

Sorption isotherms for the four experimental treatments are compared with four temperatures. The effect of osmotic pretreatment on sorption properties of dehydrated carrot cubes is clearly expressed in the shape of sorption isotherms as shown in Fig 4.36. All isotherms have a shape characteristic of hygroscopic materials, with low equilibrium moisture contents at low or moderate a_w and sharply increased moistures at higher a_w. The

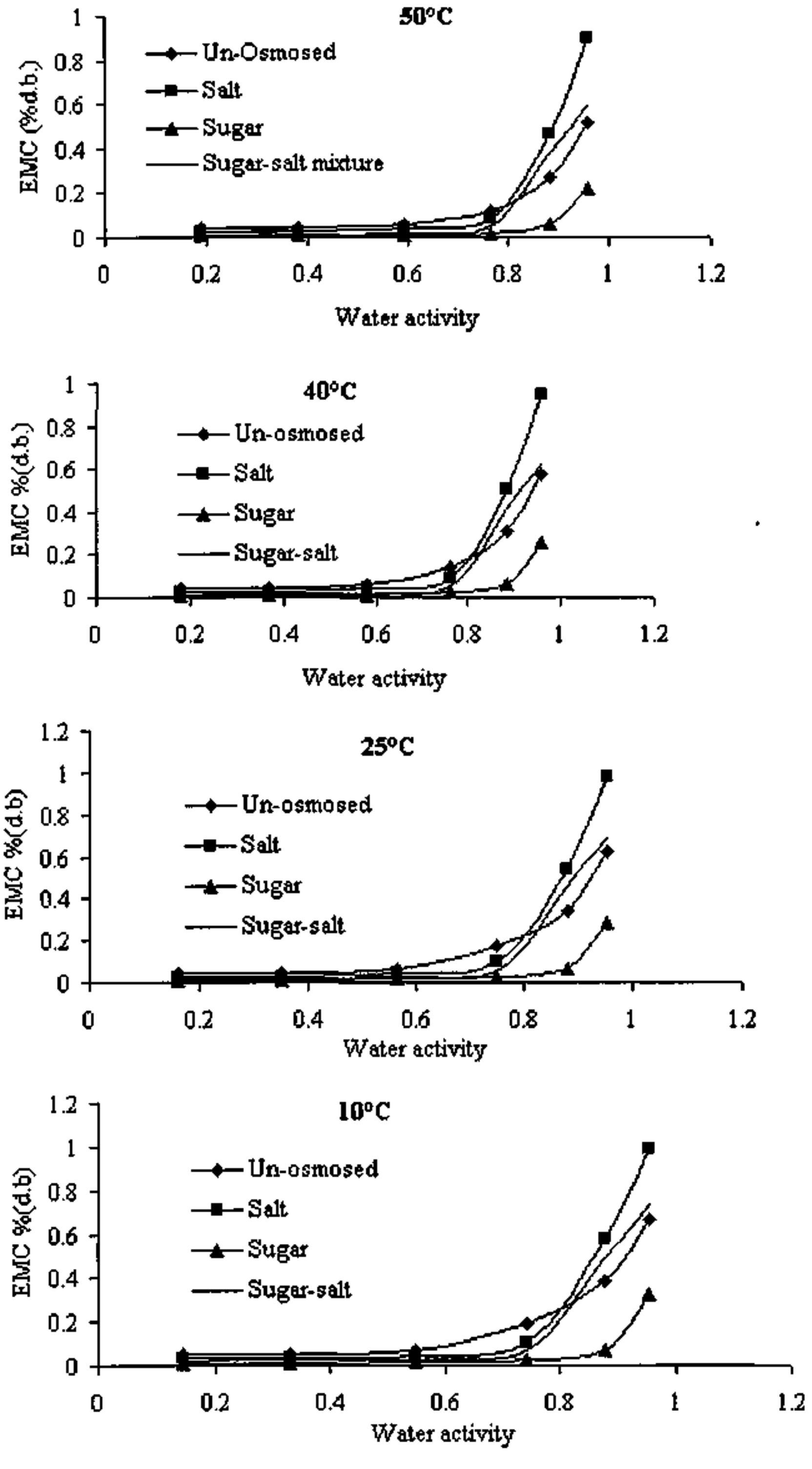


Fig 4.36 Effect of osmotic pretreatment on sorption isotherms of dehydrated carrot cubes at different temperatures

EMC of samples pretreated with salt is more as compared to un-osmosed and samples pretreated with sugar and sugar-salt mixture. This behaviour of water sorption isotherms may be due to the changes in soluble solids composition and the prevailing presence of osmotic solutes in carrot cubes. Lazarides *et al* (1995a) and Singh (2001) reported that the osmotic pretreatment of fruits in sucrose solution resulted in decrease of EMC, and thus made the product less hygroscopic. In case of carrot cubes osmotically pre-treated in salt solution, there was an increase of EMC as compared to un-osmosed samples. The corresponding increase is negligible in case of samples osmotically pretreated with mixture of sugar-salt solution. This behaviour may be because of the presence of salt and other soluble cell constituents that led to an increase of equilibrium water content, which made the dry product more hygroscopic. The intersection (inversion) of isotherms for different osmotic pretreatments at high water activity ($a_w > 0.8$) may be due to differences in composition of food and the availability of sugars (Rahman 1995). The observed difference in behaviour of sorption isotherms may be due to increased density, lowered shrinkage and porosity of osmo-convectively dehydrated product as compared to product simply dried in hot air, which was consistent with the results of Sitkiewicz *et al* (1996), Lerici *et al* (1985), Lazarides *et al* (1995b), Menkov (2000) and Uzman and Sehbaz (2000) on sorption isotherms of osmo-convectively dehydrated products.

The experimental sorption isotherms for four types of dehydrated carrot cubes for temperatures of 10, 25, 40 and 50°C and a_w from 0.11 to 0.82 is shown in Fig 4.36 and 4.37. Equilibrium moisture content increases with increase in a_w for all temperatures and decreased with increasing temperature. The EMC shift by temperature was mainly due to the change in water binding, dissociation of water or increase in solubility of solute in water, which is in close agreement with results quoted by Rahman (1995). The effect of temperature on moisture sorption isotherms had also been reported in many studies (Sanni

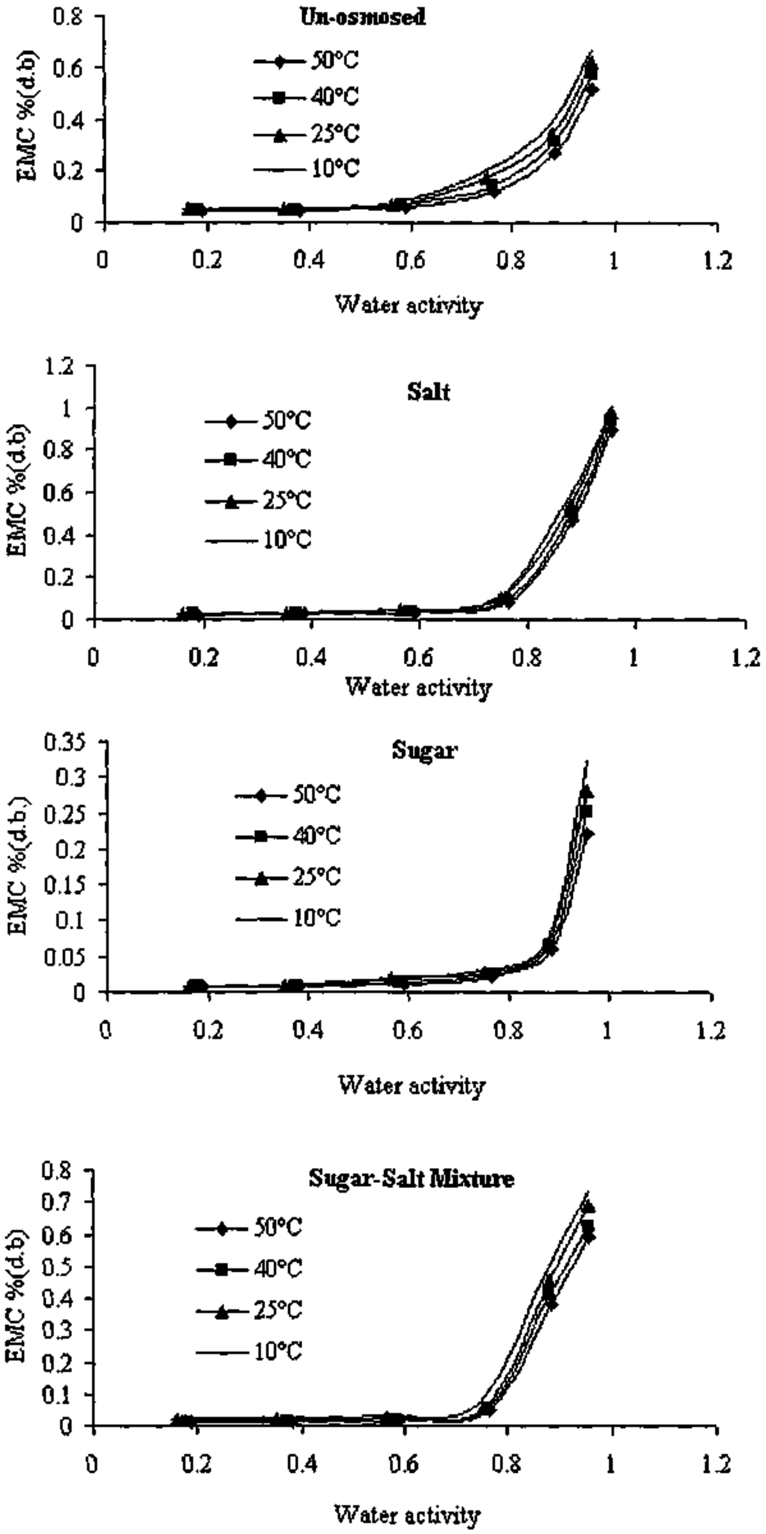


Fig 4.37 Effect of temperature on sorption isotherms of carrot cubes osmotically pretreated with different solutions before convective dehydration

et al 1999; Hossain and Bala 2000; Prothon and Ahrne 2004).

Sorption isotherm data of osmo-convectively dehydrated carrot cubes were fitted to the chung-Pfost, Modified Henderson, modified Halsey and Modified exponentialmodels. These three parameter models considered the effect of both a_w and temperature on equilibrium moisture content. These models are as under:

Chung Pfost $M = -\frac{1}{B}\ln\left[\ln a_w \frac{-(T+C)}{A}\right]$

Modified Henderson: $M = \left[\frac{\ln(1-a_w)}{-A(T+C)}\right]^{1/C}$

Modified Halsey: $M = \left[\frac{\exp(A-BT)}{-\ln a_w}\right]^{1/C}$

Modified exponential: $M = (A-BT)\exp(Ca_w)$

Where M = equilibrium moisture content, decimal (dry basis),

a_w= equilibrium relative humidity or water activity, decimal,

T= temperature (K), and

A, B, C = equilibrium constants.

Each of three constants of models has a specific physical meaning. The parameter 'A' represents the overall sorption capacity of the material at low a_w. The parameter 'B' represents the effect of temperature and parameter 'C' represents the effect of a_w.

The modified exponential model is observed to be a simpler form of the modified Henderson and modified Halsey models and can describe the experimental curve for practical applications like drying. The lowest R^2 and high χ^2 and RMSE value for Chung-Pfost, modified Henderson, and modified Halsey model leads to its rejection. The R^2 is highest and χ^2, RMSE are least for modified exponential model, which indicates that it is the best model for predicting the sorption characteristics of the convectively dehydrated un-osmosed and pre-osmosed carrot cubes in the indicated water activity region. Therefore, only the results of modified exponential model have been presented in this study. Further, sorption isotherms constants and regression parameters (Table 4.19) for convectively dehydrated un-osmosed and pre-osmosed carrot cubes with salt and mixture of sugar-salt solution gave a satisfactory fit to the modified exponential model, while those for osmo-convective dehydration in sugar gave a moderate fit. These results confirm the results those reported by Lomauro *et al* (1985). The adequacy of fit of modified exponential model for the sorption isotherm data is clear from the graphs (Fig 4.38) between experimental and predicted curves for sorption study at 50°C temperature.

Table 4.19 Estimated parameters for modified exponential EMC model for convectively dehydrated un-osmosed and pre-osmosed carrot cubes.

Coefficients	**Un-osmosed**	**Salt**	**Sugar**	**Sugar-Salt mixture**
A	0.003819	0.00036	0.000018	0.00074
B	8.702×10^{-6}	6.326×10^{-7}	4.475×10^{-8}	1.607×10^{-6}
C	6.48964	9.023132	11.3685	8.26254
Comparison Criteria				
R^2	0.9869	0.9897	0.9571	0.9718
χ^2	0.00102	0.00146	0.00044	0.00209
RMSE	0.0300	0.03585	0.01967	0.04284
E (%)	36.54	47.72	58.14	57.90

This table indicates that water activity of the environment 'C' has maximum effect on EMC of product as compared to overall sorption capacity 'A' and temperature of environment 'B' during storage of osmo-convectively dehydrated carrot cubes, osmotically pretreated with salt, sugar and mixture of sugar-salt.

4.4.4 Effect of osmotic dehydration on rehydration and shrinkage of product

The present work was undertaken to investigate the effect of soaking time in water (at room temperature) on shrinkage of rehydrated product along with the kinetics of water infusion and solute loss during the rehydration of osmotically pre-treated carrot cubes.

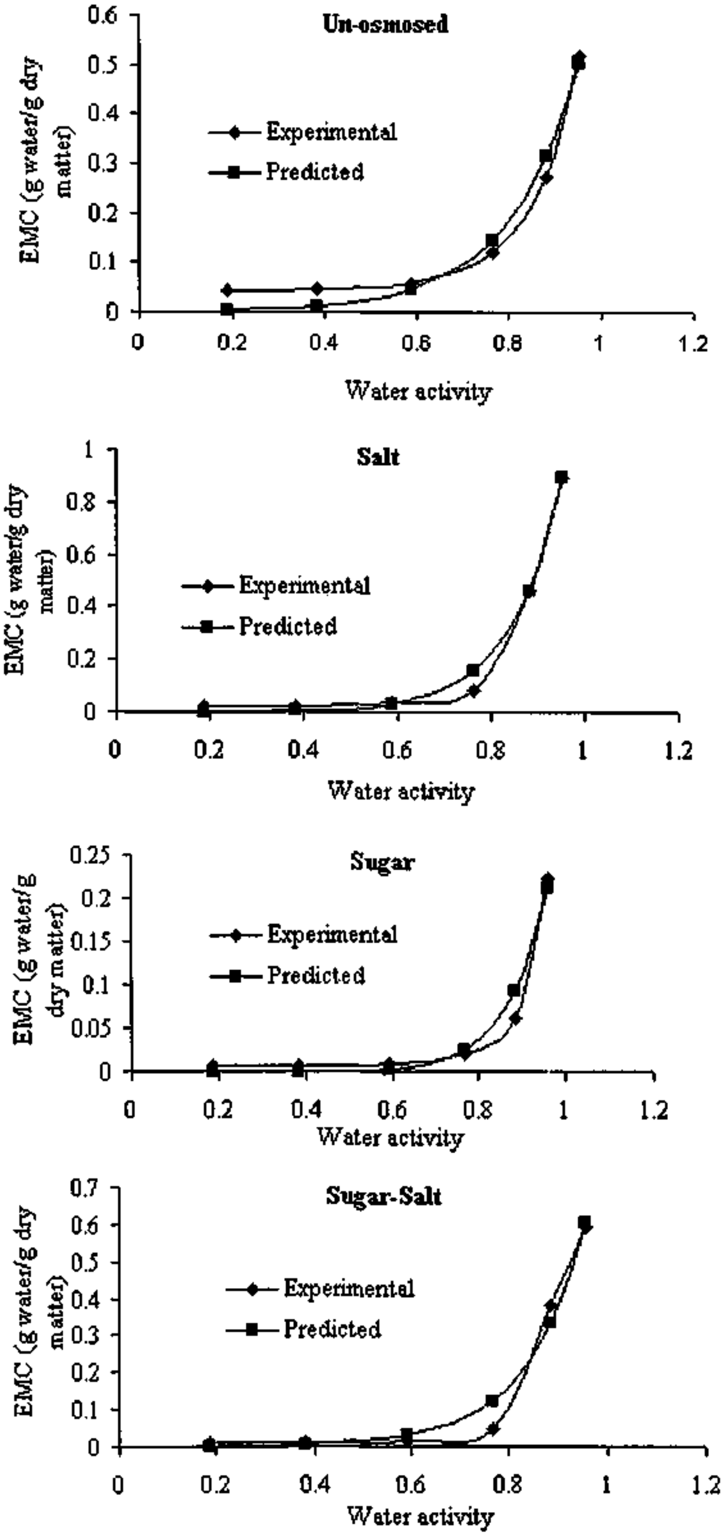


Fig 4.38 Comparison of experimental data with values predicted by modified exponential model at 50°C

Rehydration behaviour was studied in grapes (Gabas *et al* 1999), Nameko and shitake (Kalbarczyk and Widenska 2000), carrots (Ramos *et al* 1992; Reyes *et al* 2002), vegetables like potato, carrots, celery and parsley roots (Bobic *et al* 2002), osmotically dehydrated pineapple (Rastogi *et al* 2000b), and brocolli florets (Sanjuan *et al* 2001) by using different process parameters, like immersion time and water temperature. These researchers reported that, the temperature increases the rehydration rate due to decreased viscosity of the immersion medium and effect of temperature on the structure of food material, but usually not play any significant effect on rehydration capacity. In present investigation, the temperature of hydrating medium was kept constant (30°C) and moisture gain along with the loss of solids was measured with time during rehydration. It was assumed that temperature of water would be approximately 30°C during summer season. Before weighing, the superficial water was removed from the surface by adsorbent paper. The shrinkage of the samples was measured by water displacement method during rehydration.

It is clear from Fig 4.39 that the rehydration ratio is significantly affected by osmotic pretreatment. The rehydration ratio is highest for un-osmosed samples and lowest for the osmotically pre-treated samples with Sugar-salt mixture. This behaviour of low rehydration ratio of osmotically dehydrated carrot cubes may be explained on the basis that, the osmotically pretreated sample contain 8-12 % solute which got infused during osmotic dehydration, and leached in to water during rehydration process without contributing to the process. So it was only the dried matter of carrot cubes (and not the infused solute), which is responsible for absorption of water during rehydration. However, Bhuvaneswari *et al* (1999) reported that rehydration ratio of osmotically treated peas was higher than those of untreated samples.

Water uptake during rehydration of osmotically pretreated samples also depends

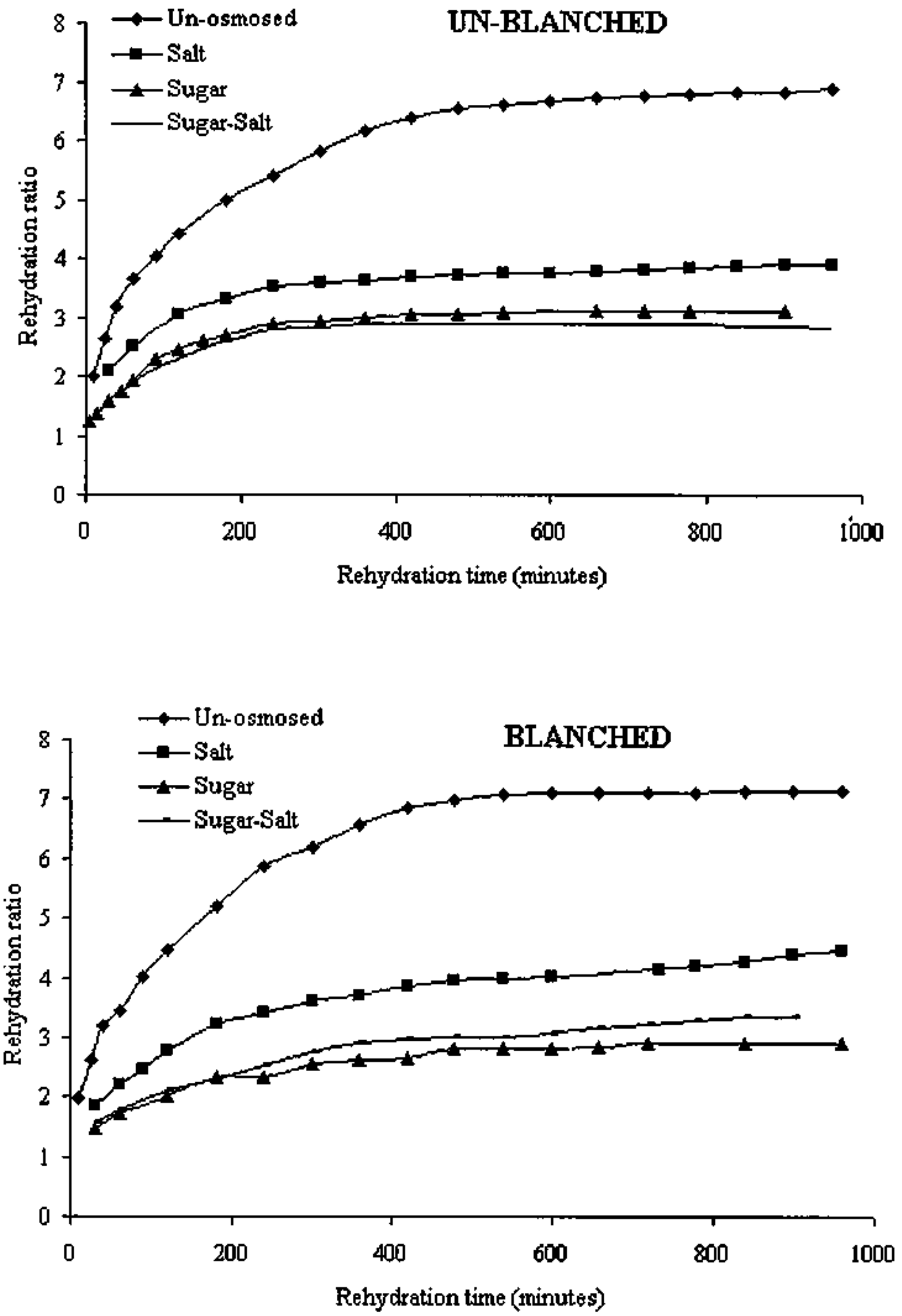


Fig 4.39 Effect of osmotic pretreatment on rehydration ratio of blanched and un-blanched carrot cubes

on the kind of osmotic substance (Fig 4.40). The figure indicates that during the rehydration, the carrot cubes, osmotically pretreated with sugar-salt samples give a lower water uptake as compared to samples treated with sucrose solution followed by samples treated with salt and un-osmosed ones. This may be due to the variation of porosity of carrot cubes due to different osmotic pretreatments applied before convective dehydration (Taiwo *et al* 2002b). The variation in the water gain and solute loss of blanched and un-blanched osmo- convectively dehydrated carrot cubes is shown in Fig 4.40. All the samples exhibited an initial high rate of moisture sorption and solute loss followed by slower water absorption and solute loss in the later stages of rehydration process. This is due to the fact that the capillary imbibition is important at early stages, which leads to an almost instantaneous uptake of water. Similar results were reported by Sopade and Obekpa 1990. As indicated in Fig 4.40, with prolonged soaking, the moisture content increases to maximum value and remains almost constant by further increase in soaking time. The shrinkage kinetics of blanched and unbleached osmotically pretreated carrot cubes is as shown in Fig 4.41. It is clear that after rehydration of 350 minutes, there is no shrinkage of rehydrated carrot cubes, which were osmotically pretreated with sugar-salt mixture. Maximum shrinkage was observed for samples, which were osmotically pretreated with salt and followed by un-osmosed (blanched) samples, which is consistent with results of Torringa *et al* (2001). This is because; drying induces many non-reversible physical and chemical changes in the food material, which could not be restored by simply adding water . Highest shrinkage for salt treated carrot cubes may be due to the structural changes occurred due to some chemical reaction. Neumann (1972) observed that polyhydroxyl compounds like glucose, sucrose improved the rehydration characteristics of fruit and vegetables.

Most of studies to assess the water intake rate by food materials were based on

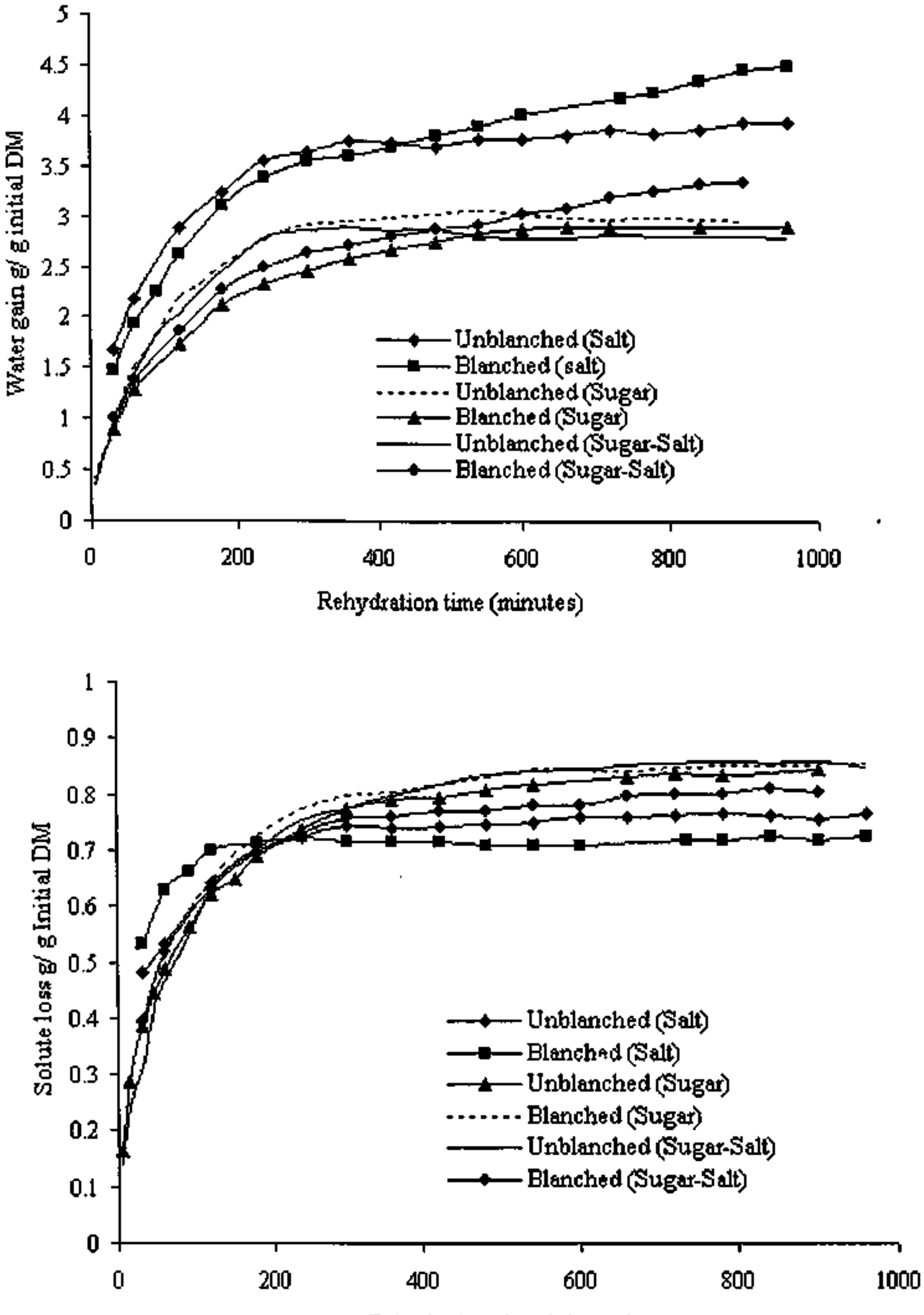
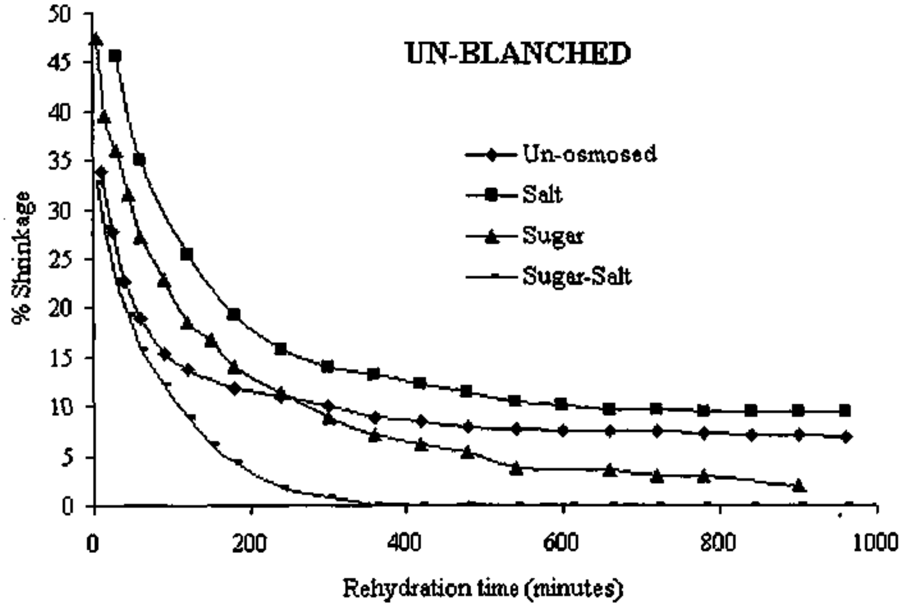


Fig 4.40 Effect of blanching and osmotic pretreatment on solute loss and water gain kinetics during rehydration of carrot cubes at 30°C



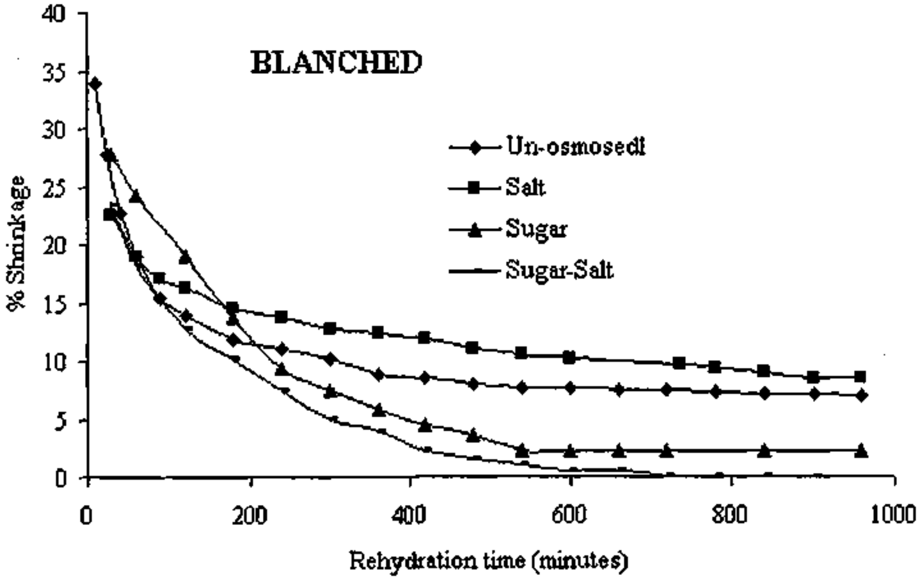


Fig 4.41 Effect of osmotic pretreatment on Percentage shrinkage of blanched and un-blanched rehydrated carrot cubes at 30°C

Fick's laws of diffusion using appropriate exponential equations (Hsu 1983). To simplify the mode of water absorption and solute outflow, non-exponential empirical equation was proposed by Peleg's (1988), which has been successfully applied to milk powder, rice, dasheen leaves, cherry tomato and various legumes (Sopade and Obekpa 1990; Sopade and Kaimur 1999; Maharaj and Sankat 2000; Azoubel and Murr 2004). The Peleg's equation is as below:

$$M_t = M_o + \frac{t}{K_1 + K_2 t}$$

At t→0 $$\frac{dM}{dt} = \frac{1}{K_1}$$

And as t→∝ $$M_e = M_o + \frac{1}{K_2}$$

$$\frac{t}{(M_t + M_o)} = K_1 + K_2 * t$$

Where

M_t = Moisture content (%d.b.) at time t

M_o = Initial moisture content (%db)

t = Rehydration time (minutes)

K_1 = Constant (minute per % m.c. db)

K_2 = Constant (reciprocal of % mc db), and

M_e = Equilibrium moisture content (%db).

A plot of $t/(M_t-M_e)$ against time, t, gives a straight line with K_1 as the ordinate-intercept and K_2, the gradient of the line (Fig 4.42). Such plot allows the characteristics of the constants to be studied. Peleg's equation adequately (with $R^2>0.98$) described the water absorption and solute loss behaviour of previously blanched and un-blanched osmotically pre-treated carrot cubes at hydration temperature of 30°C and predicted the

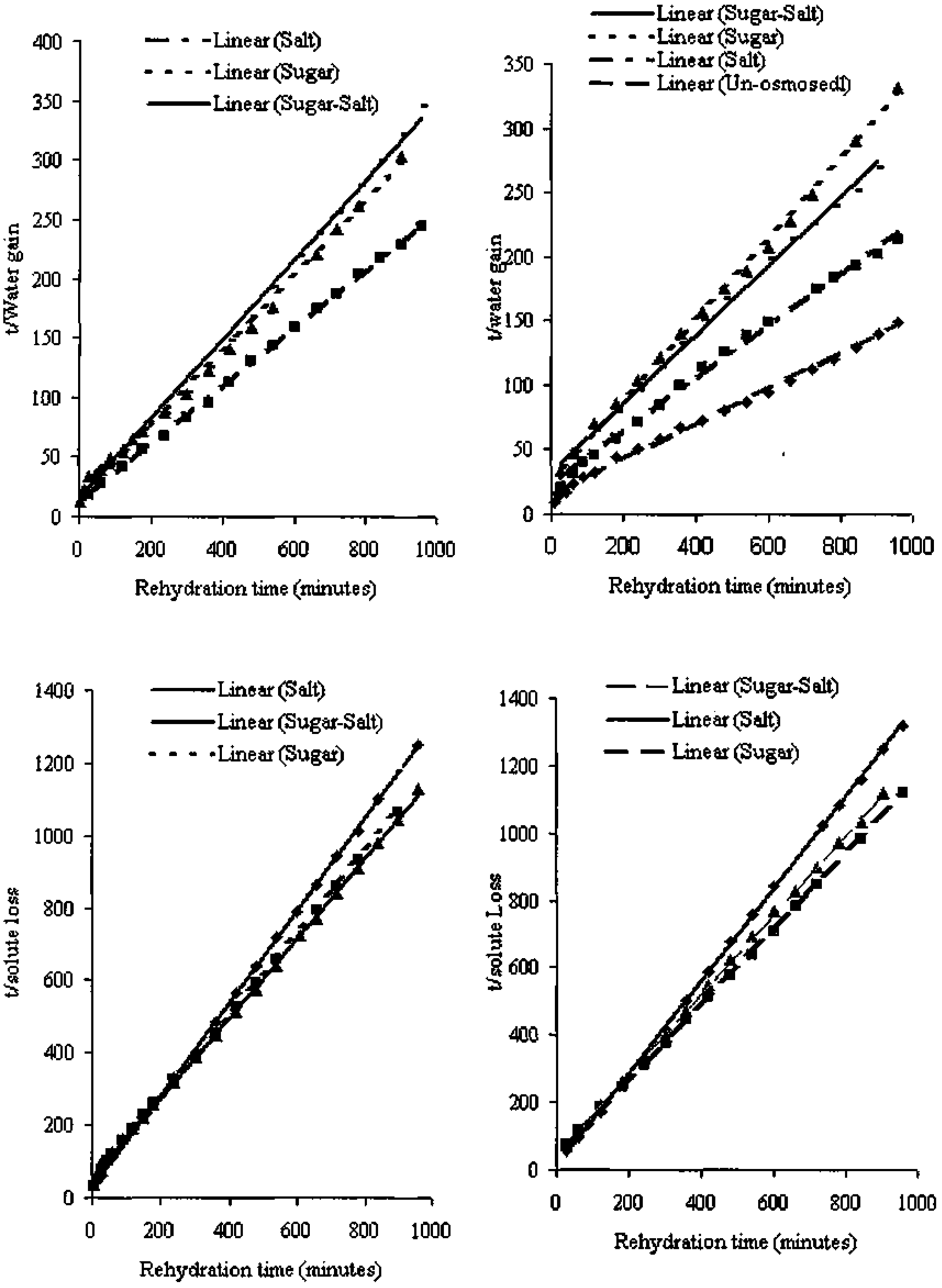


Fig 4.42 Plots for verification of Peleg's model for water gain and solute loss during rehydration of carrot cubes at 30°C

equilibrium moisture content, initial hydration and solute loss rates as shown in Table 4.20.

Table 4.20 Peleg's constants for water gain and solute loss during rehydration of carrot cubes.

Treatment	Osmotic treatment	Water Gain			Solid Loss		
		K_1	K_2	R^2	K_1	K_2	R^2
un-blanched	Salt	11.035	0.2441	0.9994	27.973	1.2749	0.9998
	Sugar	16.655	0.3085	0.9963	48.965	1.1305	0.9993
	Mixture	14.839	0.3347	0.9966	53.395	1.1013	0.9994
Blanched	Un-osmosed	14.066	0.1387	0.9964	N	N	N
	Salt	21.799	0.2064	0.996	10.657	1.3725	0.9998
	Sugar	27.412	0.3098	0.9985	44.762	1.1146	0.9998
	Mixture	31.096	0.2715	0.9961	44.541	1.1899	0.9958

The Peleg's constant K_2 describes a characteristic sorption parameter, which is inversely related to the absorption ability of foods (Sopade and Obekpa 1990). The reciprocal of constant K_2 could be used to predict the equilibrium moisture content, which does not vary with temperature (Peleg 1988; Sopade and Obekpa 1990; Sopade and Kaimur 1999; Maharaj and Sankat 2000).

Peleg's constant, K_2 (for water gain) is found to be lower for blanched, and un-osmosed carrot cubes (Table 4.20). For un-blanched pre-osmosed carrot cubes, the lowest value of K_2 is for salt treatment followed by pretreatment with sugar and sugar-salt mixture. The low K_2 values observed for samples osmotically pretreated with salt indicate the increased absorption ability and high equilibrium moisture content (water gain) of samples. This is due to the low solute concentration in the carrot cubes osmotically pretreated with salt as compared to samples osmotically pretreated with sugar and sugar-salt mixture. This is in accordance with the hydration curves shown in Fig 4.40. The curves show that the water uptake for osmotically pretreated carrot cubes with salt is in excess than that of samples osmotically pre-treated with sugar and sugar-salt mixture. Similar pattern is found for solute loss during rehydration process as indicated in Fig 4.40 and Table 4.20.

Sopade and Obekpa (1990) and Maharaj & Sankat (2000) found that Peleg's constant K_1 is inversely related to temperature and its reciprocal (1/K1) (% mc db/minute) is equivalent to initial rate of hydration. In the present study, a change in Peleg's constant K_1 is observed even at constant water temperature during rehydration. The change in K_1 may be due to the different osmotic pretreatments used before convective dehydration. The values of Peleg's constant K_1 for water gain are higher for blanched samples as compared to un-blanched ones. This indicates that the initial rate of hydration was more in un-blanched samples as compared to blanched ones. This may be due to change in structure of fruit by blanching. Peleg's constant K_1 for water gain and solute loss decreases significantly with osmotic pretreatment. Its value is highest for the samples osmotically pretreated with sugar-salt mixture followed by pretreatment with sugar, salt and un-osmosed samples. Initial hydration rate is more pronounced for salt treated un-blanched carrot cubes, where K_1 values are the lowest (Table 4.20). This unexpected increase in hydration rate for un-blanched (treated with salt) is attributed to the changes in properties of the carrot cubes due to osmotic pretreatment.

4.5 Processing of left over material of carrot cubes

The left over material of carrot cubes was used for the preparation of carrot juice and carrot gazrella.

4.5.1 Processing and evaluation of carrot juice

Vegetable and, especially, fruit juices can be used as a source of additional nutrients, such as natural sugars, organic acids and minerals (Bao and Chang 1994a). Carrot based ready-to serve drinks were prepared by blending carrot juice, sugar (to make T.S.S. =12°B), citric acid (0.25%). and sodium benzoate (200 ppm). The juice was heated at 80°C for 4 minutes for exhausting followed by addition of 2mg of Sodium Benzoate/liter (200 ppm) of juice. The hot juice was filled in sterilized glass bottles of 200 ml capacity and the bottles were sealed immediately. The pasteurization of juice bottles was done in boiling water for 30 minutes. However, separation of layer between solids and water at the time of pasteurization might be due to un-blanching of carrot pieces before extraction of juice. The recovery of carrot juice varied from 60.0 to 63.87% and that of pulp (pomace) between 35-37.2%. The carrot juice was processed and stored in 200 ml bottles (Fig 4.43). The juice remained shelf stable even after storage of 10 months at ambient temperature. However, lowering of TSS from 12°B to 11.5°B, acidity from 0.18 to 0.16 % and sensory score 8.5 to 6.5 was observed during the storage period.

Fig. 4.43 Fresh, processed and stored carrot juice

4.5.2 Processing of carrot pomace and evaluation of carrot gazrella

After juice extraction, 30-50% of carrot remained as pulp (pomace), which was by-product of carrot juice (Bao and Chang 1994a). Carrot pomace, being high in carotenoids and dietary fibre, also contain proteins, lipids, sugar, vitamins and minerals (Bao and Chang 1994b). The carrot pomace was osmotically pre-treated with sugar solution of 75°B as suggested by Singh (2001). A contradiction to the findings of Singh (2001) regarding loss of moisture of carrot fines during osmotic dehydration in sugar solution was observed. It was observed that osmotic pretreatment with 75°B sugar solution resulted in an increase of moisture of product instead of moisture reduction. This may be due to very small size of carrot shreds. So, as a consequence of this osmotic pretreatment, there was wastage of valuable sugar syrup and prolongation of complementary convective drying. Consequently, to eradicate this drawback, the carrot pomace was directly mixed with dry sugar, in the ratio (approximately 1:0.35), which was added at the time of preparation of gazrella. The addition of dry sugar however did not remove any water from carrot fines, but it increased the % dry matter, thus indirectly decreased the moisture of the carrot fines. Sodium metabisulphite (0.3%) was also added to carrot pomace and mixed properly as preservative. The mixture of carrot pomace and sugar took about 18 hours to dry up to 4-5% moisture content (w.b.) in a hot air cabinet dryer with the direction of airflow over the product at a drying air temperature of 60°C. The drying behaviour of osmotically pretreated carrot pomace is indicated in Fig 4.44. The sudden rise in drying rate may be due to the exposure of fresh surface to hot air because of turning of material at regular intervals (Fig 4.45). The dried product was packed in Aluminum-laminated packages and stored at ambient temperature. During storage, the protection of dehydrated pomace from rodents is utmost important.

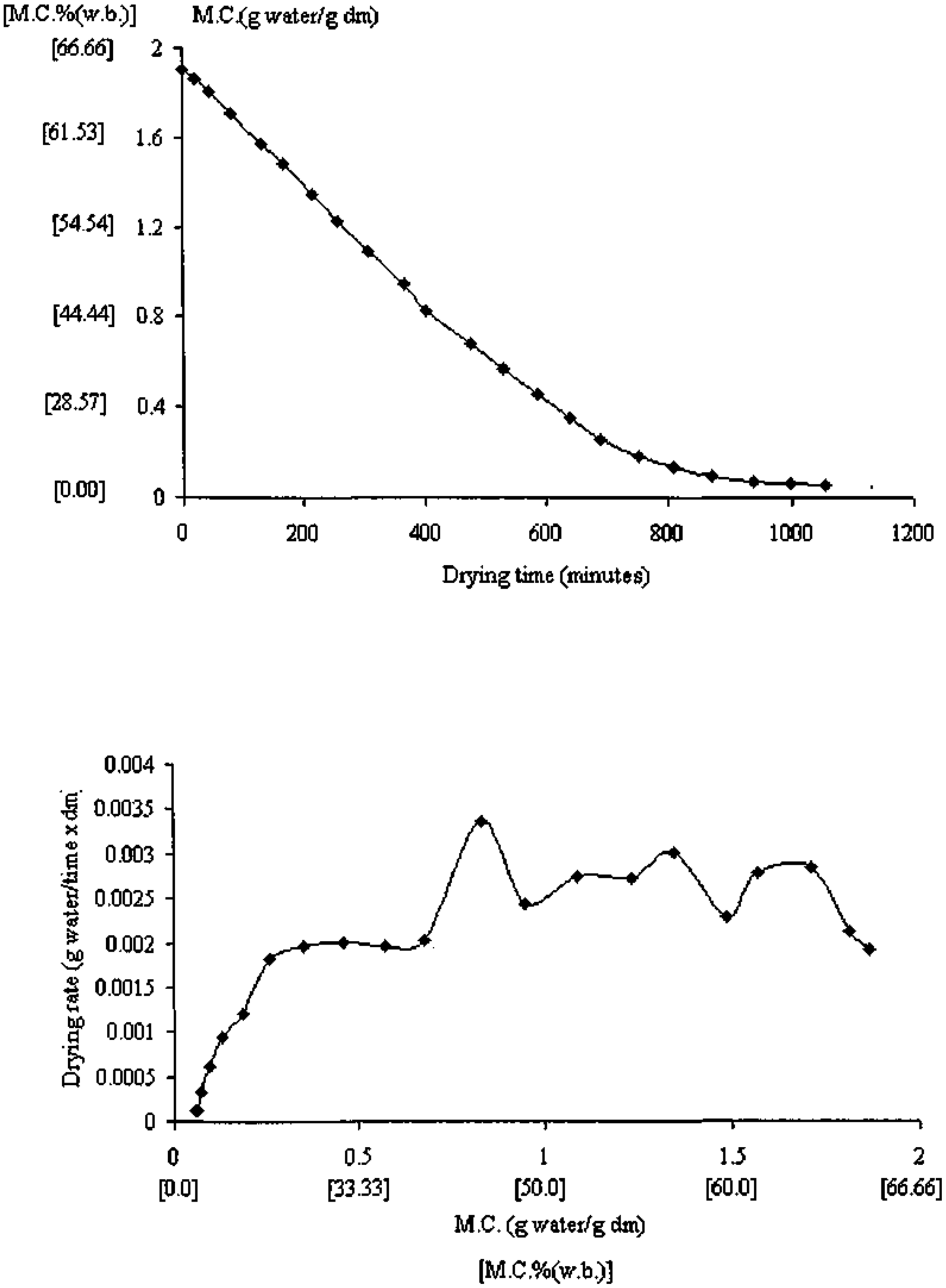


Fig 4.44 Drying behaviour of osmotically pretreated carrot pomace at 60°C with air flow over the product

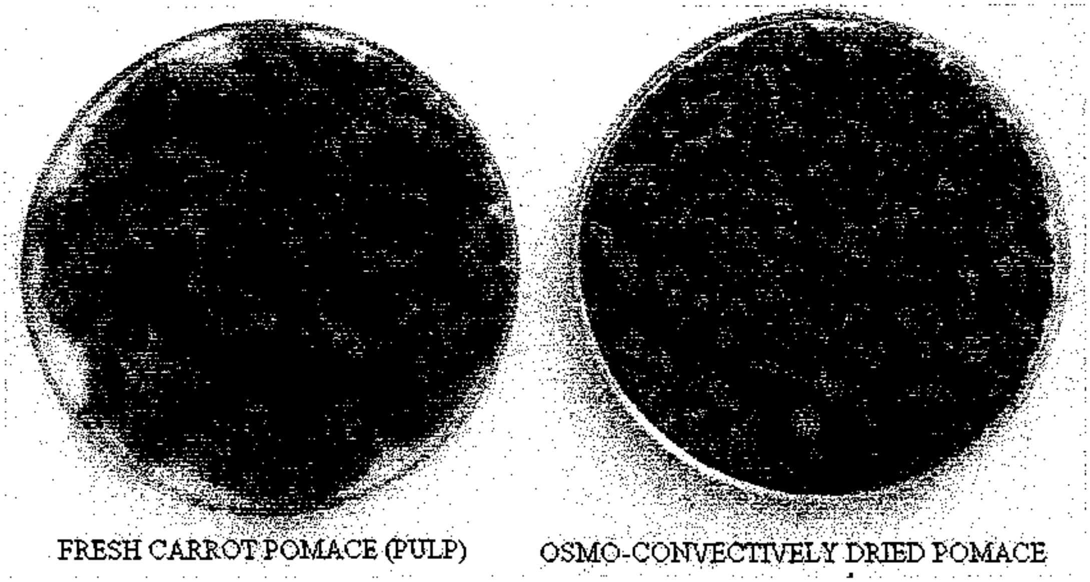


Fig. 4.45 Fresh and osmo-convectively dehydrated carrot pomace.

The gazrella was prepared at regular interval of 3 months and was evaluated for sensory attributes by panel of experts. However, loss of flavour was observed in the finished product, which might be due to the absence of juice in the carrot pomace. The overall acceptability varied between moderate to excellent.

4.6 Storage behaviour of dehydrated carrot cubes

The present study was undertaken to observe the effect of various polymeric films on the storage of dehydrated carrot cubes. Un-osmosed and pre-osmosed carrot cubes in solutions of different osmotic agents viz. salt, sugar and sugar-salt combinations carrot cubes were convectively dehydrated at 65°C and packaged in 20M (i.e.80 gauge) high density polyethylene (HDPE), 100 gauge low density polyethylene (LDPE) and Aluminum-Laminated packages. To negligee the effect of increased relative humidity, CaO_2 lumps were placed in the packages (Loesecke 2001). The samples were stored at room temperature as well as refrigeration temperature of 4 to 10°C (approximately). Vacuum packaging of the dehydrated carrot cubes was also performed, but the sharp edges of the dehydrated carrot cubes resulted in damage of the low gauge HDPE and LDPE packaging material. The variation in physiological weight loss, rehydration ratio, and firmness and colour of rehydrated product were recorded after an interval of one month starting from mid February 2004, up to the arrival of next fresh crop in the local market i.e. up to November 2004. The average ambient temperature and relative humidity (R.H.) data during the storage study is as given in Appendix-P. The rehydration of carrot cubes was done by using water at ambient temperature.

4.6.1 Effect of storage temperature and packaging material on physiological change in weight

The changes in PLW or PGW of dehydrated carrot cubes are shown in Fig 4.46, which indicates that, PLW increased up to the 3rd - 4th month of storage i.e. up to the month of May-June. Thereafter, the PLW is less due to high environment relative humidity during monsoon season. Further, the rates of PLW were higher for samples stored at ambient temperature as compared to low temperature storage. The PLW was least for the samples packaged in Aluminum-Laminated packages and highest for the 80 gauge HDPE packages. However in few cases, the physiological weight gain (instead of weight loss) was observed, which may be due to high relative humidity in the monsoon season and high permeability of low gauge packaging material. The PGW was only observed in the un-osmosed and pre-osmosed with salt samples stored at ambient temperature during the months of July-September. Such variations may be due to the highly hygroscopic nature of salt (Sereno *et al* 2001a) and highly porous structure of the un-osmosed samples. Similar to PLW, PGW is highest for 80 gauge HDPE followed by 100 gauge LDPE packages. These relative changes in values of PLW or PGW may be due to more permeability of 80 gauge HDPE packages as compared to 100 gauge LDPE (Sagar 2001). No absorption of moisture was observed in the samples, which were pre-osmosed with sugar and sugar-salt mixture during storage of seven months even in the monsoon season. This was because the osmotic pretreatment with sugar decreases the

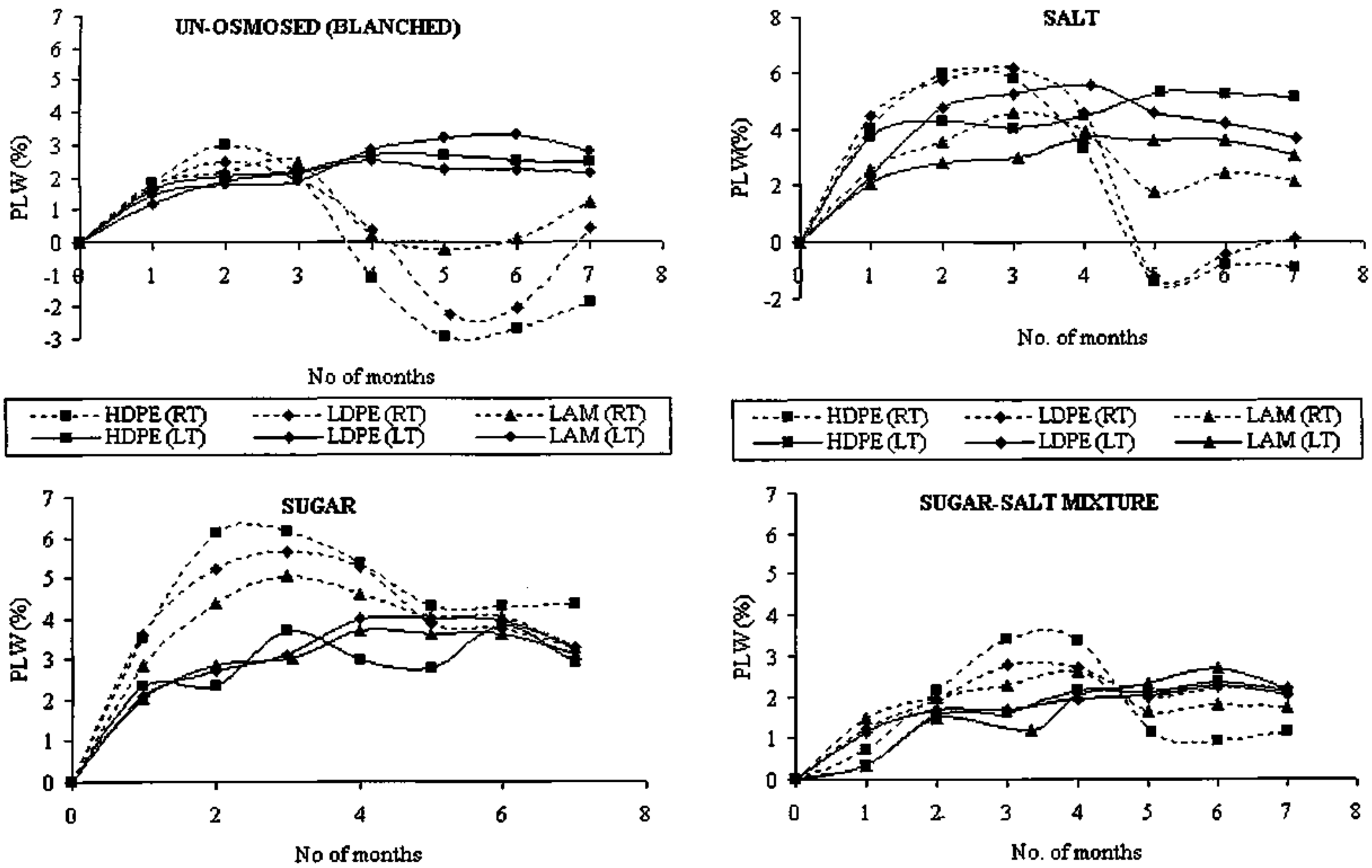


Fig 4.46 Effect of packaging material and duration on physiologial weight change of carrot cubes during storage at ambient and low temperature.

water adsorption capacity (Lazarides *et al* 1995b). No change in PGW was observed in samples stored at low temperature, which might be due to medium RH, and low temperature in refrigerated storage.

4.6.2 Effect of storage temperature and packaging material on rehydration ratio of carrot cubes

In most of cases, rehydration ratio decreased with time for all types of packaging materials and osmotic pretreatments. This may be due to the oxidation and enzymatic action, which led to cross linking in dehydrated product, and results in decrease of rehydration ratio with the passage of time. The Fig 4.47 presents the behaviour of rehydration ratio change with storage. Maximum loss of rehydration ratio is observed for un-osmosed samples. Further the decrease in rehydration ratio is relatively less for the samples stored at low temperature as compared to room temperature storage. The rehydration ratio remains almost constant in the samples stored at low temperature. There is no significant effect of type of packaging material on rehydration ratio of the product.

4.6.3 Effect of storage temperature and packaging material on colour of rehydrated carrot cubes

No significant change in colour was observed at room as well as low temperature storage for the first three months. However after fourth month, a slight discolouration was observed for the samples stored at room temperatures, especially for the un-osmosed and samples pre-treated with salt (Pereira *et al* 2004). This may be due to severeness of temperature (~ 45°C) in the months of July-August. The minimum change in colour was observed in both blanched and un-blanched samples pre-osmosed with sugar and sugar-salt mixture. The effects of storage temperature, storage period and packaging material on change in colour in terms of 'L', 'a' and 'b' values of rehydrated carrot cubes are presented below.

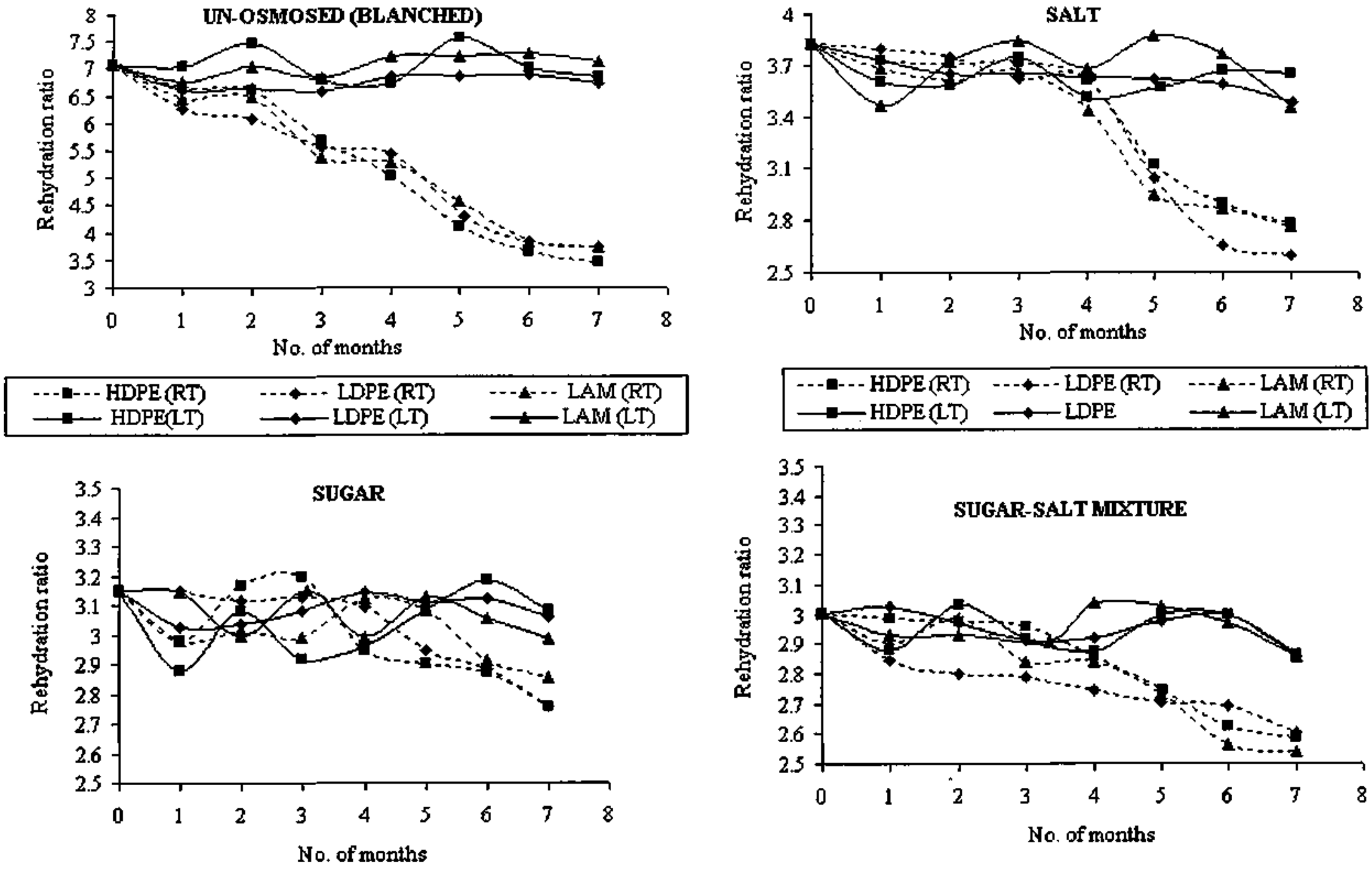


Fig 4.47 Effect of osmotic pretreatment, packaging material and storage duration on rehydration ratio of carrot cubes during storage at ambient and low temperature.

(a) Effect of storage temperature and packaging material on 'L' value of rehydrated carrot cubes

The 'L' value (lightness or darkness) is an important parameter for the overall acceptability of the product. The 'L' value increased with time at both room temperature and low temperature stored samples irrespective of type of packaging material. The trends of change of 'L' value with storage time are indicated in Fig 4.48. The changes in 'L' value were more in the samples stored at room temperature as compared to the low temperature storage. This may be due to high enzymatic activity at room temperature.

The variation in 'L' value is observed with respect to the type of packaging material for room temperature and low temperature storage. The increase in 'L' value is more in the samples packaged in HDPE packages and was least in the aluminum-laminated packages except samples pretreated with mixture of sugar-salt. In case of samples pretreated with solution of sugar-salt mixture, the 'L' value was more for samples packaged in LDPE, followed by HDPE and Aluminum-laminated packages at room temperature. This change may be attributed to the degree of transmission of the light through the packaging material. Non-availability of light and very slow enzymatic/ non-enzymatic activity at low temperature prevents the change in colour of the stored product.

(b) Effect of storage temperature and packaging material on 'a' value of rehydrated carrot cubes

The chromatic parameter 'a' (redness or greenness) is the most important parameter in case of carrots, because positive value of 'a' indicates degree of redness of the product. The trend of change of 'a' value with storage time is indicated in Fig 4.49. In most of the cases, the 'a' value decreased with time irrespective of type of packaging material. However, this change is negligible for low temperature storage as compared to room temperature storage. This may be due to non-availability of light and very slow enzymatic/ non-enzymatic activity at refrigerated temperature. The decrease of 'a' value

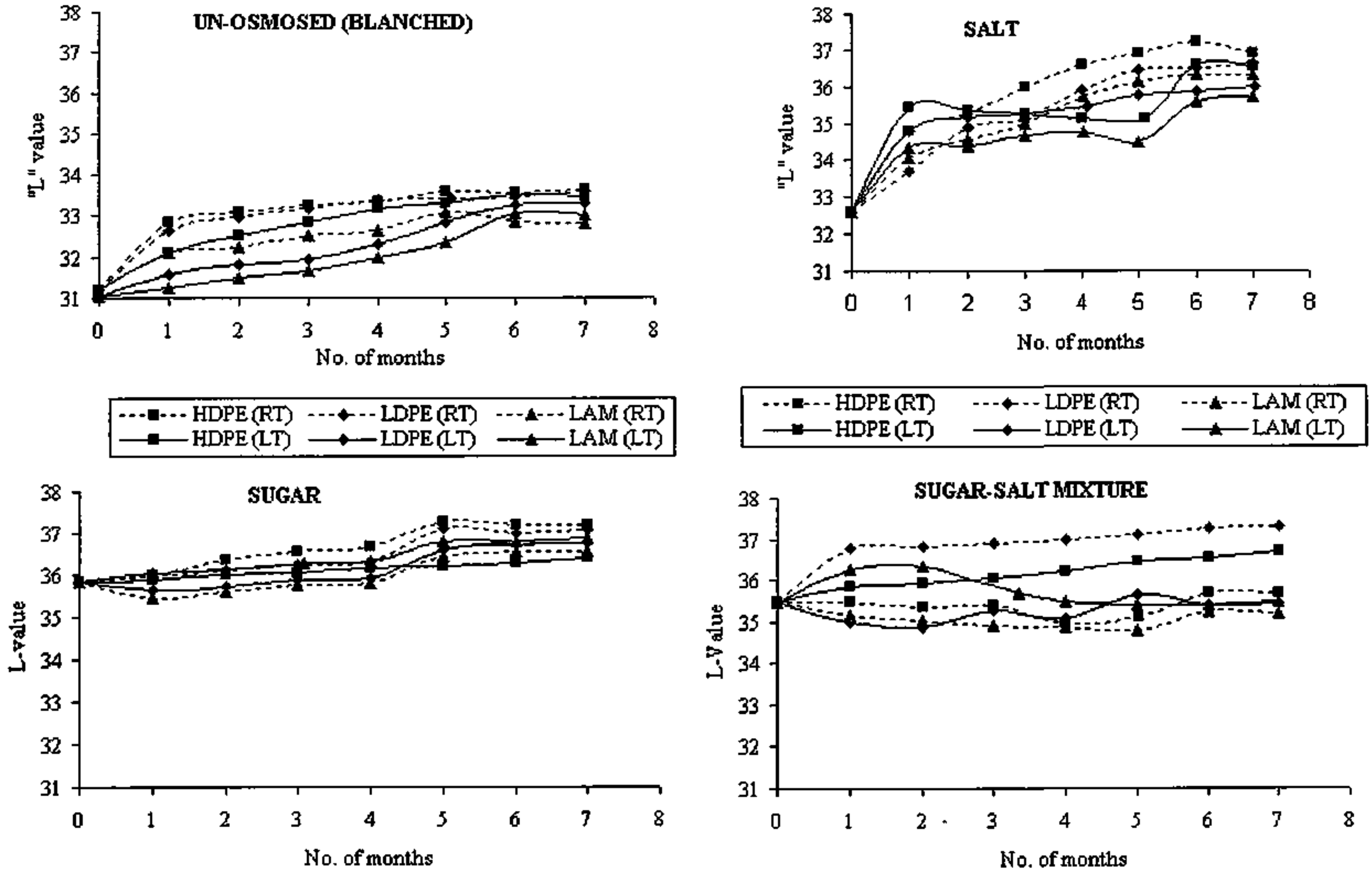


Fig 4.48 Effect of rehydrated osmotic pretreatment, packaging material and duration on 'L' value of rehydrated carrot cubes during storage at ambient and low temperature.

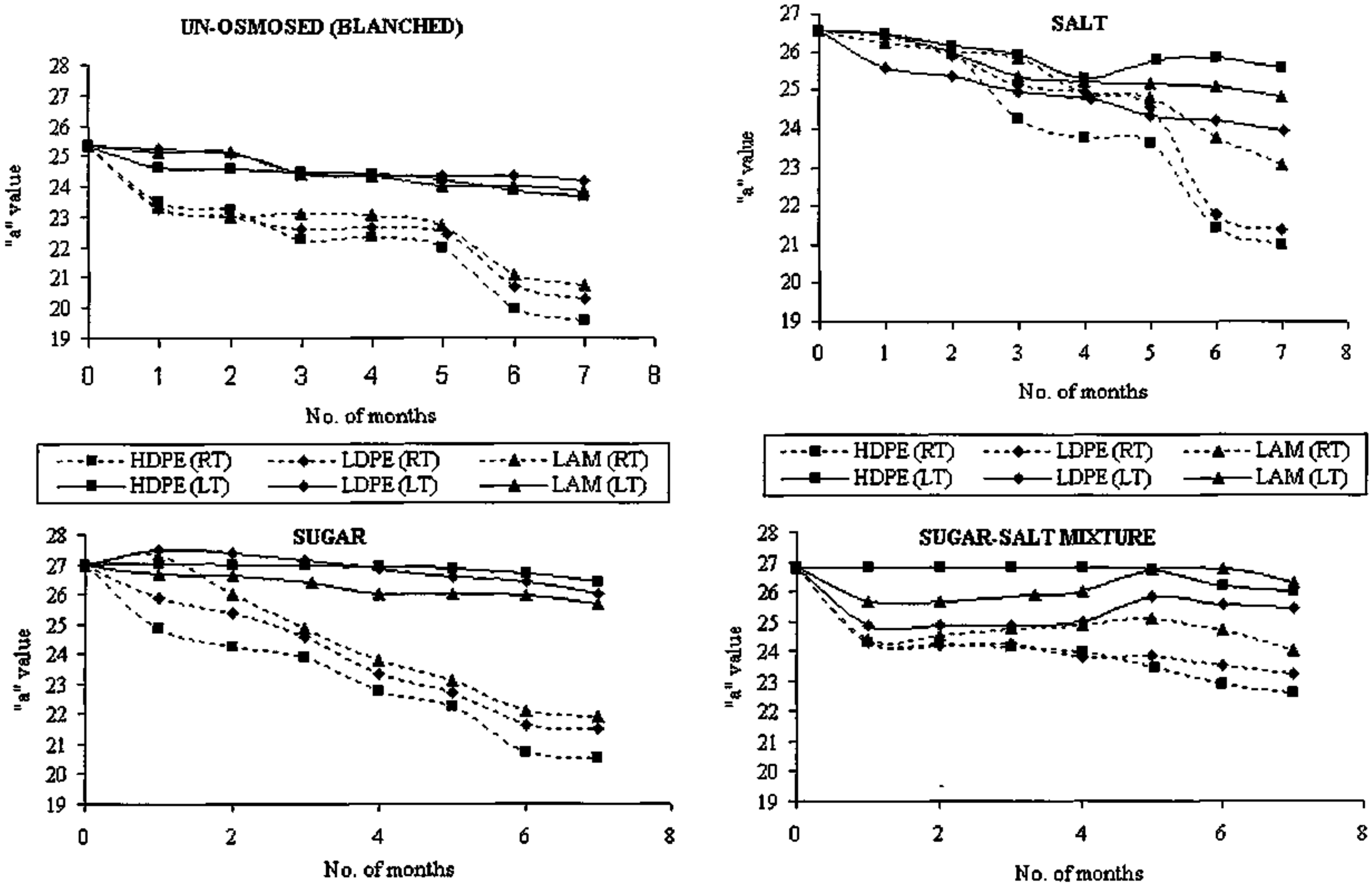


Fig 4.49 Effect of rehydrated osmotic pretreatment, packaging material and duration on 'a' value of rehydrated carrot cubes during storage at ambient and low temperature.

was found highest in the samples stored at room temperature after the 5th to 6th month of storage, which may be due to high atmospheric temperature during the months of May-June. In case of room temperature storage, maximum change (decrease) in 'a' value was observed in the samples packaged in HDPE packages, which may be due to low gauge of packaging material. The change was minimum in samples stored in Aluminum-laminated packages, which may be due to its non-transmittive nature to light. The change in 'a' value was least for the samples pretreated with mixture of sugar-salt followed by sugar. The maximum change in 'a' value occurred for the samples pre-osmosed with salt and un-osmosed samples.

(c) Effect of storage temperature and packaging material on 'b' value of rehydrated carrot cubes

The parameter 'b' (yellowness or blueness) indicated the changes in central core (xylem) of the carrots. In most of the cases, the 'b' value increased with time at both room temperature and low temperature storage irrespective of type of packaging material. The Fig 4.50 indicated that the changes in 'b' value were minimum for storage up to 4th month. Thereafter, it increased which might be due to increase in moisture content due to high RH in the surrounding, which enhanced the rate of chemical changes. The change in 'b' value was fast in the samples stored at room temperature as compared to the low temperature storage. This may be due to high rate of enzymatic activity at room temperature storage.

The values of 'b' were higher in the samples in HDPE packages and lower in LDPE packages stored at room temperature. This variation may be due to the different levels of transmission of light through the packages. Minimum changes in 'b' value occurred in case of samples pretreated with sugar-salt mixture stored at low temperature as well as at room temperature even after the storage period of seven months. Maximum change in 'b' value occurred in case of samples pre-osmosed with salt and un-osmosed ones. The variation in 'b' value may be explained on the basis of preservative action of

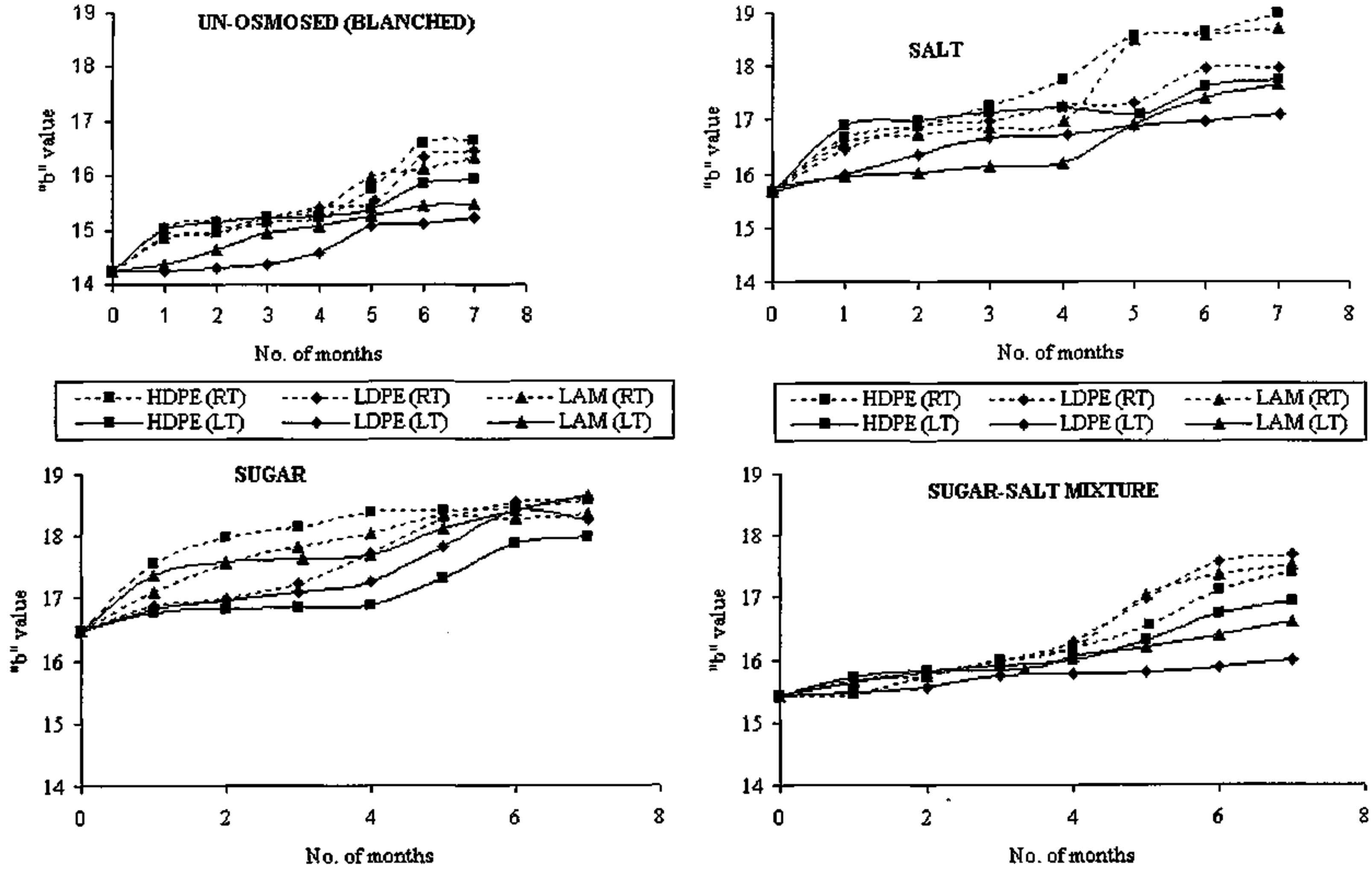


Fig 4.50 Effect of rehydrated osmotic pretreatment, packaging material and duration on 'b' value of rehydrated carrot cubes during storage at ambient and low temperature.

sugar and mixture of sugar-salt, which resulted in lowering of water activity of the samples.

4.6.4 Effect of storage temperature and packaging material on texture/ firmness of rehydrated carrot cubes

An increase in firmness of the rehydrated product was observed up to first/second month of storage; thereafter it decreased during storage irrespective of pre-treatment and packaging material. The decrease was most pronounced after 2nd to 3rd month of storage, which can be observed from the sudden decline in the slope of the curves in Fig 4.51. During storage, textural changes were generally caused by enzymatic action, change in moisture, or reactions in food polymers, which leads to cross linking and toughening of dehydrated product. Such products rehydrate to lesser extent and exhibit low firmness. The firmness of carrot cubes varied between 625 to 845, 1245 to 1785, and 2547 to 3247 g for rehydrated carrot cubes osmotically pretreated with salt, sugar and mixture of sugar-salt respectively, during the storage period of seven months irrespective of packaging material and storage temperature. The decrease in firmness was more pronounced in the samples stored at room temperature as compared to low temperature stored samples. It is also evident from the Fig 4.51 that the loss in firmness is more in the samples packed in the HDPE films and minimum for the samples packaged in LDPE packages. The firmness of samples packaged in Aluminum-Laminated films between the samples stored in HDPE and LDPE packages. Minimum firmness is observed for the un-osmosed samples, due to pre-blanching of the samples before convective drying. Lewicki and Lukaszuk (2000); Krokida *et al* (2002) and Salvatori *et al* (1998) also stated similar changes in texture of osmotically dehydrated apples.

It could be inferred from the above discussion that the fruits experienced the maximum PLW or PGW in case of HDPE (80 gauge) and LDPE (100 gauge) followed by aluminum-laminated (100 gauge) packages. At room temperature storage losses are higher

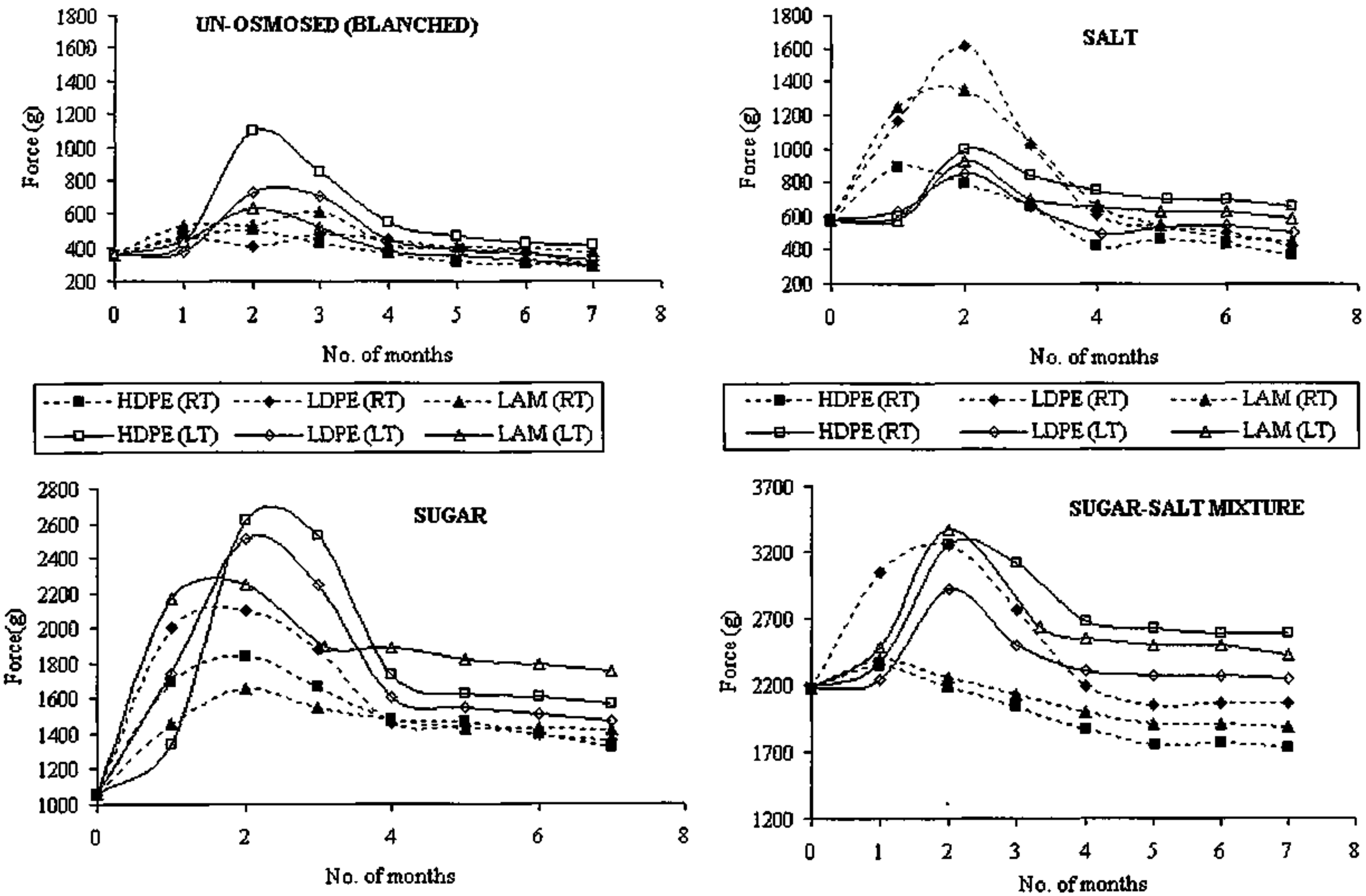


Fig 4.51 Effect of osmotic pretreatment, packaging material and storage duration on firmness of rehydrated carrot cubes during storage at ambient and low temperature.

when the temperature was high and RH was low. The minimum physiological losses were observed during the low temperature storage. Osmotic pretreatment significantly improved the colour and other quality attributes of the carrot cubes for storage of 7 months. The shrinkage of rehydrated carrot cube with no osmotic pretreatment varied from 30-50% during storage, whereas in case of osmotic pretreatment with mixture of sugar-salt, it was almost negligible through out the storage period. The shrinkage of rehydrated samples osmotically pretreated with sugar varied from 1 to 5% and 14-35% for rehydrated carrot cubes osmotically pretreated with salt. The reasons responsible for shrinkage has been explained in section 4.4.5. There was no significant difference in the quality parameters as far as packaging of dehydrated product in HDPE, LDPE and aluminum-laminated packages. However, it is universally known that the quality of the product can be retained in aluminum laminated packages as compared to HDPE and LDPE packages due to its low permeability and transmission of light. But due to higher costs of Aluminum–laminated packages, HDPE packages of higher gauge can also be used, as no significant change was observed in quality of carrot cubes during storage.

The effect on quality of dehydrated and rehydrated carrot cubes osmotically pretreated in solutions of different osmotic agents irrespective of packaging material, which were stored for 10 months at ambient as well as low temperature could be visually compared from the Fig 4.52 to 4.55.

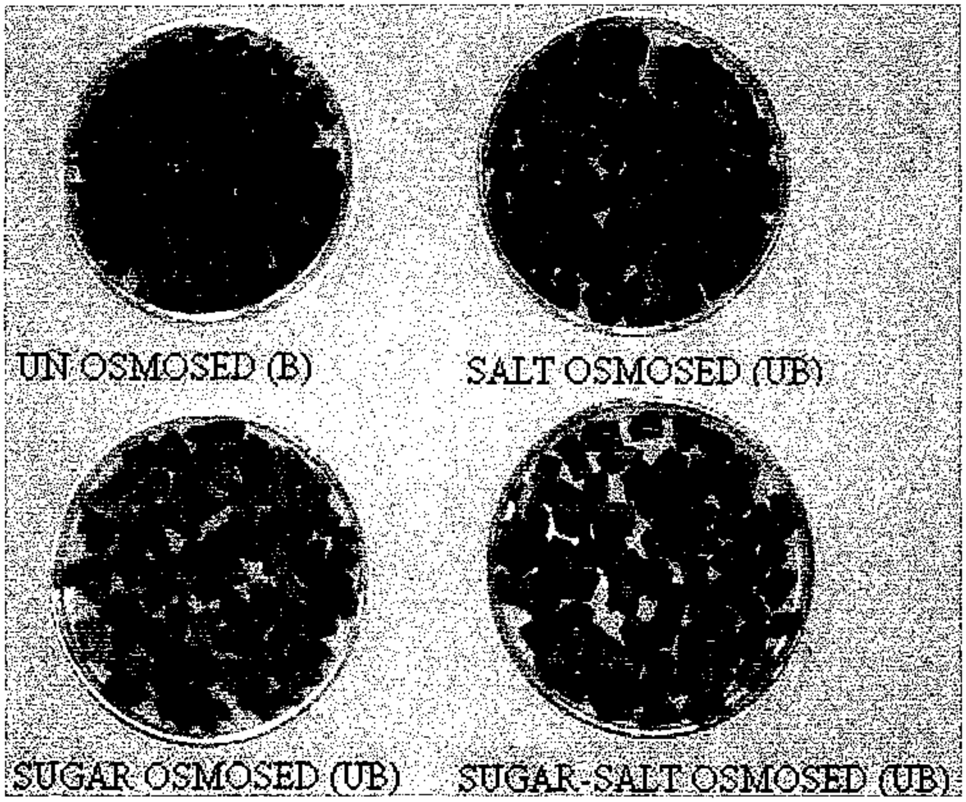


Fig 4.52 Dehydrated carrot cubes stored at ambient temperature for 10 months

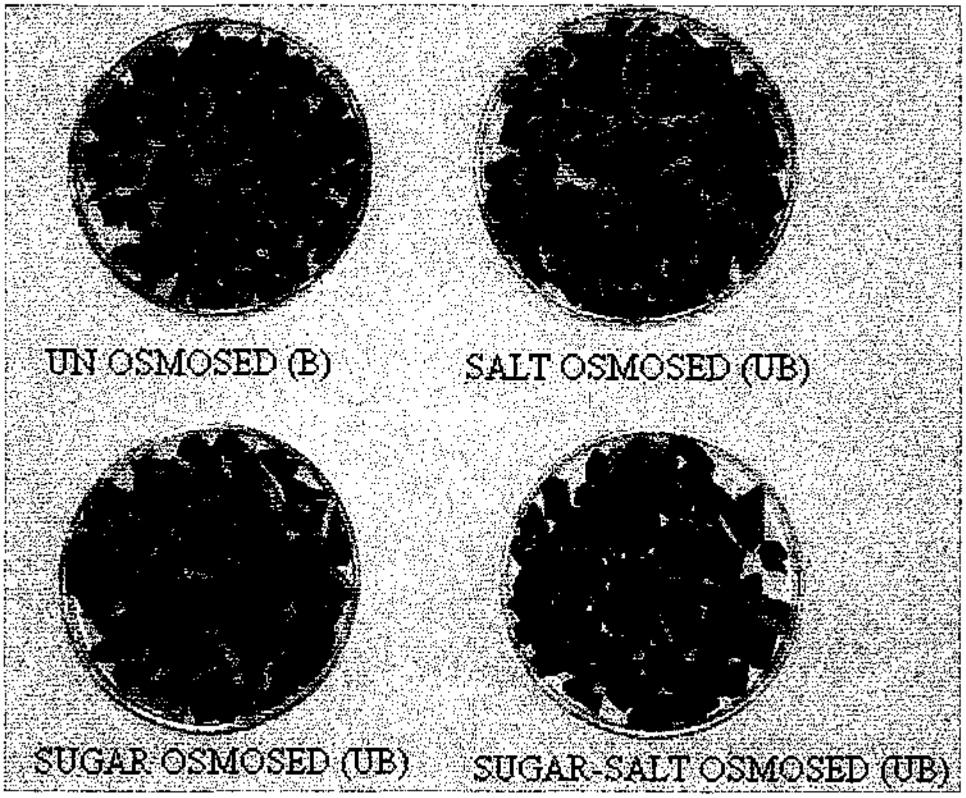


Fig 4.53 Dehydrated carrot cubes after 10 months stored at low temperature.

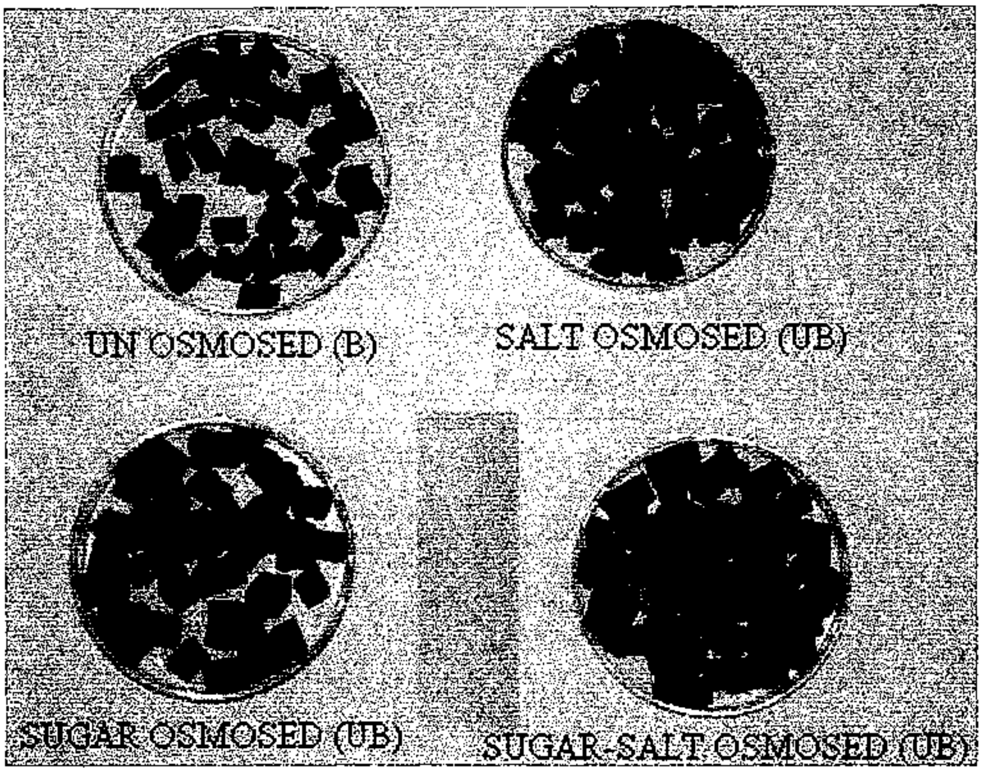


Fig 4.54 Carrot cubes rehydrated after 10 months ambient temperature storage.

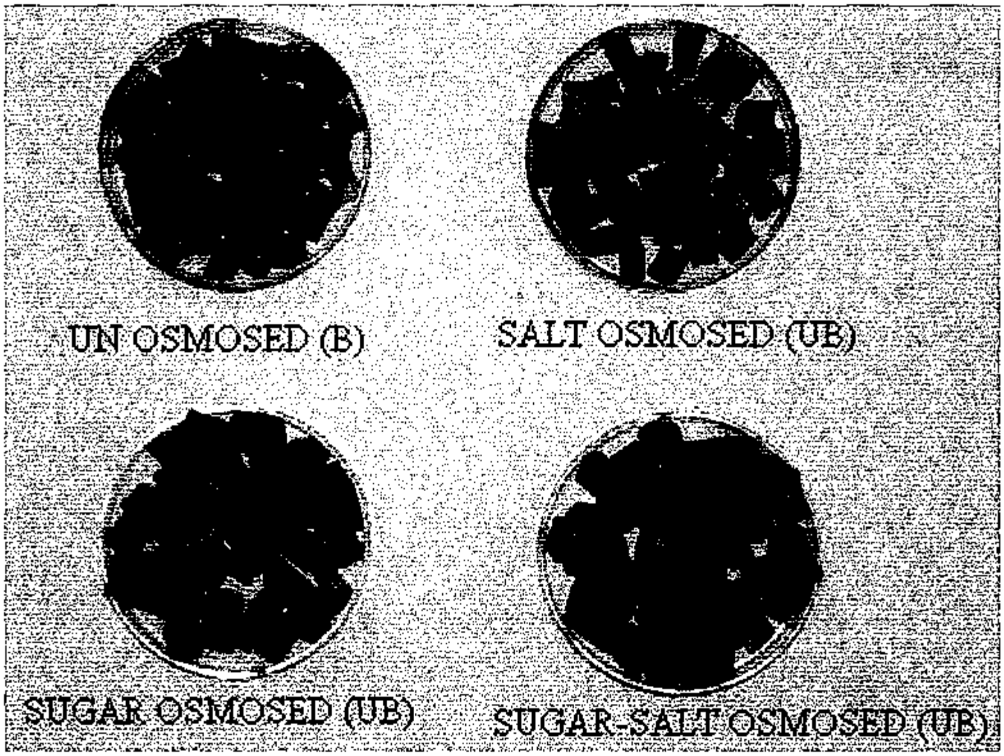


Fig 4.55 Carrot cubes rehydrated after 10 months low temperature storage.

CHAPTER V

SUMMARY AND CONCLUSIONS

To study mass transfer kinetics of water loss and solute gain during osmotic dehydration, carrot cubes of size 1cm x 1 cm x 1cm were osmotically treated in solutions of salt (5, 10 and 15% concentration), sugar (45, 50 and 55°B) and mixture of sugar-salt (50°B+ 5% salt, 50°B+10% salt and 50°B+15% salt) having solution temperatures (35, 45 and 55°C) and solution to fruit ratios (4, 5 and 6) for different time intervals varying from 10 to 240 minutes. Response surface methodology (RSM) by adopting central composite rotatable design (CCRD) was used to analyze and predict the optimum condition of the osmotic dehydration process of carrot cubes using three independent variables: osmotic solution concentration (5-10 and 15% in salt; 45, 50 and 55°B in sugar; 5, 10 and 15% salt in 50°B sugar in sugar-salt mixture solution), solution temperatures (30, 40 and 50°C for salt solution; 35, 45 and 55°C for sugar and sugar-salt mixture solution) and process time (60, 90 and 120 minutes for salt; 120, 180 and 240 minutes for sugar and sugar-salt mixture solution) by using fixed solution to fruit ratio of 6 for salt and 5 for sugar and sugar-salt mixture solution. Sodium metabisulphite @ 0.3% was added to osmotic solution or blanching solution as preservative. During experimentation, no blanching had been performed for the carrot cubes to be pretreated in osmotic solution. However blanching was done for the un-osmosed samples. After osmotic pretreatment the carrot cubes were convectively dehydrated at 60°C drying air temperature to moisture content 4-5% (w.b.). After osmo-convective dehydration the samples were rehydrated for 8-10 hours in water at ambient temperatures. The main criterion for optimization was maximum possible water loss, rehydration ratio, and overall acceptability; lower solute gain and shrinkage as low as possible. After osmotic pretreatment at optimum conditions, convective dehydration kinetics were studied at 55, 65 and 75°C at air velocity of 1.6 m/s. The impact of osmotic pretreatments on various quality parameters like rehydration kinetics, shrinkage, equilibrium moisture content (EMC), colour and firmness etc. were also investigated. The dehydrated samples were packaged an HDPE, LDPE and Aluminum laminated packages along with CaO_2 lumps, and were stored at ambient as well as low temperature. The left over material of carrot cubes was utilized to extract carrot juice and the carrot pomace (pulp) thus obtained was stored after osmo-convectively using dried sugar and then further used to prepare gazrella. The following conclusions were drawn from the study:

1. Osmotic dehydration resulted in water removal from the product, depending up on the type of osmotic agent, concentration and temp of osmotic solution, duration of osmotic process. All the treatment variables significantly affected water loss and solute gain during osmotic dehydration in all the three types of osmotic solutions, except solution to fruit ratio in few cases.
2. The rate of water loss and solute gain increased with increase of osmotic solution concentration for all the three types of osmotic agents. The addition of sodium chloride to sugar solution caused a decrease in the soluble solid uptake and an increase in the rate of osmotic dehydration. The highest efficiency of osmotic dehydration was in samples exposed to 50°B+10% salt solution.
3. The water loss and solute gain increased with increase of process duration except during osmotic dehydration in salt solution. During osmotic dehydration of carrot cubes in salt solution, an increase in moisture (instead of decrease) observed after duration of 100 minutes at all concentrations, temperatures and solution to fruit ratios. The change in water loss, solute gain was rapid in the first period of osmotic dehydration, especially at higher concentration and temperature of sugar solution.

4. Negative impact of temperature was observed on water loss during osmotic dehydration in salt and sugar solution, might be due to decreased viscosity of osmotic solution. The decreased viscosity resulted in fast impregnation of solute in to the product. Therefore, when the ultimate aim of osmotic dehydration would be water removal, the temperature should be kept low, whereas when the ultimate aim was to increase the solute content (like jam, murrabba), the temperature should be kept high but within permissible limits.

5. Osmotic pretreatment resulted in up to 10, 25 and 45% water removal and a solute gain up to 2.5, 7.6 and 8.2 g solute/ 100 g of fresh fruit for osmotic dehydration in salt, sugar and sugar-salt mixture respectively under the above mentioned conditions of solution concentration, temperature and solution to fruit ratio.

6. The optimum conditions generated by RSM were: process time of 90, 220 and 180 minutes; temperature of 30, 49 and 46.5°C; concentration of 11, 58°B and 50°B+10% salt for osmotic dehydration in solutions of salt, sugar and sugar-salt mixture respectively.

7. During blanching of carrot cubes of dimensions 1 cm x 1 cm x 1 cm, losses in total solid were observed during first minute of blanching . The blanching for specified time of 3 minutes resulted in average total solid losses 16.66%, whereas, these losses were 13.58% after blanching for one minute.

8. The convective drying of carrot cubes takes place in the falling rate period. The average drying times were 450, 525, 752 and 812 minutes for un-osmosed, pre-osmosed with salt, sugar and sugar-salt mixture respectively at 65°C drying air temperature and 1.6 m/s air velocity.

9. Osmotic dehydration resulted in increase of total convective dehydration time. Due to resistance (hindrance to moisture movement) created by the solute gain to water

removal, the osmotic pretreatment in salt, sugar and sugar-salt mixture solution added approximately 75, 105 and 175 minutes respectively to the convective dehydration time of un-osmosed (blanched) carrot cubes at 55°C drying air temperature, even though drying of osmotically pretreated samples had been started from too low initial moisture levels. Similar behaviour was observed for drying at 65 and 75°C except higher drying rate and lowering of total convective dehydration time.

10. The activation energy for the convective drying of carrot cubes was 21.66 KJ/mole K for un-osmosed samples, which was 9.76, 14.55, 15.86 KJ/mole K in case of salt, sugar, and mixture of sugar and salt respectively.
11. The osmotic dehydration resulted in increase in dehydration ratio after convective dehydration due to impregnation of solute during osmotic dehydration. Thus the impregnated solute can be sold at the cost of dehydrated product. But ultimately this would cause loss to the consumer on the cost of better quality of the rehydrated product, because the solute would be ultimately leached out during rehydration.
12. Osmotic dehydration resulted in lowering of rehydration ratio, because the impregnated osmotic solute does not contribute to the water absorption process during rehydration process. Maximum reduction of rehydration ratio was observed for samples osmotically pretreated with sugar-salt mixture followed by sugar and salt.
13. Shrinkage of dehydrated and rehydrated product was reduced by osmotic pretreatment. Shrinkage in rehydrated products, which were osmotically pretreated in solution of sugar-salt mixture, was negligible and the product was comparable to the fresh product. However, slight shrinkage was observed in rehydrated samples osmotically pretreated in sugar solution.

14. Addition of $CaCl_2$ to osmotic or blanching solution before convective dehydration increased the firmness of the product non-significantly, except the carrot cubes which were osmotically pretreated in salt solution. In carrot cubes in salt and $CaCl_2$ solution, a decrease in firmness of the rehydrated product was observed.
15. The osmotic dehydration improved the quality of the dried and rehydrated product. It also improved the colour, texture, and reduced shrinkage of the product.
16. The osmosis in salt solution resulted in increase of EMC of the product, whereas osmotic pretreatment in sugar solution decreased the EMC. The EMC of the carrot cubes, which were osmotically pretreated in sugar-salt mixture, was found between the un-osmosed (blanched) and sugar treated samples.
17. Azuara model was best fitted to the experimental data for osmotic dehydration, Modified Midilli model for convective dehydration, Peleg's model for rehydration kinetics and two-term exponential model for sorption isotherm behaviour of carrot cubes.
18. At low temperature storage, all the samples were of acceptable quality after 10 months of storage regardless of packaging material used. At ambient temperature storage, changes in colour were observed only in un-osmosed (blanched) and osmotically pretreated in salt solution. Due to higher costs of Aluminum–laminated packages, HDPE packages of higher gauge can also be used.
19. The rehydrated carrot cubes osmotically pretreated in solution of sugar-salt mixture were comparable to those of fresh crop even after ambient room temperature storage for 10 months.
20. This low cost crop could also be converted to value added products if processed properly. Preparing cubes of uniform size and performing osmotic dehydration in solution of sugar-salt mixture in order to increase the overall acceptability in terms

of appearance, colour, texture etc can add the value to the product. Further left over material of carrot cubes can be processed to carrot juice, which can be sold at high price. The pomace (pulp) thus obtained after extraction of juice could be stored for future use after osmo-convective dehydration with dry sugar. This dehydrated pomace could further be used to prepare gazrella (an Indian sweetmeat) during off season.

21. The juice remained shelf stable even after storage of 10 months at ambient temperature. However, lowering of TSS from 12°B to 11.5°B, acidity from 0.18 to 0.16 % and sensory score 8.5 to 6.5 was observed during the storage period.
22. The gazrella from osmo-convectively carrot pomace lacked slightly in flavour. The overall response of acceptability varied between moderate to excellent. Therefore carrot juice and gazrella could become available during off-season too if processed properly by following the developed techniques.

It was concluded from the present study, that the osmotic dehydration resulted in increased convective dehydration time, improvement in colour, texture, overall acceptability, and lowered the shrinkage and activation energy for the convective dehydration. Out of all the osmotic pretreatments, sugar-salt solution pretreatment gave the rehydrated product similar to fresh product even after storage period of 10 months. Azuara model and modified Midilli model can predict the kinetics of osmotic and convective dehydration respectively. The osmotic pretreatment in salt solution resulted in increase of EMC, whereas osmotic pretreatment in sugar solution decreased the EMC of the product. The samples, which were osmotically pretreated with sugar and sugar-salt mixture solution, remained acceptable up to 10 months storage under ambient condition. Whereas, all the samples stored at low temperature remained acceptable regardless of packaging material even after storage of 10 months. The juice remained fit for consumption at ambient temperature after 10 months. Gazrella, which was prepared from left over material, had overall response of acceptability between moderate to excellent.

Suggestions for future study:

1. Effect of addition of Ascorbic acid (an anti-oxidant) to the un-blanched carrot cubes to increase the shelf life of the product stored at room temperature may be studied.
2. The various combinations of sugar and salt may be tried to increase the efficiency and to minimize the cost of the osmotic dehydration process.
3. The dried pomace (juice by-product) can be used as an ingredient for bread, cake, mixed with ice cream, corn grits and other extruded products for the purpose of increasing dietary fibre in food intake.
4. The vacuum packaging of the dehydrated carrot cubes in appropriate packaging material may be studied to prevent oxidation effect of the stored product.
5. The osmotic dehydration and blanching process may be optimized for the preparation of carrot candy.
6. The osmotic dehydration process can be improved by changing pH of osmotic solution, applying vacuum, high pressure etc.
7. Other osmotic agents like corn starch syrup; glycerol etc can be used as osmotic agents.
8. To improve colour of the carrot juice and carrot pomace, blanching of left over material of carrot cubes may be performed.

CHAPTER VI

REFERENCES

Achanta S and Okos M R (1996) Predicting the quality of dehydrated foods and biopolymers. Research needs and opportunities. *Drying Technol* **14**: 1329-68.

Ade Omowaye B I O, Rastogi N K, Angersbach A and Knorr D (2002a) Osmotic dehydration behavior of red paprika (*Capsicum annuum* L.). *J Food Sci* **67**: 1790-96.

Ade Omowaye B I O, Rastogi N K, Angersbach A and Knorr D (2002b) Osmotic dehydration of bell peppers: influence of high intensity electric field pulses and elevated temperature treatment. *J Food Engng* **54**: 35-43

Adu B and Otten L (1996) Microwave heating and mass transfer characteristics of white beans. *J Agric Eng Res* **64**: 71-8.

Akpinar E, Midilli A and Bicer Y (2003) Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modeling. *Energy Conversion and Management* **44**:1689-1705.

Akritidis C B, Tsatsaelis C A and Bagiatis (1988) Equilibrium moisture content of pumpkin seed. *Trans ASAE* **31**: 1824-27.

Alzamora S M, Chirife J and Viollaz P E (1979) A simplified model for predicting the temperatures of foods during air dehydration. *J Food Technol* **14**:369-80.

Alvarez M D, canet w and Tortosa M E (2001) Kinetics of thermal softening of potato tissue (Cv. Monalisa) by water heating. *Eur Food Res Technol* **212**: 588-96.

Andrzej L (1991) Effect of saccharose on water sorption and rehydration of dried carrot. In: *Drying '91'*. Mujumdar A S and Filkova I (ed). pp 489-498 Conference. Prague, Czechoslovakia. Aug. 1990. PO Box 211, 1000 AE Amsterdam, Netherlands; Elsevier Sci Publishers.

Anonymous (2003a) *A Reference Annual*. pp: 404-404 Publication Division, Ministry of Information and Broadcasting, Govt. of India.

Anonymous (1989) Quality and Preservation of Vegetables.(ed. Eskin, N. A. M.). CRC press Inc., Florida: 75-119.

Anonymous (2003b) Health Corner of News Letter of Indian Society for Technical Education. **XXIII** (6): 24.

Arya S S, Natesan V, Parihar D B and Vijayarghavan P K (1979) Stability of carotenoids in dehydrated carrots. *J Food Technol* **14**:579.

Azoubel P M and Murr F E X (2000) Mathematical modelling of the osmotic dehydration of cherry tomato (*Lycopericon esculentum var. cerasiforme*). *Cienç Technol Aliment* **20**: 1-10.

Azoubel P M and Murr F E X (2004) Mass transfer kinetics of osmotic dehydration of cherry tomato. *J Food Engng* **61**: 291-95.

Azuara E, Beristain C I and Garcia H S (1992) Development of a mathematical model to predict kinetics of osmotic dehydration. *J Food Sci Technol* **29**: 239-42.

Bao B and Chang K C (1994a) Carrot juice color, carotenoids, and non-starchy polysaccharides as affected by processing conditions. *J Food Sci* **59**:1155-58.

Bao B and Chang K C (1994b) Carrot pulp chemical composition, color and water-holding capacity as affected by blanching.. *J Food Sci* **59**:1159-67.

Barat J M E, Chiralt A and Fito P (1998) Equilibrium in cellular food osmotic solution systems as related to structure. *J Food Sci* **63**: 836-40.

Barat J M, Fito P and Chiralt A (2001) Modeling of simultaneous mass transfer and structural changes in fruit tissues. *J Food Engng* **49** :77-85.

Bawa A S, Gujral H S (2000) Effect of osmotic agents on the drying behaviour and product quality in raisin processing. *J Sci and Industrial Res* **59**: 63-6.

Beristain C I, Azura E, Cortes R and Garcia H S (1990) Mass transfer during osmotic dehydration of pineapple rings. *International J Food Sci Technol*, **25**: 576-81.

Bhuvaneswari S, Sreenaryanan V V, Kailappan R and Parvathy K (1999) Osmotic dehydration of peas. *Indian Food Packer* **53**: 10-12.

Bidaisee G and Badrie N (2001) Osmotic dehydration of cashew apples (*Anacardium occidentale* L.): quality evaluation of candied cashew apples. *International J Food Sci Technol* **36**: 71-78.

Biswal R N and Bozorgmehr, K (1992) Mass transfer in mixed solute osmotic dehydration of apple rings. *Trans ASAE* **35**: 257-62.

Biswal R N and Maguer L (1989) Mass transfer in plant materials in contact with aqueous solution of ethanol and sodium chloride: equilibrium data. *J Food Process Engng* **11**:159-76.

Biswal R N, Bozorgmehr K, Tompkins F D and Liu X (1991) Osmotic concentration of green beans prior to freezing. *J Food Sci* **56**: 1008-12.

Biswal R N, Wilhelm L R, Rojas A and Mount J R (1997) Moisture diffusivity in osmotically concentrated diced sweet potato during air drying. *Trans ASAE* **40**: 1383-90.

Bobic Z, Bauman I and Curic D (2002) Rehydration ratio of fluid bed-dried vegetables. *Sadhana* **27** : 365-74.

Bolin H R, Huxall C C, Jackson R and Ng K C (1983) Effect of osmotic agents and concentration of fruit quality. *J Food Sci* **48**: 202-05.

Bongirwar D R and Sreenivasan A (1977) Studies on osmotic dehydration of banana. *J Food Sci Technol* **14**: 104-13.

Brennen J G (1989) Dehydration of food stuffs. In: Hardman T M (ed) *Water and Food Quality*. pp 33-70 . Elsevier Applied Sci, London and New York.

Chadha K L (2002) Handbook of Horticulture. Published by Indian Council of Agric Research, Pusa, New Dehli. :374.

Chang M J, Han M R and Kim M H (2003) Effect of salt addition in sugar based osmotic dehydration on mass transfer and browning reaction of green pumpkin. *Agric Chem Biotechnol* **46**: 92-96.

Chaudhari A P, Kumbhar B K, Singh B P N and Maharaj Narain (1993) Osmotic dehydration of fruits and vegetables - a review. *Indian Food Industry* **12** :20-27.

Chen C and Morey R V (1989) Comparision of four ERH/EMC equations. *Trans ASAE* **32**: 983-90.

Chenlo F, Moreira R, Pereira G and Ampudia A (2002) Viscosities of aqueous solutions of sucrose and sodium chloride of interest in osmotic dehydration processes. *J Food Engng* **54**: 347-52.

Chinnan M S (1984) Evaluation of selected mechanical models for describing thin layer drying of in-shell pecans. *Trans ASAE* **27**: 610.

Chopra C S (2001) Osmo-vacuum drying of carrots: Effect of salted syrup on drying behaviour and product quality. *Beverage and Food World* September: 15-17.

Chopra C S and Verma N S (1994) Osmo-vacuum drying of carrots: Effect of size of pieces on drying behavior and product quality. *Beverage and Food World*, **29**:7-8.

Chua K J, Mujumdar A S, Chou S K, Hawladar M N A and Ho J C (2000) Convective drying of banana, guava and potato pieces: Effect of cyclic variations of air temperature on drying kinetics and color change. *Drying Technol* **18**: 907-936.

Colson K H and Young J H (1990) Two component layer drying model of unshelled peanuts. *Trans ASAE* **33**: 241-46.

Conway J, Castaigne F, Picard G. and Vevan X (1983) Mass transfer considerations in the osmotic dehydration of apples. *Can Inst Food Sci Technol J* **16**:25-29.

Crank J (1975) *Mathematics of Diffusion.* 2nd ed. Oxford University Press, London.

Dandamrongrak R, Young G and Mason R (2002) Evaluation of various pretreatments for the dehydration of banana and selection of suitable drying models. *J Food Engng* **55**: 139-46.

Dauthy M E (1995) *Fruit and vegetable processing*. FAO Agricultural Buletin No. 119. Food and Agriculture Organization of United Nations, Rome.

Davidson V J, Xiang L and Brown R B(2004) Forced-air drying of ginseng root: 1. Effect of air temperature on quality. *J Food Engng* **63**: 361-67.

Diamente L M and Munro P A (1993) Mathematical modeling of the thin layer solar drying of sweet potato slices. *Solar Energy* **51**: 271-76.

Dixon G M and Jen J J (1977) Changes of sugars and acids of osmovac dried apple slices. *J Food Sci* **42**:1126-27.

Doymaz I (2004a) Convective air drying characteristics of thin layer carrots. *J Food Engng* **61**: 359-64.

Doymaz I (2004b) Drying of white mulberry. *J Food Engng* **61**: 341-46.

Erle U and Schubert H (2001) Combined osmotic and microwave-vacuum dehydration of apples and strawberries. *J Food Engng* **49**: 193-99.

Ertekin C and Yaldiz (2004) Drying of eggplant and selection of a suitable thin layer drying model. *J Food Engng* **63**: 349-59.

Ertekin F K and Cakaloz T (1996a) Osmotic dehydration of peas. I. Influence of process variables on mass transfer. *J Food Processing and Preservation* **20**: 87-104.

Ertekin F K and Cakaloz T (1996b) Osmotic dehydration of peas: II. Influence of osmosis on drying behaviour and product quality. *J Food Processing and Preservation,* **20**:105-19.

Ertekin F K and Sultanoglu M (2000) Modeling of mass transfer during osmotic dehydration of apples. *J Food Engng* **46**: 243-50.

Escriche I, Garcia Pinchi R, Andres A and Fito P (2000) Osmotic dehydration of kiwi fruit (*Actinidia chinensis)*: Fluxes and mass transfer kinetics. *J Food Process Engng* **23**: 191-205.

Farkas D F and Lazar M E (1969) Osmotic dehydration of apple pieces: Effect of temperature and syrup concentration rates. *Food Technol* **23**: 90-92.

Feng H and Teng J (1999) Determination of moisture diffusivity of Red Delicious apple tissues by thermogravimetric analysis. *Drying Technol* **18**: 1183-99.

Firodia A (2004)Send the best and brightest to the farms. *Indian Express*, July 22:9

Fito P (1994) Modelling of vacuum osmotic dehydration of food. *J Food Engng* **22**: 313-28.

Flink J M (1979) Dehydrated carrot slices: influence of osmotic concentration on drying behavior and product quality. *Food Process Engng* **1**: 412-18.

Floros J D and Chinnan M (1987) Optimization of pimiento pepper lye peeling using response surface methodology. *Trans ASAE* **30**: 560-65.

Floros J D and Chinnan M (1988) Seven factor response surface optimization of a double stage lye (NaOH) peeling process for pimiento peppers. *J Food Sci* **53**: 631-38.

Francis J F (2000) *Willey encyclopedia of Food Sci and Technolnolgy*. Vol **4**. John Wiley and Sons, Inc, New York : 2399-2405.

Gabas A L, Menegalli F C and Romero T (1999) Effect of chemical pretreatment on the physical properties of dehydrated grapes. *Drying Tecnol* **17**: 1215-1226.

Gekas V and Lamberg I (1991) Determination of diffusion coefficients in volume-changing sustems-Application in the case of potato drying. *J Food Engng* **14**: 317-26.

Gonzalez A M, Canovas G V B and Cavalieri R P (1993) Mass transfer and textural changes during processing of apples by combined methods. *J Food Sci* **58**: 1118-24.

Guide for sensory evaluation of foods-Part I. 1971. Optimum requirements. Indian Standards Institution, New Delhi. IS: 6273.

Hass G J, Precott J and Cante C J (1974) Rehydration and respiration of dry and partially dry vegetables. *J Food Sci* **39**: 681.

Hatamipour M S and Mowla D (2002) Shrinkage of carrots during drying in an inert medium fluidized bed. *J Food Engng* **35**: 247-52.

Hawkes J and Flink J M (1978) Osmotic concentration of fruit slices prior to freeze dehydration. *Journal of Food Processing and Preservation*, (2):265-84.

Hernandez J A, Pavon G and Garcia M A (2000) Analytical solution of mass transfer equation considering shrinkage for modeling food-drying kinetics. *J Food Engng* **45**: 1-10.

Hossain M A and Bala B K (2000) Moisture isotherm characteristics for red chilli. *Drying Technol* **18**: 503-15.

Hsu K H (1983) A diffusion model with a concentration dependent diffusion coefficient for describing water movement in legumes during soaking. *J Food Sci* **48**: 618-22, 643.

Ibanoglu S and Ainsworth P (2004) Application of response surface methodology for studying the viscosity changes during canning of tarhana, a cereal-based food. *J Food Engng* **64**: 273-75.

Islam M N and Flink J M (1982) Dehydration of potato. II. Osmotic concentration and its effect on air drying behaviour. *J Food Technol* **17**:387-403.

Jackson T H and Mohammed B B (1971) The Shambat process: New development arising from the osmotic dehydration of fruits and vegetables. *Sudan J Food Sci and Technol* **3**:18-22.

Jayaraman K S (1988) Development of intermediate moisture tropical fruit and vegetable products- Technological problems and prospects. In: Seow C C, Teng T T and Quah C H (ed) *Food Preservation by Moisture Control.* pp 175-198. Elsevier Applied Sci, London and New York.

Johnson P N T, Brennan J G and Addo-Yobo F Y (1998) Air-drying characteristics of Plantain (*Musa* AAB). *J Food Engng* **37**: 233-42.

Kalbarczyk J and Widenska A (2000) Rehydration of nameko (Pholiota nameko) and shiitake (Lentinus edodes) fruitbodies dried conventionally and sublimatically. *Electronic J Polish Agril Universities* **3**:

Kaleemullah S, Kailappan R, Varadharaju N (2002a) Studies on osmotic-air drying characteristics of papaya cubes. *J Food Sci Technol* **39**: 82-84.

Kaleemullah S, Kailappan R, Varadharaju N and Devadas C T (2002b) Mathematical modeling of osmotic dehydration kinetics of papaya. *Agricl Mechanization in Asia, Africa and Latin America* **33**: 30-34.

Kalra C L (1990) Role of blanching in vegetable processing. *Indian Food Packer*, Sep-Oct: 3-15.

Kalra C L, Kulkarni S G and Berry S K (1987) The carrot (*Daucus carota* L.)-A most popular root vegetable. *Indian Food Packer*, Nov-Dec: 46-73.

Kar A and Gupta D K (2001) Osmotic dehydration characteristics of button mushrooms. *J Food Sci Technol* **38**: 352-57.

Kar A and Gupta D K (2003) Air drying of osmosed button mushrooms. *J Food Sci Technol* **40**: 23-27.

Karathanos V T, Kostaropoulus A E and Saravacos G D (1995) Air-drying behavior of osmotically dehydrated fruits. *Drying Technol* **13**:1503-21.

Karathanos V T, Villalobos G and Saravacos G D (1990) Comparison of two methods of estimation of the effective moisture diffisivity from drying data. *J Food Sci* **55**: 218-31.

Karel M (1976) Technology and application of new intermediate moisture foods. R. Davies, G. G. Birch and K. J. Parker. Eds p.4. Applied Sci. Publishers, London.

Kechaou N and Maalej M (1999) Desorption isotherms of imported banana application of the GAB theory. *Drying Technol* **17**: 1201-13.

Khuri A I and Cornell J A (1987) *Response Surfaces Design and Analysis*. Marcel Dekker, Inc. New York.

Kowalska H and Lenart A (2001) Mass exchange during osmotic pretreatment of vegetables. *J Food Engng* **49**: 137-40.

Krokida M K and Maroulis Z B (1997) Effect of drying method on shrinkage and porosity. *Drying Technol* **15**: 2441-58.

Krokida M K, Kiranoudis C T and Maroulis Z B (1999) Viscoelastic behaviour of dehydrated products during rehydration. *J Food Engng* **40**: 269-77.

Krokida M K, Kiranoudis C T, Maroulis Z B and Marinos Kouris D (2000) Effect of pretreatment on color of dehydrated products. *Drying Technol* **18**: 1239-50.

Krokida M K, Oreopoulou V, Maroulis Z B and Marinos Kouris D(2001) Effect of osmotic dehydration pretreatment on quality of french fries. *J Food Engng* **49**: 339-45.

Lahsasni S, Kouhila M, Mahrouz M and Jaouhari J T (2004) Drying kinetics of prickly pear fruit (Opuntia ficus indica). *J Food Engng* **61**: 173-79.

Laroche C and Gervais P (2003) Achivement of rapid osmotic dehydration at specific temperatures could maintain high Saccharomyces cerevisiae viability. *Appl Microbial Biotechnol* **60**: 743-47.

Lazarides H N (1994) Osmotic dehydration: developments and prospects. In: Singh R P and Oliveria F (ed) *Minimal Processing and Process Optimization of Foods*. pp 73. CRC Press, Boca Raton, FL.

Lazarides H N and Mavroudis N E (1995) Freeze/thaw effects on mass transfer rates during osmotic dehydration. *J Food Sci* **60**: 826-28, 857.

Lazarides H N and Mavroudis N E (1996) Kinetics of osmotic dehydration of a highly shrinking vegetable tissue in a salt-free medium. *J Food Engng* **30**: 61-74.

Lazarides H N, Fito P, Chiralt A, Gekas V and Lenart (1999) Advances in Osmotic Dehydration. In: Oliveria F A R and Oliveria J C (ed) *Processing Foods: Quality optimization and Process Assessment.* 175-99. CRC Press, New York.

Lazarides H N, Gekas V and Mavroudis N (1997) Apparent mass diffusivities in fruit and vegetable tissues undergoing osmotic processing. *J Food Engng* **31**: 315-24.

Lazarides H N, Katsanidis E and Nickolaidis A (1995a) Mass transfer kinetics during osmotic preconcentration aiming at minimal solid uptake. *J Food Engng* **25**:151-66.

Lazarides H N, Nickolaidis A and Katsanidis E (1995b) Sorption changes induced by osmotic preconcentration of apple slices in different osmotic media. *J Food Sci* **60**: 348-50, 359.

Lee C Y, Bourne M C and Van Buren J P (1979) Effect of blanching treatments on the firmness of carrots. *J Food Sci* **44**: 615-16.

Lenart A and Flink J M (1984) Osmotic concentration of potato. I. Criteria for the end point of the osmosis process. J Food Technol, (19):45-63, II. Spatial distribution of the osmotic effect. *J Food Technol* **19**:65-89.

Lenart A (1994) Osmotic dehydration of fruits before drying. In: Singh R P and Oliveira (ed) *Minimal processing and Process Optimization of Foods: An interface.* pp 87. CRC Press, Boca Raton, FL.

Lenart A (1996) Osmo-convective drying of fruits and vegetables: Technology and application. *Drying Technol* **14**: 391-413.

Lenart A and Cerkowniak M (1996) Kinetics of convection drying of osmodehydrated apples. *Polish J Food Nutrition Sci* **5**: 73-82.

Lerici C R, Pinnavaia G, Dalla Rosa M and Bartolucci L (1985) Osmotic dehydration of fruit: influence of osmotic agents on drying behavior and product quality. *J Food Sci* **50**: 1217-19, 1226.

Lewicki P P and Lukaszuk A (2000) Effect of osmotic dewatering on rheological properties of apple slices. *J Food Engng* **49**: 119-26.

Litvin S, Mannheim C H and Miltz (1998) Dehydration of carrots by a combination of freeze drying, microwave heating and air or vacuum drying. *J Food Engng* **36**: 103-11.

Liu J Y, Simpson W T, Verrill S P (2001) An inverse moisture diffusion algorithim for the determination of diffusion coefficient. *Drying Technol* **19**: 1555-68.

Loesecke H W V (2001) *Drying and Dehydration of Foods*. Agrobios (India) Jodhpur.

Lomauro C J, Bakshi A S and Labuja T P (1985) Moisture transfer properties of dry and semimoist foods. *J Food Sci* **50** : 397-400.

Madamba P S and Lopez R I (2002) Optimization of the osmotic dehydration of mango (*Mangifera indica* L.) slices. *Drying Technol* **20**: 1227-42.

Maharaj V and Sankat C K (2000) The rehydration characteristics and quality of dehydrated dasheen leaves. *Can Agricl Engng* **42**: 81-85.

Maskan A, Kaya S and Maskan M (2002) Hot air sun drying of grape leather (pestil). *J Food Engng* **54**: 81-88.

Maskan M (2000) Microwave/air and microwave finish drying of banana. *J Food Engng* **44**: 71-78.

Maskan M and Gogus F (1998) Sorption isotherms and drying characteristics of Mulberry (*Morus alba*). *J Food Engng* **37**: 437-49.

Matteo M D, Cinquanta L, Galiero G and Crescitelli S (2003) A mathematical model of mass transfer in spherical geometry: plum (*Prunus domestica*) drying. *J Food Engng* **58**: 183-192.

Matusek A and Meresz P (2002) modeling of sugar transfer during osmotic dehydration of carrots. *Periodica Polytechnica SER CHEM ENG* **46**: 83-92.

Mavroudis N E, Gekas V and Sjoholm I (1998a) Osmotic dehydration of apples - effects of agitation and raw material characteristics. *J Food Engng* **35**: 191-209.

Mavroudis NE, Gekas V and Sjoholm I (1998b) Osmotic dehydration of apples. Shrinkage phenomena and the significance of initial structure on mass transfer rates. *J Food Engng* **38**: 101-23.

Mazza G (1983) Dehydration of carrots. Effects of predrying treatments on moisture transport and product quality. *J Food Technol* **18**: 113-23.

McMinn W A M and Magee T R A (1997) physical characteristics of dehydrated potatoes-Part II. *J Food Engng* **33**: 49-55.

Menkov N D (2000) Moisture sorption isotherms of lentil seeds at several temperatures. *J Food Engng* **44**: 205-11.

Midilli A and Kucuk H (2003) Mathematical modeling of thin layer drying of pistachio by using solar energy. *Energy Conversion and Management* **44**: 1111-22.

Midilli A, Kucuk H and Yapar Z (2002) A new model for single layer drying. *Drying Technol* **20**:1503-13.

Mohammed S and Hussein R (1994) Effect of low temperature blanching, cysteine-HCl, N-acetyl-L-cysteine, Na metabisulphite and drying temperatures on the firmness and nutrient content of dried carrots. *J Food Processing and Preservation* **18**: 343-48.

Moraga G, Navarrete N M and Chiralt A (2004) Water sorption isotherms and glass transition in strawberries: influence of treatment. *J Food Engng* **62**: 315-21.

Mudahar G S, Toledo R T, Floros J D and Jen J J (1989) Optimization of carrot dehydration process using response surface methodology. *J Food Sci* **54**:714-19.

Mulet A, Berna A and Rossello C (1989a) Drying of carrots. I. Drying models. *Drying Technol* 7: 537-57.

Mulet A, Berna A, Rossello C and Pinaga F (1989b) Drying of carrots. II. Evaluation of drying models. *Drying Technol* 7 : 641-61.

Nabais R M, Madalena C V and Malcata F X (1996) Modeling the transport of Lactic Acid, Sodium Chloride and Reducing Sugars in Carrot slices submerged in brines: Part I. Univariate approach. *J Food Engng* **28**: 153-77.

Nanjundaswamy A M, Radhakrishnaiah S G, Balachandran C, Saroja S and Murthy reddy K B S (1978) Studies on development of new categories of dehydrated products from indigenous fruits. Indian Food Packer 22: 91-93.

Negi P S and Roy S K (2000) Effect of low-cost storage and packaging on quality and nutritive value of fresh and dehydrated carrots. *Journal of the Science of Food and Agriculture* **80** :2169-75.

Neumann H J (1972) Dehydrated celery: Effects of predrying treatments and rehydration procedures on reconstitution. *J Food Sci* **37**: 437-41.

Nieto A, Salvatori, Castro M A and Alzamora S M (1998) Air drying behaviour of apples as affected by blanching and glucose impregnation. *J Food Engng* **36**: 63-79.

Nsonzi F and Ramaswamy H S (1998) Osmotic dehydration kinetics of blueberries. *Drying Technol* **16**: 725-41.

Ochoa M R, Kesseler A G, Pirone B N, Marquez C A and Michelis De A (2002) Volume and area shrinkage of whole sour cherry fruits (Prunus cerasus) during dehydration. *Drying Technol* **20**: 147-56.

Official methods of Analysis of AOAC International 984.25 (2000) AOAC International, 17th ed. Maryland :14

Ozen B F, Dock L L, Ozdemir M and Floros J D (2002) Processing factors affecting the osmotic dehydration of diced green peppers. *International J Food Sci Technol* **37** : 497-502.

Pabis S (1999) The initial phase of convective drying of vegetables and mushrooms and the effect of shrinkage. *J Agric Engng Res* **72**: 187-95.

Panagiotou N M, Karathanos V T and Maroulis Z B (1999) Effect of osmotic agent on osmotic dehydration of fruits. *Drying Technol* **17**: 175-89.

Pandey M C and Aich J C (1989) Equalibrium moisture content of dehydrated mushroom (Pleurotus sajor caju). *J Food Sci Technol* **26**: 108-09.

Park K J, Bin A and Brod F P R (2001) Sorption isotherms data and mathematical models for pear bartlett *(Pyrus sp.)* with and without osmotic dehydration. *Ciencia e Tecnologia de Alimentos* **21**: 73-77

Park K J, Bin A, Brod F P R and Park T H K B (2002a) Osmotic dehydration kinetics of pear D'anjou (*Pyrus communis* L.) *J Food Engng* **52**: 293-98.

Park K J, Bin A, Brod F P R (2002b) Drying of pear d'Anjou with and without osmotic dehydration. *J Food Engng* **56**: 97-103.

Pathak P K, Agrawal Y C and Singh B P N (1991) Thin layer drying model for rapeseed. *Trans ASAE* **34**: 2505-08.

Peleg M (1988) An empirical model for the description of moisture sorption curves. *J Food Sci* **53**: 1216-19.

Pereira L M, Rodrigues A C C, Sarantopoulos C I G L, Junqueira V C A, Cunha R L and Hubinger M D (2004) Influence of modified atmosphere packaging and osmotic dehydration on the quality maintenance of minimally processed guavas. *J Food Sci* **69**: 172-77.

Pokharkar S M (2001) Kinetic model for osmotic dehydration of green peas prior to air drying. *J Food Sci Technol* **38**:557-60.

Pokharkar S M and Prasad S (1997) A model for osmotic concentration of banana slices. *J Food Sci Technol* 34: 230-32.

Pokharkar S M and Prasad S (1998) Mass transfer during osmotic dehydration of banana slices. *J Food Sci Technol* **35**: 336-38.

Pokharkar S M and Prasad S (2002) Air drying behaviour of osmotically dehydrated pineapple. *J Food Sci Technol* **39**: 384-87.

Ponting J D (1973) Osmotic dehydration of fruits: Recent modifications and applications. *Process Biochemistry* **8**:18-22.

Ponting J D, Watters G G, Forrey R R, Jackson R and Stanley W L (1966) Osmotic dehydration of fruits. *Food Technol* **1366**:125-28.

Prabhanjan D G, Ramaswamy H S and Raghavan G S V (1995) Microwave-assisted convective drying of thin layer carrots. *J Food Engng* **25**: 283-93.

Prado M E T, Alonso L F T and Park K J (2000) Shrinkage of dates (Phoenix dactilyfera L.) during drying. *Drying Technol* **18**: 295-310.

Prakash S, Jha S K and Datta N (2004) Performance evaluation of blanched carrots dried by three different driers. *J Food Engng* **62**: 305-13.

Prothon F and Ahrne L M (2004) Application of the Guggenheim, Anderson and De Boer model to correlate water activity and moisture content during osmotic dehydration of apples. *J Food Engng* **61**: 467-70.

Raghavan G S V, Tulasidas T N, Sablani S S and Ramaswamy H S (1995) A method of determination of concentration dependent effective moisture diffusivity. *Drying Technol* **13** :1477-88.

Rahamn M S and Lamb J (1991) Air drying behaviour of fresh and osmotically dehydrated pineapple. *J Food Process Engng* **14**: 163-71.

Rahman M S (1992) Osmotic dehydration kinetics of foods. *Indian Food Industry* **11**: 20-24.

Rahman M S and Lamb J (1990) Osmotic dehydration of pineapple. *J Food Sci Technol* **27**: 150-52.

Rahman S (1995) *Food Properties Handbook.* CRC Press, London.

Rai P, Majumdar G C, DasGupta S and De S (2004) Optimizing pectinase usage in pretreatment of mosambi juice for clarification by response surface methodology. *J Food Engng* **64**: 397-403.

Ramamurthy M S, Bongirwar D R and Bandyopadhyay C (1978) Osmotic dehydration of fruits: possible alternative to freeze drying. *Indian Food Packer* **32**: 108-111.

Ramesh M N, Wolf W, Tevini D and Jung G (2001) Influence of processing parameters on the drying spice paprika. *J Food Engng* **49**: 63-72.

Ramos A Q, Bourne M C and Morales A A (1992) Texture and rehydration of dehydrated carrots as affected by low temperature blanching. *J Food Sci* **57**: 1127-28,1139.

Ramos A Q, Bourne M C, Barnard J and Morales A A (1998) Optimization of low temperature blanching of frozen jalapeno pepper (*Capsicum annum*) using response surface methodology. *J Food Sci* 63: 519-22.

Ramos A Q, Bourne M, Barnard J, Laredo R G, morales A A,Esquivel and Melendez R M (2002) Low temperature blanching of frozen carrots with Calcium Chloride solutions at different holding times on texture of frozen carrots. *J Food Processing and Preservation* **26**: 361-74.

Rastogi N K and Raghavarao K S M S (1995) Kinetics of osmotic dehydration of coconut. *J Food Processing and Engng* **18**: 187-97.

Rastogi N K and Niranjan K (1998) Enhanced mass transfer during osmotic dehydration of high pressure treated pineapple. *J Food Sci* **63**: 508-11.

Rastogi N K and Raghavarao KSMS (1997) Water and solute coefficients of carrot as a function of temperature and concentration during osmotic dehydration. *J Food Engng* **34**: 429-40.

Rastogi N K, Angersbach A and Knorr D (2000a) Synergistic effect of high hydrostatic pressure pretreatment and osmotic stress on mass transfer during osmotic dehydration. *J Food Engng* **45**: 25-31.

Rastogi N K, Angersbach A, Niranjan K and Knorr D (2000b) Rehydration kinetics of high-pressure pretreated and osmotically dehydrated pineapple. *J Food Sci* **65**: 838-41.

Rastogi N K, Eshtiaghi M N and Knorr D (1999) Accelerated mass transfer during osmotic dehydration of high intensity electrical field pulse pretreated carrots. *J Food Sci* **64**: 1020-23.

Rastogi N K, Raghavarao K S M S and Niranjan K (1997) Mass transfer during osmotic dehydration of banana: Fickian diffusion in cylindrical configuration. *J Food Engng* **31**: 423-32.

Reppa A, Mandela J, Kostaropoulos and Saravacos G D (1999) Influence of solute temperature and concentration on the combined osmotic and drying. *Drying Technol* **17** : 1449-58.

Reugg M (1980) Calculation of the activity of water in sulphuric acid solutions of various temperatures. *Lebensm Wiss U Technol* **13**: 22-24.

Reyes A, Alvarez P I and Marquardt F H (2002) Drying of carrots in fluidized bed: I-Effects of drying conditions and modeling. *Drying Tecnol* **20**: 1463-83.

Roy S S, Taylor T A and Kramer H L (2001) Textural and ultrastructural changes in carrot tissue as affected by blanching and freezing. *J Food Sci* **66**: 176-80.

Ruiz-Cabrera M A, Salgado C M A, Waliszewski K K N, Garcia A M A (1997) The effect of path diffusion on the effective moistire diffusivity in carrot slabs. *Drying Technol* **15**: 169-181.

Sabarez H, Price W E, Back P J and wolf L A (1997) Modeling the kinetics of drying of d'Agen plums (*Prunus domestica*). *Food Chem* **60**: 371-82.

Sablani S S and Rahman M S (2003) Effect of syrup concentration, temperature and sample geometry on equilibrium distribution coefficients during osmotic dehydration of mango. *Food Research International* **36**: 65-71.

Sablani S S, Rahman M S and Habsi H A (2003) Effect of convection air-drying on apparent density, porosity and moisture diffusivity of potato and apple. *J Food Sci Technol* **40** : 592-96.

Sablani S S, Rahman S and Habsi N A (2000) Moisture diffusivity in foods- An overview. In: Drying Technology in Agriculture and Food Sciences. pp 35-59. Oxford & IBH Publishing Co. Pvt. Ltd. N. Delhi.

Sacchetti G, Gianotti A and Dalla Rosa M (2001) Sucrose-salt combined effect on mass transfer kinetics and product acceptability. Study on apple osmotic treatment. *J Food Engng* **49**: 163-73.

Sagar V R (2001) Preparation of onion powder by means of osmotic dehydration and its packaging and storage. *J Food Sci Technol* **38**: 525-28.

Salvatori D, Andres A, Albors A, Chiralt A and Fito P (1998) Structural and compositional profiles in osmotically dehydrated apple. *J Food Sci* **63**: 606-10.

Salvatori D, Andres A, Chiralt A and Fito P (1999a) Osmotic dehydration progression in apple tissue. I. Spatial distribution of solutes and moisture content. *J Food Engng* **42**: 125-32.

Salvatori D, Andres A, Chiralt A and Fito P (1999b) Osmotic dehydration progression in apple tissue. II. Generalized equations for concentration prediction. *J Food Engng* **42**: 133-38.

Sanjuan N, Carcel J A, Clemente G and Mulet A (2001) Modelling of the rehydration process of brocolli florets. *Drying Technol* **212**: 449-53.

Sanni L O, Kolawole A G, Akingbala J O and Kuye A (1999) Effect of drying methods on moisture sorption isotherms of fufu at three temperatures. *Drying Technol* **17**: 285-97.

Saputra D and Tambunan A H (2001) Osmotic dehydration of pineapple. First Asia-Australia Drying Conference, Bali, Indonesia, October 1999. *Drying Technol* **19**: 415-25.

Sarsavadia P N, Sawhney R L, Pangavhane D R and Singh S P (1999) Drying behaviour of brined onion slices. *J Food Engng* **40**: 219-26.

Saurel R, Raoult-Wack A L, Rios G and Guilbert S (1994) Mass transfer phenomena during osmotic dehydration of apple I. Fresh plant tissue. *International J Food Sci and Technol* **29**:531-542.

Sereno A M, Hubinger M D, Comesana J F and Correa A (2001a) Prediction of water activity of osmotic solutions. *J Food Engng* **49**: 103-14.

Sereno A M, Moreira R and Martinez E (2001b) Mass transfer coefficients during osmotic dehydration of apple in single and combined aqueous solutions of sugar and salt. *J Food Engng* **47**: 43-49.

Sharma G P, Prasad S and Datta A K (2003) Drying kinetics of garlic cloves under convective drying conditions. *J Food Sci Technol* **40**: 45-51.

Shepherd H and Bhardwaj R K (1988) Thin layer drying of pigeon pea. *J Food Sci* **53**: 1813-17.

Shi J and Maguer M L (2002) Osmotic dehydration of foods: Mass transfer and modeling aspects. *Food Reviews international* **18**: 305-35.

Shi X Q and Maupoey P F (1993) Vacuum osmotic dehydration of fruits. *Drying Technol* **11**:1429-42.

Simal S, Bauza de Mirabo F, Deya E and Rossello C (1997a) A simple model to predict mass transfers in dehydration by osmosis. *Z Lebensm Unters Forsch A* **204**: 210-14.

Simal S, Benedito J, Sanchez E S and Rossello C (1998) Use of ultrasound to increase mass transport rates during osmotic dehydration. *J Food Engng* **36**: 323-36.

Simal S, Deya E, Frau M and Rossello C (1997b) Simple Modelling of Air drying curves of fresh and Osmotically pre-treated apple cubes. *J Food Engng* **33**: 139-50.

Singh H (2001) Osmotic dehydration of carrot shreds for *Gazraila* preparation. *J Food Sci Technol* **38**:152-54.

Singh S, Shivhare U S, Ahmed J and Raghavan (1999) Osmotic concentration kinetics and quality of carrot preserve. *Food Research International* **32**: 509-14.

Sitkiewicz I, Lenart A and Lewicki P P (1996) Mechanical properties of osmotic-convection dried apples. Polish J of Food Nut and Sci 5/46:105.

Sopade P A and Kaimur (1999) Application of Peleg's equation in desorption studies of food systems: A case study with Sago (*Metroxylon sagu rottb.*) starch. *Drying Technol* **17** : 975-89.

Sopade P A and Obekpa J A (1990) Modeling water absorption in soyabean, cowpea and peanuts at three temperatures using Peleg's equation. *J Food Sci* **55**: 1084-87.

Speck P, Escher F and Solms J (1977) Effect of salt pretreatment on quality and storage stability of air-dried carrots. *Lebensm Wiss Technol* **10**: 308-13.

Spiazzi E and Mascheroni R (1997) Mass transfer model for osmotic dehydration of fruits and vegetables. I. Development of the simulation model. *J Food Engng* **34**: 387-410.

Statistica for Windows 5.0. (1995) *Computer program manual.* StatSoft, Inc. Tulsa.

Taiwo K A, Angersbach A and Knorr D (2002a) Influence of high intensity electric field pulses and osmotic dehydration on the rehydration characteristics of apple slices at different temperatures. *J Food Engng* **52**: 185-92.

Taiwo K A, Angersbach A and Knorr D (2002b) Rehydration studies on pretreated and osmotically dehydrated apple slices. *J Food Sci* **67**: 842-47.

Tedjo W, Taiwo K A, Eshtiaghi M N and Knorr D (2002) Comparison of pretreatment methods on water and solid diffusion kinetics of osmotically dehydrated mangos. *J Food Engng* **53**: 133-42.

Teixeira M B F and Tobinaga S (1998) A diffusion model for describing water transport in round squid mantle during drying with a moisture-dependent effective diffusivity. *J Food Engng* **36**: 169-81.

Telis V R N, Murari R C B D L and Yamashita F (2004) Diffusion coefficients during osmotic dehydration of tomatoes in ternary solutions. *J Food Engng* **61**: 253-59.

Telis V R N, Romanelli P F, Gabas A L and Romero J T (2003) Salting kinetics and salt diffusivities in farmed Pantanal caiman muscle. *Pesq Agropec Bras, Brasillia* **38**: 529-35.

Thakor N J, Sokhansanj S, Sosulski F W and Yannacopoulos S (1999) Mass and dimensional changes of single canola kernel during drying. *J Food Engng* **40**: 153-60.

Themelin A, Raoult Wack A L, Lebert A and Danzart M (1997) Multicriteria optimization of food processing combining soaking prior to air drying. *Drying Technol* **15**: 2263-79.

Togrul I T and Pehlivan D (2002) Mathematical modeling of solar drying of apricots in thin layers. *J Food Engng* **55**: 209-16.

Togrul I T and Pehlivan D (2003) Modelling of drying kinetics of single apricot. *J Food Engng* **58**: 23-32.

Toledo R T (2000) *Fundamentals of Food Process Engineering.* CBS Publishers and Distributors, New Delhi.

Torreggiani D, Forni E, Rizzolo A (1988) Osmotic dehydration of fruit. II. Influence of the osmosis time on the stability of processed cherries. *J Food Processing Preservation* **12**: 27-44.

Torringa E, Esveld E, Scheewe I, Berg R van den and Bartels P (2001) Osmotic dehydration as a pre-treatment before combined microwave-hot-air drying of mushrooms. *J Food Engng* **49**: 185-91.

Tulasidas T N, Raghavan G S and Norris E R (1993) Microwave and Convective drying of grapes. *Trans ASAE* **36**: 1861-65.

Uzman D and Sahbaz P (2000) Drying kinetics of hydrated and gelatinized corn starches in the presence of sucrose and sodium chloride. *J Food Sci* **65**: 115-22.

Vazquez G, Chenlo F, Moreira R and Castoyas (1999a) The dehydration of garlic. I. Desorption isotherms and modeling of drying kinetics. *Drying Technol* **17**: 1095-1108.

Vazquez G, Chenlo F, Moreira R and Castoyas (1999b) The dehydration of garlic. II. The effect of pretreatments on drying kinetics. *Drying Technol* **17**: 1109-1120.

Venkatachalapathy K and Raghavan G S V (1999) Combined osmotic and microwave drying of strawberries. *Drying Technol* **17**: 837-53.

Viberg U, Freuler S, Gekas V and Sjoholm I (1998) Osmotic preconcentration of strawberries and shrinkage effects. *J Food Engng* **35**:135-45.

Videv K, Tanchev S, Sharma R C and Joshi V K (1990) Effect of sugar syrup concentration and temperature on the rate of osmotic dehydration of apples. *J Food Sci Technol* **27**: 307-08.

Vijayanand P, Nagin Chand and Eipeson W E (1995) Optimization of osmotic dehydration of cauliflower. *J Food Processing and Preservation* **19**: 229-42.

Vivanco M M, Sobral P J do A and Hubinger M D (2002) Osmotic dehydration of tilapia fillets in limited volume of ternary solutions. *Chemical Engng J* **3966**: 1-7.

Walde S G, Math R G, Chakkravarthy and Rao D E (1992) Preservation of carrots by dehydration techniques-a review. *Indian Food Packer*, Nov-Dec:37-42.

Waliszewski K N, Corzo C, Pardio V T and Garcia M A (1999) Effect of proteolytic enzymes on colour changes in banana chips during osmotic dehydration. *Drying Technol* **17**: 947-54.

Waliszewski K N, Texon N I, Salgado M A and Garcia M A (1997) Mass transfer in banana chips during osmotic dehydration. *Drying Technol* **15**: 2597-2607.

Yaldiz O, Ertekin C and Uzun H I (2001) Mathematical modeling of thin layer solar drying of Sultana grapes. *Energy* **26**:457-65.

Yang D C and Maguer M L (1987) Mass transfer kinetics of osmotic dehydration of blue berry. *J Food Preserv.* **16**: 215-31.

Yao Z and Maguer Mle (1996) Mathematical modelling and simulation of mass transfer in osmotic dehydration processes. I. Conceptual and mathematical models. *J Food Engng* **29**:349-60.

Yao Z and Maguer Mle (1997a) Mathematical modelling and simulation of mass transfer in osmotic dehydration processes. II. Simulation and model verification. *J Food Engng* **32**: 21-32.

Yao Z and Maguer-Mle (1997b) Mathematical modelling and simulation of mass transfer in osmotic dehydration processes. III. Parametric study. *J Food Engng* **32**: 33-46.

Yusheng Z and Poulsen K P (1988) Diffusion in potato drying. *J Food Engng* **7**: 249-62.

Zogzas N P and Maroulis Z B (1996) Effective moisture diffusivity estimation from drying data. A comparison between various methods of analysis. *Drying Technol* **14**: 1543-73.

APPENDICES

APPENDIX-A

Date of Experiment:
Wt of Empty Petridish: W_1 (g)
Wt of Petridish + Fresh fruit: W_2 (g)
Wt of Petridish + Oven dried fruit: W_3 (g)

Type of Solution:
Concentration of Osmotic Solution:
Solution to Fruit Ratio:

Initial Dry matter (%) of fresh fruit **(A)** $= \frac{(W_3 - W_1)}{(W_2 - W_1)} * 100$

Duration (Min)	Wt of FF **(B)**	Vol of S	t_i	t_o	Vol of F **(C)**	Wt of EPD **(D)**	Wt of PD+ ODF **(E)**	Wt of EPD **(W)**	Wt of PD + 10 ml S **(G)**	Wt of PD + DF **(H)**	Wt of PD + DS **(J)**	Wt of F AOD **(K)** = (E-D)	Wt Loss **(L)**= (K-B)	DM BOD **(M)** = $\frac{(A*B)}{100}$	DM AOD **(N)** = H-D	SG **(P)** = $(N-M)$	WL **(R)** = L+P	WL /100g FF = $\frac{R}{B}*100$	SG /100g FF = $\frac{P}{B}*100$	ρ of F= $\frac{K}{C}$	S Conc %= (J-E) *100
10																					
25																					
40																					
60																					
90																					
120																					
150																					
180																					
210																					
240																					

Where
F= Fruit; FF= Fresh Fruit; S= Solution; DF= Dry Fruit; DS= Dry Solution; PD= Petridish; EPD= Empty Petridish; t_i = Initial time at which fruit was place in osmotic solution; t_o = Final time at which fruit was taken out from osmotic solution; AOD = After osmotic dehydration; BOD = Before osmotic dehydration; ODF = Osmotically dehydrated fruit;

APPENDIX –B

Effective Diffusivity For Osmotic Dehydydration (Theory and Methodology)

The basic governing equation of Fick's unsteady state one-dimensional diffusion is of the form

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial Z^2} \qquad \text{for } -L < Z < L \text{ and } t>0 \qquad (1)$$

Where C is the concentration of the diffusing substance, D the diffusion coefficient, and t and Z the time and space coordinates respectively. The different analytical solutions of equation (4.1) found by Crank (1975) for several geometries and boundary conditions relate the amount of mass transferred, in terms of a series of exponential functions. The analytical solution for slab geometry being placed in an agitating liquid medium is as below:

$$MR = \frac{M - M_e}{M_o - M_e} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_{em} q_n^2 t}{L^2}\right] \qquad (2)$$

Where M_t is the total amount of moisture in the carrot cubes at time t; M_∞ is the corresponding quantity at equilibrium; L is half of the slab thickness and q_n are the non-zero positive roots of the equation

$$\tan q_n = -\alpha q_n \qquad (3)$$

Similarly

Similarly for solute gain during osmotic dehydration

$$SGR = \frac{SG - SG_\infty}{SG_0 - SG_\infty} = \frac{C - C_e}{C_o - C_e} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_{es} q_n^2 t}{L^2}\right] \qquad (4)$$

Where C_t is the total amount of solute in the carrot cubes at time t; C_∞ is the corresponding quantity at equilibrium.

Where $\alpha = m\frac{V_L}{V_s}$ (5)

m= Partition Coefficient.

V_L = Volume of Liquid (i.e. solution)

V_S= Volume of Carrot cubes (Solid)

The volume of the carrot cubes was measured by equation developed by regression analysis of weight and volume of carrot cubes as given below.

Volume of carrot cubes = 0.993 * weight of carrot cubes – 0.5211

Determination of Partition Coefficient (m):

Partition coefficient is being defined as

$$C_\infty^L = mC_\infty^S \quad (6)$$

Where

C_∞^L= Volumetric solute concentration (g of solute/ cm^3) in solution at infinite time.

C_∞^S= Volumetric solute concentration (g of solute/cm^3) in fruit at infinite time.

The C_∞^S {Volumetric solute concentration (g of solute/cm^3) in fruit at infinite time} can be calculated by the following steps:

STEP-I: Find mass concentration of solute in fruit at infinite time:

By applying Azuara equation (1992) plot a graph between time and (time/solute gain)

$$SG_t = \frac{\beta t SG_\infty}{1+\beta t}$$

$$\frac{SG_t}{t} = \frac{\beta SG_\infty}{1+\beta t}$$

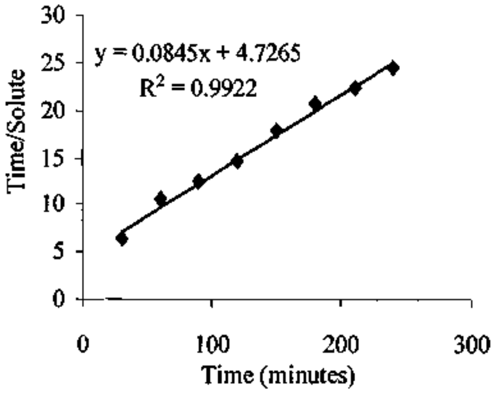
$$\frac{t}{SG_t} = \frac{1+\beta t}{\beta SG_\infty}$$

$$\frac{t}{SG_t} = \frac{1}{\beta SG_\infty} + \frac{t}{SG_\infty}$$

$$\frac{t}{SG_t} = \frac{1}{SG_\infty}(t) + \frac{1}{\beta SG_\infty}$$

It is an equation of straight line between t and $\left(\frac{t}{SG_t}\right)$

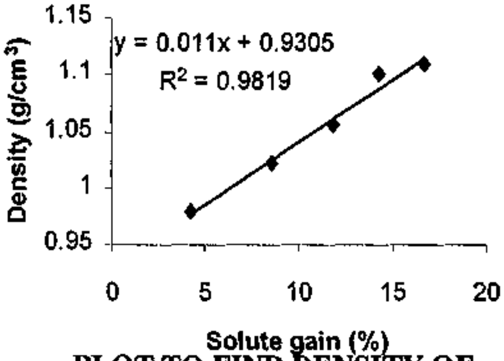
Where $SG_\infty = \frac{1}{Slope}$



PLOT TO FIND SOLUTE GAIN AT INFINITE TIME

STEP-II: Find density of Carrot cubes at infinite time

Plot a graph between density and solute gain (%), which would be a straight line.



PLOT TO FIND DENSITY OF FRUIT AT INFINITE TIME

ρ_∞ = Density of fruit at infinite time = slope of line*solute gain (%) at infinite time +

Intercept on density axis

STEP-III

Volumetric solute conc. in fruit at infinite time $= C_{\infty}^{Carrots} = \dfrac{SG_{\infty}}{Density} = \dfrac{C_{\infty}^{S}}{\rho_{\infty}}$

STEP-IV: Similarly plot a graph between time and time/(conc of solution)

And find Volumetric conc. of solution at infinite time (C_{∞}^{S}) as (1/slope of line).

STEP-IV: Find the value of m (partition coefficient)

$$C_{\infty}^{L} = mC_{\infty}^{S}$$

$$m = \frac{C_{\infty}^{L}}{C_{\infty}^{S}}$$

STEP-V Find the value of α

$$\alpha = m\frac{V_L}{V_S}$$

STEP-VI Find the values of q_n

$$\tan q_n = -\alpha q_n$$

For each value of α, the values of first six roots (q_n) of equation (3) are given in Appendix-II (a)

STEP-VII Solve equation (4)

$$SGR = \frac{SG - SG_{\infty}}{SG_0 - SG_{\infty}} = \frac{C - C_e}{C_o - C_e} = \sum_{n=1}^{\infty}\frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2}\exp\left[\frac{-D_{es}q_n^2 t}{L^2}\right]$$

The equations (2) and (4) were solved for the effective diffusivity of solute (D_{es})and moisture (D_{em}) during osmotic dehydration for first six terms of the Fourier series by a computer program as given in Appendix-II (b).

Similarly solve equation (2)

$$MR = \frac{M - M_e}{M_o - M_e} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_{em} q_n^2 t}{L^2}\right]$$

Where M_t is the total amount of moisture in the carrot cubes at time t; M_{∞} is the corresponding quantity at equilibrium.

M_t = m. c. of carrot cubes at time t= Initial m.c.(%) –moisture (%) removed in time t

=Initial m.c.% (W.b) - WL/100 g FF

and M_e= Initial m.c. % (w.b) – WL at infinite time/100 g FF

Find mass concentration of solute in carrot cubes at infinite time by Azuara equation (1992) as below.

$$WL_t = \frac{\beta t WL_{\infty}}{1+\beta t}$$

$$\frac{WL_t}{t} = \frac{\beta WL_{\infty}}{1+\beta t}$$

$$\frac{t}{WL_t} = \frac{1+\beta t}{\beta WL_{\infty}}$$

$$\frac{t}{WL_t} = \frac{1}{\beta WL_{\infty}} + \frac{t}{WL_{\infty}}$$

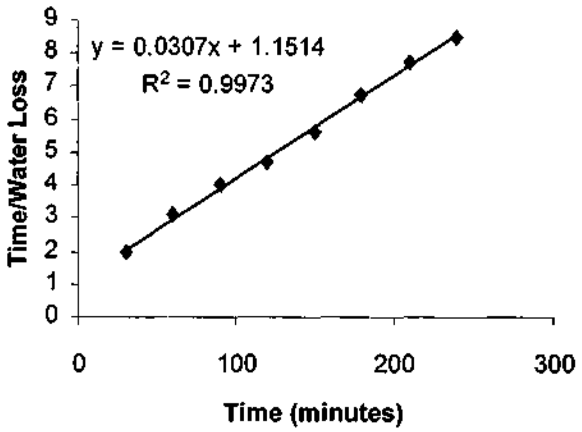
$$\frac{t}{WL_t} = \frac{1}{WL_{\infty}}(t) + \frac{1}{\beta WL_{\infty}}$$

This is an equation of straight line between t and $\left(\frac{t}{WL_t}\right)$ having

$$Slope = \frac{1}{WL_{\infty}} \quad \text{and}$$

$$Intercept = \frac{1}{\beta WL_{\infty}}$$

Therefore, to calculate WL at infinite time/100 g FF, plot a graph between time and (time/water loss) as below



TYPICAL PLOT TO FIND WATER LOSS AT INFINITE TIME

From the slope of this plot, find the value of water loss at infinite time.

Then find

M_e = m.c. (%) at infinite time = Initial m.c. (%)- WL/100 g FF at infinite time

For larger value of α

$q_n = (2n+1)\frac{\pi}{2}$ (If n starts from zero)

$q_n = (2n-1)\frac{\pi}{2}$ (If n starts from one)

Then equation (2) reduces to

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[\frac{-D_e(2n-1)^2 t}{L^2}\right]$$

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[\frac{-D_e(2n-1)^2 t}{L^2}\right] \qquad (5)$$

APPENDIX- B (i)

First six roots of equation $\tan q_n = -\alpha q_n$

α	q_1	q_2	q_3	q_4	q_5	q_6
Infinity	1.5708	4.7124	7.854	10.9956	14.1372	17.2788
9.0000	1.6385	4.7359	7.8681	11.0057	14.1451	17.2852
4.0000	1.7155	4.7648	7.8857	11.0183	14.1549	17.2933
2.3333	1.804	4.8014	7.9081	11.0344	14.1674	17.3036
1.5000	1.9071	4.849	7.9378	11.0558	14.1841	17.3173
1.0000	2.0288	4.9132	7.9787	11.0856	14.2075	17.3364
0.6667	2.1746	5.0037	8.0305	11.1296	14.2421	17.3649
0.4286	2.3521	5.1386	8.1334	11.201	14.299	17.4119
0.2500	2.5704	5.354	8.3029	11.3349	14.408	17.5034
0.1111	2.8363	5.7172	8.6587	11.6532	14.687	17.7481
0.0000	3.1416	6.2832	9.4248	12.5664	15.708	18.8496

Source : Crank (1975)

To calculate roots of equation $\tan q_n = -\alpha q_n$ at values of α other than the values given in table, following equations were developed by regression analysis.

$q_1 = 1.57141 + (0.8535 / \exp(\alpha/0.3112)) + (0.5484/ \exp(\alpha/1.416)) + (0.1656/ \exp(\alpha/9.726))$; $\chi^2=0.00004$

$q_2=4.68453+(0.9929/\exp(\alpha/0.1612))+(0.4868/\exp(\alpha/0.7189))+(0.1187/ \exp(\alpha/10.52))$; $\chi^2= 6.076\times10^{-6}$

$q_3= 7.86682+(0.9542 * \exp(-\alpha/0.1014)) + (0.4707* \exp(-\alpha/0.3646))+ (0.1331* \exp(-\alpha/2.005))$; $\chi^2= 0.00004$

$q_4=11.0035+(1.094 * \exp(-\alpha/0.08243)) + (0.3908* \exp(-\alpha/0.3832))+ (0.07801* \exp(-\alpha/2.746))$; $\chi^2=0.00001$

$q_5=14.14386+(1.137 * \exp(-\alpha/0.06799)) + (0.3579* \exp(-\alpha/0.3342))+ (0.06891* \exp(-\alpha/2.212))$; $\chi^2=9.2789\times10^{-6}$

$q_6= 17.2858+(1.087 * \exp(-\alpha/0.5424)) + (0.3886* \exp(-\alpha/0.2308))+ (0.08849* \exp(-\alpha/1.478))$; $\chi^2=7.2032\times10^{-6}$

APPENDIX- B (ii)

Computer program used for calculation of effective diffusivities for osmotic dehydration by using equation for value of n=6 only for positive valus of D (m^2/s).

$$MR = \frac{M - M_e}{M_o - M_e} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_e q_n^2 t}{L^2}\right]$$

```
#include <iostream.h>

#include<conio.h>
#include<math.h>
void main()
{
long double D,p,m,L,t,a, alfa ,Z,q,B,X,A,M,q1,B1,A1;
 cout<<"\n\nplease give the value of moisture ratio  (m) = ";
 cin>>m;
 cout<<"\nplease give the value of half length (L) in cm =";
 cin>>L;
  cout<<"\nplease give the value of time (t) in minute=";
 cin>>t;
 cout<<"\nplease give the value of alfa =";
 cin>>alfa;
 cout<<"\nplease give the value of n=";
 cin>>a;
  q1=1.57141 + (0.8535 / exp(alfa/0.3112)) + (0.5484/ exp(alfa/1.416))+ (0.1656/
exp(alfa/9.726));
  A1= (2*alfa*(1+alfa))/(1+alfa+(alfa*alfa*q1*q1));
  B1 =(t*q1*q1)/(L*L);
  D=-log(m/A1)/B1;
 AV:
 X=0;
 for(p=1;p<=a;p++)
 {
```

```
  if(p==1) q = 1.57141 + (0.8535 / exp(alfa/0.3112)) + (0.5484/ exp(alfa/1.416))+
(0.1656/ exp(alfa/9.726));
  if(p==2)q=4.68453+(0.9929/exp(alfa/0.1612))+(0.4868/exp(alfa/0.7189))+(0.1187/
exp(alfa/10.52));
  if(p==3) q= 7.86682+(0.9542 * exp(-alfa/0.1014)) + (0.4707* exp(-alfa/0.3646))+
(0.1331* exp(-alfa/2.005));
  if(p==4) q=11.0035+(1.094 * exp(-alfa/0.08243)) + (0.3908* exp(-alfa/0.3832))+
(0.07801* exp(-alfa/2.746));
  if(p==5) q=14.14386+(1.137 * exp(-alfa/0.06799)) + (0.3579* exp(-alfa/0.3342))+
(0.06891* exp(-alfa/2.212));
  if(p==6) q= 17.2858+(1.087 * exp(-alfa/0.5424)) + (0.3886* exp(-alfa/0.2308))+
(0.08849* exp(-alfa/1.478));
 A=(2*alfa *(1+alfa))/(1+alfa+(alfa*alfa*q*q));
 B=((q*q*t)/(L*L));
 Z=A*exp(-(D*B));
 X=X+Z;
 }
                M=X-m;
                if(M>= 0.0000001)
                 {
                 D=D+(D/1000);
                 goto AV;
                  }
        cout<<"\t\n\n** Value of the diffusivity is="<<D<<endl;
         cout<< "\t\n\** Value of final diffusivity in m^2/s is "<< D/600000<<endl;
        cout<<"\t\n\n** Measured MR=\t"<<X;
          cout<<"\t\n\n **and The difference between the given MR and measured MR ";
          cout<<" \n is=  "<<M;
          getche();
         }
```

APPENDIX-C

Date of Experiment:

Wt of EPD : W_1 (g)

Wt of PD+ FF: W_2 (g)

Wt of PD+DF: W_3 (g)

Temperature of Solution:

Solution to Fruit ratio:

Initial dry matter (%) of FF (A) $= \frac{(W_3 - W_1)}{(W_2 - W_1)} * 100$

Type of S	Conc	Time	Wt of FF **(B)**	t_i	t_o	Wt of EPD **(C)**	Wt of PD+F **(D)**	Wt of EPF **(E)**	Wt of PF+F **(G)**	Wt of PD+ DF **(H)**	Wt of PD+ DF **(I)**	Wt of F in PD **(J)**= $D - C$	Wt of F in PS **(K)**= $G - E$	Wt of F AOD **(L)**=J+K	Wt loss **(M)**= $L - B$	DM of F BOD **(N)**= B*A

Continued…

% DM of F AOD **(P)**= $\frac{(I - D)}{(D - C)} * 100$	Total DM of F AOD **(Q)**= $\frac{D * L}{100}$	SG **(R)** $= Q - N$	WL=Wt loss+SG **(T)**= M+R	WL/100g FF **(U)**= $\frac{T}{B} * 100$	SG/100g FF **(V)**= $\frac{R}{B} * 100$	Wt of F ACD **(W)** $= H - E$	Ratio Of F ACD **(X)**= $\frac{W}{K}$	Wt of F in PD ACD **(Y)**= $\frac{J}{X}$	Wt of OCD F **(Z)** =W+Y	Drying Ratio **DR**= $\frac{B}{Z}$

Where: F= Fruit; FF=Fresh Fruit; S=Solution; EPD = Empty petridish; PD= Petridish; DF= Dry fruit; AOD= After Osmotic Dehydration; BOD= Before Osmotic Dehydration; ACD= After Convective Dehydration; OCD= Osmo-Convective dehydration; t_i = Initial time at which fruit was place in osmotic solution; t_o = Final time at which fruit was taken out from osmotic solution.

APPENDIX -D

Computer Program in C++ to calculate effective diffusivity for convective dehydration by using equation only for positive values of D (m^2/s).

$$\frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \exp\left[\frac{-(2n+1)^2 \pi^2 D_e t}{4L^2}\right]$$

Where $(M_t-M_e)/(M_o-M_e)$ was converted simply to (M_t/M_o)

```
#include <iostream.h>
#include<conio.h>
#include<math.h>
main()
{
long double D,n,m,L,t,Z=0,A,B,X,N,e=0,q;
cout<<"\n***OPTIMZED EFFICTIVE DIFFUSIVITY CALCULATION FOR CONVECTIVE DRYING**";
cout<<"\n\n please give the value of moisture ratio= ";
cin>>m;
cout<<"\n**please give the value of half length in centimeter =";
cin>>L;
cout<<"\n**please give the value of time in minutes=";
cin>>t;
cout<<"\n***Please give the value of n=";
cin>>e;
D=(-0.405284734*L*L*log(1.23370055*m))/t;
AV:
X=0;
for(n=0;n<=e;n++)
 {
        A= (pow((2*n + 1),-2));
        q= (2*n+1)*(2*n+1)*(3.141592654*3.141592654*0.25);
        B= q*D*t/(L*L);
 Z= 0.810569469*A*exp (-B);
 X=X+Z;
 }
```

```
N=X-m;
      if(N>=0.000000001)
{
     D=D+(D/1000);
     goto AV;
}
     cout<<"\t\n\n** Value of the optimized difusivity is="<<D;
cout<<"\t\n\n** Measured MR using D=\t"<<D<<"is="<<X;
cout<<"\n\n **The Value of final diffusivity is"<< D/600000;
cout<<"\t\n\n **and The difference between the given MR and measured MR "<<N;
cout<<"\n\n\t******************* THANKS**********************";
getche();
     }
```

APPENDIX- E

Values of water activity in sulphuric acid solutions of various temperatures

H_2SO_4 Conc. (%)	Temperature			
	10°C	25°C	40°C	50°C
5	0.9804	0.9807	0.9811	0.9814
10	0.9554	0.956	0.9566	0.957
15	0.923	0.9241	0.9253	0.9261
20	0.8779	0.8805	0.8829	0.8848
25	0.8183	0.8235	0.8284	0.8317
30	0.7429	0.7521	0.7601	0.7655
35	0.6514	0.6621	0.6756	0.6846
40	0.548	0.5656	0.5811	0.5914
45	0.4389	0.4584	0.4768	0.4891
50	0.3307	0.3509	0.3703	0.3827
55	0.2317	0.2502	0.2685	0.2807
60	0.1471	0.1628	0.1783	0.1887
65	0.0821	0.0933	0.1054	0.1135
70	0.0377	0.0445	0.0523	0.0575
75	0.0142	0.0177	0.022	0.0249
80	0.0039	0.0053	0.0072	0.0085

SOURCE: Reug M (1980) Lebensm Wiss. U. Technol. 13: 22-24

APPENDIX-F

Data of osmotic dehydration kinetics of carrot cubes in solutions of salt, sugar and sugar-salt mixture

(a)Salt

	(I) Conc. =10%; Temp=45°C; R=4				(II) Conc.=10%; Temp=45°C; R=5				(III) Conc. =10%; Temp=45°C; R=6			
Time (min)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)
10	10.69903	3.398142	8.918967	9.697733	9.456907	2.733191	10.18602	6.56755	8.620803	2.6256	6.798267	8.4478
25	14.49351	4.350176	7.224733	6.89325	12.58788	3.419803	7.968617	4.421544	12.26803	3.810323	5.66275	7.655067
40	15.95527	4.746484	5.97115	5.491133	14.9853	4.25678	9.151767	4.338117	15.40107	4.145142	4.95878	6.024583
60	17.01125	5.069286	5.015333	4.548867	15.36247	4.428531	7.024283	3.203517	16.0892	5.073286	4.867517	5.98856
90	17.39216	5.687452	3.684033	5.799017	15.96251	4.877334	6.61965	2.8336	16.24306	4.918035	3.3591	5.7582
120	17.4658	5.66406	2.8189	4.165317	16.21345	4.99898	7.401433	2.309733	16.67382	5.089758	2.792117	3.899658
150	17.5958	5.600546	2.339183	3.015217	16.22565	5.245235	6.2401	2.236183	16.23214	4.922619	2.01045	0.973352
180	16.60486	5.647532	1.521472	2.6998	15.93524	5.35698	3.232883	2.06195	16.43891	4.910088	1.757767	0.746057
210	16.8956	5.606997	1.393882	2.173767	15.72637	5.41568	2.3978	1.875033	15.71737	4.911125	1.283855	2.4374
240	16.25421	5.612011	1.058653	1.915983	15.78548	5.43542	2.175283	1.675617	15.87458	4.911243	1.16355	2.133167

	(IV) Conc. =10%;Temp=55°C; R=5				(V) Conc.=10%; Temp=35°C; R=5				(VI) Conc.=15%; Temp=35°C; R=4			
Time (min)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)
10	8.593447	2.12452	10.39282	5.74587	9.199607	2.393325	9.017267	4.767383	9.196678	3.322552	6.755	3.927633
25	11.01245	2.587588	7.136333	6.33256	11.87886	3.12545	6.400217	3.318667	12.87585	4.56998	5.674433	3.06255
40	11.9875	3.254521	5.535033	6.1795	13.5875	3.819162	5.75	3.20485	14.78988	5.928856	5.0815	3.405433
60	12.45687	3.758568	4.114217	6.14587	15.37029	4.54785	6.146633	3.2809	16.10618	6.330746	4.4453	2.66275
90	13.14523	3.878589	3.252367	5.01254	16.47024	5.455545	7.869467	4.201417	17.17773	7.425585	3.89495	2.805483
120	12.88785	3.74587	2.282917	3.60735	16.54756	5.67854	6.935583	4.161067	16.98998	7.636524	2.767533	2.3257
150	12.25181	3.715546	1.568357	2.75515	16.55546	5.555478	5.6863	2.80915	16.84903	7.77989	2.13065	2.0032
180	12.15875	3.523624	1.279133	1.8032	16.58786	5.438107	5.491333	2.064833	16.569	7.858696	1.652473	1.742283
210	11.87887	3.125252	1.028693	1.212545	15.87858	5.388785	2.1479	1.689217	16.299	8.033177	1.327495	1.655887
240	11.53985	3.023654	0.834508	0.8462	15.77457	5.34954	1.79305	1.426928	16.21987	8.034125	1.140458	1.44977

	(VII) Conc. =15%;Temp=35°C; R=6				(VIII) Conc.=15%;Temp=45°C; R=5				(IX) C=15%; Temp =55°C; R=4			
Time (min)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	9.150406	2.945155	8.518433	4.597517	9.457977	3.25647	7.869917	6.338017	9.221155	2.742282	10.15318	7.958417
25	10.75061	3.455859	4.807167	2.5513	12.87586	4.356254	6.218783	4.696267	11.43647	3.256987	6.50205	4.5706
40	13.81858	4.456998	5.587683	2.71895	14.01879	5.012524	4.823933	4.06605	13.25545	4.566856	6.038483	6.760217
60	14.56889	4.834237	4.393683	2.166933	15.55421	5.78989	4.389767	4.029233	13.93827	5.125452	4.751367	7.777713
90	15.8859	5.77171	4.1822	2.227067	16.66805	6.54235	3.8548	4.389983	13.88789	5.088989	3.12675	7.387467
120	16.81684	5.895789	4.88715	1.771917	17.0727	6.785847	2.61055	4.415133	12.8887	4.415763	1.8514	2.022333
150	16.8899	6.159634	4.168467	1.614522	16.75456	6.69689	2.371667	3.127183	11.98998	4.35265	1.21829	1.548628
180	16.94444	6.60396	3.678233	1.71655	15.89889	6.657468	1.582348	2.490117	11.85699	4.222365	0.986967	1.182095
210	16.89756	7.021255	2.999783	1.986917	15.50784	6.565854	1.241495	1.944633	11.7589	4.199898	0.828578	0.998283
240	15.61774	6.561132	1.442507	1.254712	15.10255	6.487117	0.997315	1.586373	11.65687	4.102235	0.709538	0.819473

	(X) Conc.=15%; Temp=55°C; R=6				(XI) Conc.=5%; Temp= 45°C; R=5				(XII) Conc.=5%; Temp=55°C; R=4			
Time (min)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	9.942021	2.89989	10.97823	7.636533	6.255694	1.067626	4.961217	8.012549	8.657898	0.785875	10.12268	21.857
25	12.02553	3.889589	6.661183	5.6184	8.78598	1.088798	3.871883	7.256984	11.01161	0.885989	6.777083	12.66467
40	13.25564	4.756698	5.310633	5.75355	10.15485	1.09998	3.261067	5.425083	11.33306	0.912547	4.533567	8.909433
60	15.30205	5.852116	5.630333	10.48723	12.27596	1.192217	3.3593	4.563333	12.78599	0.954524	4.152467	7.474017
90	14.54879	5.452337	3.1107	4.13875	13.57587	1.29086	2.9635	4.096733	13.25489	0.965899	3.091483	5.39385
120	13.85665	4.927191	2.004483	2.128317	13.85674	1.291025	2.3743	3.074333	12.9857	0.958657	2.173117	3.8414
150	13.32252	4.433135	1.435518	1.271885	14.06727	1.125423	1.99985	1.539448	12.68568	0.854626	1.6232	1.8618
180	12.65667	4.233252	1.04714	0.94696	13.75456	1.098989	1.54481	1.202688	11.99898	0.756895	1.161607	1.101553
210	12.58557	3.846314	0.885052	0.652582	12.89885	1.087889	1.094177	1.003682	11.78858	0.689589	0.951518	0.756562
240	12.32542	3.801102	0.73583	0.556438	12.56989	0.998988	0.892867	0.712112	11.65425	0.622793	0.808987	0.52993

	(XIII) Conc.=5%; Temp=55°C; R=6				(XIV) Conc.=5%; Temp=35°C; R=4				(XV) Conc.=5%; Temp=35°C; R=6			
Time (min)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)
10	10.23652	0.785988	8.97785	9.908067	9.415818	0.652348	6.7657	7.561483	6.570658	0.689589	3.7706	3.779167
25	12.12549	0.89989	5.074583	5.24405	12.31365	0.785898	4.761417	4.474667	10.12542	0.898959	3.5904	2.56195
40	14.25452	0.999899	4.55375	4.136083	13.78545	0.923652	3.84815	4.039333	12.13513	1.102355	3.286633	2.42465
60	15.87889	1.005898	4.022583	2.795717	14.86457	0.985745	3.091067	3.17215	13.69944	1.372249	2.8962	2.598067
90	17.12021	1.258989	3.405067	3.484167	17.48282	1.215479	3.400183	4.4472	15.22049	1.89899	2.546333	5.195083
120	16.89752	1.354544	2.439267	3.646117	17.35658	1.269265	2.479383	4.706167	15.68998	1.97854	2.091033	6.7034
150	15.98998	1.268956	1.64185	2.153217	16.5745	1.215267	1.689267	2.665617	16.68755	1.911083	2.063533	3.271767
175	15.75237	1.125999	1.310655	1.23321	15.87599	1.161458	1.23372	1.78295	15.89998	1.875899	1.45232	2.39305
210	15.45258	1.025699	1.06522	0.836038	15.75869	1.121254	1.035075	1.334167	15.45875	1.79899	1.14213	1.65173
240	15.29857	0.961254	0.907273	0.63055	15.60489	1.099899	0.880842	1.09227	15.25365	1.689589	0.960897	1.138038

(b) Sugar

	(I) Conc.=50°B; Temp= 35°C; R=5				(II) Conc.=50°C; Temp=45°C; R=4				(III) Conc.=50°C; Temp=45°C; R=5			
Time (min)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)	Water loss	Solute gain	D_{ew}x10^{-9} (m^2/s)	D_{es}x10^{-9} (m^2/s)
15	9.56874	2.756854	1.838267	1.169772	10.22542	2.25543	1.537312	0.871233	10.12422	2.8998	1.39118	1.256025
30	15.2456	4.643308	2.311917	1.627015	12.5764	4.335928	1.152522	1.259773	16.56432	4.675575	1.81435	1.592548
60	19.12548	5.715592	1.835933	1.231915	18.02134	6.421273	1.17699	1.377665	21.56872	5.87865	1.544897	1.25356
90	22.33579	7.284773	1.719967	1.35361	21.96632	6.620055	1.17523	0.9774	24.92613	6.88795	1.382012	1.152342
120	25.42534	8.211153	1.779933	1.325738	23.89795	7.492184	1.053747	0.946765	26.43469	7.77895	1.178143	1.11817
150	26.78477	8.421352	1.654113	1.125803	26.24252	8.154367	1.0389	0.909642	28.95938	8.44889	1.16298	1.077315
180	26.81303	8.729273	1.38288	1.024145	27.3125	8.619903	0.951253	0.85916	31.12354	9.105194	1.163015	1.07646
210	27.25098	9.458044	1.245708	1.086315	28.98674	9.53101	0.945952	0.94034	32.98441	9.295437	1.17391	0.973307
240	28.32392	9.785462	1.243372	1.051627	30.58015	10.42381	0.957738	1.059273	33.58246	10.00353	1.084472	1.04738

	(IV) Conc.=50°B; Temp=45°C; R=6				(V) Conc.=50°B; Temp=55°C; R=5				(VI) Conc.=55°B; Temp=55°C; R=4			
Time (min)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
15	8.816288	2.306593	0.94987	0.847182	11.81915	3.109043	0.88355	1.122807	14.1254	2.57895	0.824018	0.833357
30	13.04606	4.670614	0.998668	1.62342	18.8854	4.89895	1.091647	1.346612	19.3577	3.124562	0.642562	0.486415
60	19.16571	5.094286	1.051332	0.961393	27.36149	5.997265	1.125823	0.999377	32.27627	4.614763	0.867518	0.514837
90	21.66541	6.237644	0.891348	0.95479	33.69343	7.88995	1.137855	1.151507	41.17028	5.83563	0.937302	0.542785
120	25.37664	6.920268	0.918348	0.882307	37.84674	8.7854	1.08823	1.081327	44.84629	7.022545	0.835738	0.586812
150	29.91134	8.187692	1.045477	1.008262	43.84761	9.889565	1.21628	1.127322	53.65012	7.908493	0.979165	0.59534
180	31.37931	9.32543	0.973288	1.145777	44.8965	10.03785	1.074635	0.973158	54.23307	9.613404	0.836032	0.744865
210	31.72507	9.425687	0.856327	1.009888	45.8985	10.34167	0.974573	0.896873	57.81715	9.676653	0.831462	0.647657
240	35.00417	9.431367	0.81021	0.885058	46.45144	11.7558	0.879985	1.119138	59.79116	10.78546	0.789857	0.725637

	(VII) Conc.=55°B;Temp=55°C; R=6				(VIII) Conc.=55°B; Temp=45°C; R=5				(IX) Conc.=55°B; Temp=35°C; R=4			
Time (min)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
15	18.4526	2.1875	1.2573	0.9676	12.8940	1.6063	0.880755	1.3508	12.0125	1.08547	1.177932	1.10930
30	26.2547	2.7556	1.2383	0.7512	18.7581	2.3283	0.907855	1.3902	16.3281	1.7497	1.069673	1.40531
60	30.1129	3.3364	0.8082	0.5426	29.7420	2.7554	1.118155	1.1875	20.4572	2.7055	0.83092	1.66601
90	35.2632	3.9998	0.7338	0.5142	34.2465	4.3774	0.986808	1.1478	27.5194	3.0619	1.429672	1.46773
120	45.0954	4.9762	0.8990	0.5909	38.6077	4.2401	0.944255	1.1588	32.7754	3.0921	1.277088	1.16854
150	50.6678	6.1022	0.9182	0.7110	43.0767	4.7260	0.954167	1.1325	35.5023	3.1785	1.266692	9.55825
180	56.2236	6.7566	0.9670	0.7327	45.7400	4.7752	0.909828	1.0133	38.9065	3.2109	1.229158	1.01087
210	59.9696	7.3566	0.9708	0.7571	48.5050	5.8792	0.89647	0.9254	41.2714	3.5622	0.977807	1.17628
240	62.3365	8.1022	0.9410	0.8342	52.7010	5.0489	0.76856	0.8739	40.1261	3.9998	0.855808	1.26607

Time (min)	(X) Conc.=55°B; Temp=35°C; R=6				(XI) Conc.=45°B; Temp=45°C; R=5				(XII) Conc.=45°B; Temp=55°C; R=4			
	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
15	13.44669	2.160846	1.656658	2.0337	9.519068	1.998898	0.868715	0.905687	14.25421	2.38989	0.973497	0.794957
30	18.4356	2.661372	1.531582	1.527724	16.39349	3.498986	1.218045	1.312913	17.92278	3.758959	0.758357	0.797292
60	27.5687	3.298556	1.701533	1.164403	22.89756	5.307109	1.165183	1.480298	28.10994	5.124364	0.918738	0.731955
90	30.51786	3.422258	1.40094	0.834928	26.24351	5.693101	1.016932	1.136203	36.75631	6.755688	1.049718	0.846387
120	32.47786	3.668556	1.201983	0.719025	31.0278	6.834253	1.075843	1.252902	40.56425	7.875967	0.966057	0.867558
150	36.08679	4.687155	1.225483	0.957412	32.34419	7.3047	0.941172	1.167322	45.17793	8.861231	0.977748	0.891838
180	39.46974	5.108908	1.288148	0.970673	35.80774	7.556614	0.988013	1.055675	49.61568	9.599109	1.016112	0.890283
210	40.875	5.84445	1.222327	1.181853	37.57427	7.908415	0.953152	1.016033	50.22322	9.437329	0.897848	0.733665
240	41.40224	6.077109	1.11012	1.166092	40.0951	8.292678	0.992643	1.013452	51.12254	10.54275	0.82201	0.841035

Time (min)	(XIII)Conc.=45°B;Temp=55°C; R=6				(XIV) Conc.=45°B;Temp=35°C; R=4				(XV) Conc.=45°B; Temp=35°C; R=6			
	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
15	12.50509	2.502145	0.852348	0.888875	13.87255	1.79133	1.343842	3.534187	11.1254	0.998755	0.825062	0.825487
30	21.81534	3.866557	1.081977	1.014902	18.78735	2.030595	1.206475	2.259333	18.65284	1.803248	1.083237	1.307257
60	31.22977	4.289634	1.086217	0.619925	25.53467	2.57648	1.098402	1.820767	28.57843	2.460585	1.255947	1.206078
90	37.56237	5.442236	1.043523	0.656047	32.97286	2.96248	1.221533	1.6318	34.54672	2.98	1.228475	1.183943
120	44.30689	6.55836	1.101125	0.710885	39.91768	3.792021	1.384338	2.308067	39.60356	3.33552	1.234753	1.12563
150	48.09203	7.556855	1.055413	0.757275	41.98564	3.8557	1.248583	1.95175	42.40647	3.55226	1.155325	1.035022
180	52.23546	8.12548	1.070135	0.735503	43.47682	3.782939	1.135478	1.526835	43.99498	3.672396	1.052205	0.930952
210	52.78896	9.122524	0.941862	0.816765	44.561	3.835194	1.038108	1.369108	45.68756	4.137117	0.992508	1.07643
240	53.55686	10.13767	0.855142	0.932468	45.98875	3.936	0.990807	1.312713	46.52364	4.223039	0.911175	0.99788

(c) Sugar-salt mixture

	(I) Conc.=50°B+10% salt; Temp=45°C; R=4					(II) Conc.=50°B+10% Salt; Temp=45°C; R=5				
Time (min)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	15.25698	3.185786	1.528623	1.90625	1.954333	17.18621	3.210542	1.343335	2.333167	1.594855
25	23.25645	4.12548	1.528623	1.7231	1.286605	27.25468	4.587854	2.101177	2.2668	1.256785
40	30.12025	4.89898	1.528623	1.7921	1.124957	34.50861	5.42543	2.32289	2.253683	1.084083
60	36.56875	6.52365	1.528623	1.766683	1.3183	38.04864	7.254687	2.448062	1.830667	1.274258
90	43.90265	7.25236	1.528623	1.746633	1.087942	44.18757	8.45875	2.828595	1.67725	1.154058
120	47.8959	8.56986	1.528623	1.613995	1.160108	49.23564	9.254687	3.036592	1.621608	1.042322
150	51.01235	9.12212	1.528623	1.527013	1.068008	52.98789	10.25463	3.18574	1.576377	1.04255
180	52.94213	10.12548	1.528623	1.419268	1.149158	53.99899	11.45215	3.252067	1.387698	1.131562
210	53.56875	10.58756	1.528623	1.260547	1.112993	56.85746	11.99898	3.41254	1.400787	1.098548
240	54.75144	11.02542	1.528623	1.18534	0.897855	58.2366	12.45698	3.52345	1.33689	1.068217

	(III) Conc.=50°B+10% Salt; Temp=35°C; R=5					(IV) Conc.=50°B+10% Salt; Temp=55°C; R=5				
Time (min)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	15.2542	2.94226	1.284948	2.085233	2.18475	20.8789	3.372904	1.321583	2.982067	1.8863
25	24.4523	3.587854	1.53428	2.064767	1.99999	33.1274	5.8774	1.941682	2.916067	2.188417
40	31.23252	5.644963	1.85946	2.084	1.922817	39.0024	7.070582	2.227175	2.521633	1.96395
60	36.01246	6.235689	1.935874	1.849883	1.562517	42.65303	8.120254	2.322557	2.020217	1.72585
90	42.12545	7.923515	2.064514	1.7247	1.721783	52.25212	8.925879	2.654305	2.12285	1.398823
120	44.87587	9.208861	2.235251	1.497228	1.863617	56.01474	9.87989	2.68547	1.907883	1.308435
150	48.78547	9.29898	2.312916	1.479642	1.514558	58.31754	10.89758	2.718638	1.71465	1.320414
180	50.21452	9.39898	2.451376	1.336078	1.314793	61.65165	11.69878	2.72874	1.714517	1.330352
210	52.45678	9.549577	2.546245	1.305667	1.179763	61.7958	12.25469	2.694866	1.482135	1.311028
240	55.24569	9.98789	2.622288	1.370705	1.185968	63.04807	12.7854	2.69878	1.4003	1.328943

Time (min)	(V) Conc.=50°B+10%; Temp=45°C; R=6					(VI) Conc=50°B+10% Salt; Temp=45°C; R=6				
	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	17.61466	3.9999	1.226469	2.039933	2.221567	20.4847	3.255783	2.435702	2.760233	1.54819
25	29.9989	4.85969	1.793945	2.269833	1.288222	32.15621	4.856876	2.462108	2.6377	1.425455
40	37.58968	6.367185	2.16095	2.208417	1.357387	37.29872	5.594461	2.966798	2.208233	1.496589
60	41.85017	7.7898	2.202402	1.8291	1.342247	45.11132	7.998989	3.086096	2.172583	1.456042
90	48.18092	8.9998	2.34665	1.642858	1.195615	53.21808	8.98986	3.18574	2.105833	1.2281
120	52.96055	9.99899	2.626584	1.532042	1.11686	56.34202	9.569899	3.230537	1.8278	1.049393
150	58.56329	10.9998	2.66847	1.594347	1.103905	59.06979	11.01021	3.27658	1.67025	1.144327
180	59.74217	11.75898	2.764428	1.407528	1.07905	61.24128	11.98989	3.3758	1.555733	1.176752
210	61.71031	12.78598	2.769133	1.466723	1.156542	62.81	12.23125	3.415909	1.454052	1.063713
240	63.40353	13.56365	2.408135	0.698552	1.216087	64.18636	13.02124	2.999737	1.380067	1.021458

Time (min)	(VII) Conc. =50°B+5% Salt; Temp=45°C; R=5					(VIII) Conc.=50°B+15% salt; Temp=55°C; R=4				
	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	15.62293	3.027514	0.84102	2.260283	1.77205	19.01232	5.688066	2.051395	2.654617	4.6016
25	24.35563	3.85698	1.139365	2.120183	1.121774	27.23652	7.56895	2.809208	2.1331	3.22955
40	30.25832	4.9998	1.2547	2.0268	1.155905	37.67647	8.86887	3.425248	2.542483	2.78185
60	36.02195	6.568587	1.324587	1.91905	1.313125	44.52775	10.01254	3.717924	2.41395	2.404317
90	42.29235	7.56368	1.457913	1.8108	1.160273	49.25634	11.25432	3.795487	2.033383	2.10575
120	45.16095	8.89898	1.582819	1.586692	1.225467	53.85647	12.12542	4.035479	1.925633	1.922667
150	47.06221	9.56985	1.649758	1.409403	1.160327	56.16489	12.86985	4.236872	1.742983	1.841033
180	48.27596	10.12365	1.833274	1.257435	1.10509	57.52364	13.12523	4.317914	1.569497	1.640247
210	52.09123	10.65868	1.789842	1.352747	1.08476	58.90525	13.58696	4.603059	1.462258	1.602668
240	55.21354	11.12124	1.581439	1.47156	1.073015	59.54235	13.98989	4.527232	1.333231	1.59821

	(IX)Conc.= 50°B+15% salt;Temp =55°C; R=6					(X) Conc.=50°B+15%; Temp=55°C; R=4				
Time (min)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	21.14884	6.012542	1.949366	3.055883	5.087133	18.2569	4.432161	1.965955	2.785767	3.04975
25	31.69665	9.12543	2.599951	2.673833	4.649117	26.5689	5.012546	2.599567	2.311783	1.5484
40	40.27726	9.580208	3.379909	2.692667	3.218167	33.47589	6.53687	2.691629	2.283667	1.626712
60	46.74559	11.00207	3.592194	2.4584	2.919017	40.37712	7.965055	2.969056	2.2486	1.607987
90	51.25556	12.01224	3.963434	2.02505	2.424133	47.06468	8.957883	3.06928	2.136317	1.366113
120	55.87659	12.96598	4.15786	1.894467	2.266967	49.55502	9.35326	3.374645	1.832983	1.124072
150	59.4544	13.10212	3.849172	1.81845	1.875983	52.87564	10.86975	3.548955	1.7712	1.272021
180	62.0012	13.78589	3.600292	1.749983	1.880067	53.6875	11.48127	3.59874	1.550855	1.222215
210	62.78588	13.98999	3.982983	1.573702	1.714283	55.4587	12.21524	3.711615	1.490477	1.25391
240	62.9998	14.56325	3.98547	1.395655	6.7365	55.8978	12.89589	3.596526	1.344408	1.322593

	(XI)Conc.=50°B+15% Salt; Temp=35°C; R=6					(XII)Conc. =50°B+5% Salt;Temp =55°C;R=4				
Time (min)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	20.64783	4.87569	2.64671	3.589433	3.567717	16.12522	3.347811	0.849287	1.779617	2.634917
25	29.9989	5.785973	2.150252	2.968217	1.9877	27.00626	4.21223	1.081962	1.911767	1.639753
40	37.23206	7.219764	3.095589	2.85895	1.9135	35.35444	5.12525	1.489026	2.025367	1.499995
60	42.18335	8.850018	3.025846	2.488133	1.920983	38.90555	5.99898	1.65247	1.634115	1.363337
90	48.04145	9.35645	3.161785	2.25435	1.439418	47.29432	6.89656	1.812269	1.642883	1.203367
120	52.56273	10.63532	3.700073	2.169717	1.434678	52.5689	7.89885	2.199927	15.7599	1.202337
150	54.44828	11.07479	3.365087	1.94245	1.264692	57.56874	8.85657	1.98754	1.60436	1.253402
180	55.89567	11.87564	3.369874	1.778017	1.262705	58.25635	9.52325	1.85478	1.384267	1.261177
210	56.5647	12.78989	3.374479	1.595965	1.350383	59.8989	9.99989	1.717519	1.291333	1.24538
240	56.99898	13.7568	4.133139	1.440577	1.565922	60.89895	10.25634	1.71254	1.1931	1.182162

Time (min)	(XIII) Conc. =50°B+5% Salt; Temp =55°C; R=6					(XIV) Conc. =50°B+5% Salt; Temp =35°C;R=4				
	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	16.99696	3.89658	0.769068	1.989067	2.6991	13.23489	2.75689	0.858831	1.618365	2.08335
25	29.62409	4.98998	1.055868	2.311433	1.7353	22.51689	3.025648	1.053944	1.7869	0.995153
40	36.64099	5.754568	1.365478	2.192967	1.430417	28.97681	5.125468	1.315624	1.826267	1.723317
60	43.86597	6.8989	1.40256	2.110667	1.360777	34.38305	6.012356	1.332564	1.713	1.576132
90	49.03065	8.23652	1.590545	1.79515	1.296247	41.16939	7.10212	1.387243	1.671567	1.48328
120	54.21542	9.78587	1.780226	1.715667	1.416142	45.98059	8.569667	1.500252	1.625693	1.721667
150	58.49448	10.36526	1.926901	1.693233	1.301157	47.85687	9.001201	1.632349	1.442172	1.573415
180	59.87568	10.89658	1.938602	1.515118	1.234445	48.96447	9.102021	1.542529	1.279222	1.353878
210	60.99898	11.2012	1.954255	1.380575	1.142418	51.54941	9.002531	1.41254	1.275642	1.12434
240	62.12524	12.1202	1.695077	1.288062	1.28412	52.80576	9.201254	1.507664	1.208007	1.048428

Time (min)	(XV) Conc. =50°B+5% Salt; Temp =35°C; R=6				
	Water loss	Solute gain	Salt gain	$D_{ew}x10^{-9}$ (m^2/s)	$D_{es}x10^{-9}$ (m^2/s)
10	16.58645	2.423808	0.772686	2.414617	1.280838
25	25.56856	3.125214	0.994641	2.220417	0.823857
40	32.8657	4.241253	1.136263	2.272783	0.923097
60	37.8546	5.125465	1.312104	2.021483	0.88775
90	43.56878	6.850306	1.332769	1.831783	0.784377
120	46.089	7.822333	1.477244	1.569692	1.028903
150	49.58964	8.241256	1.43567	1.517683	0.918661
180	51.58978	8.99898	1.41594	1.41698	0.933003
210	53.56858	9.65852	1.32564	1.367318	0.948615
240	55.98957	10.25347	1.280194	1.406865	0.97245

APPENDIX-G

Statistical parameters for effective diffusivity of water and solute

(a) For salt as osmotic agent

NO	Conc (%)	Temp (°C)	R	Moisture Ratio				Solute Gain Ratio			
				Resi_Sq	E%	RMSE	D (m^2/s)	RESI_SQ	%	RMSE	D (m^2/S)
I	10	45	4	1.89E-7	0.032	0.0001	3.994E-9	2.17E-7	0.0322	0.0001	4.640E-9
II	10	45	5	9.54E-8	0.018	9E-05	6.239E-9	2.93E-7	0.0468	0.0002	3.130E-9
III	10	45	6	1.38E-7	0.024	0.0001	3.032E-9	1.91E-7	0.0574	0.0001	5.941E-9
IV	10	55	5	5.96E-7	0.094	0.0002	3.742E-9	3.14E-7	0.0494	0.0002	5.485E-9
V	10	35	5	3.22E-7	0.035	0.0001	5.723E-9	1.35E-7	0.0217	0.0001	3.092E-09
VI	15	35	4	1.36E-7	0.022	0.0001	3.487E-9	2.16E-7	0.0375	0.0001	2.504E-9
VII	15	35	6	1.48E-7	0.022	0.0001	4.466E-9	3.37E-7	0.0543	0.0002	2.260E-9
VIII	15	45	5	2.22E-7	0.036	0.0001	3.596E-9	1.79E-7	0.0313	0.0001	3.708E-9
IX	15	55	4	8.47E-6	0.147	0.0009	3.545E-9	3.94E-7	0.0714	0.0002	4.102E-9
X	15	55	6	6.52E-7	0.089	0.0002	3.779E-9	4.77E-7	0.0699	0.0002	3.919E-9
XI	5	45	5	3.48E-7	0.049	0.0001	2.632E-9	5.88E-7	0.0856	0.0002	5.015E-9
XII	5	55	4	5.89E-7	0.086	0.0002	3.539E-9	2.72E-7	0.0374	0.0001	6.439E-9
XIII	5	55	6	5.58E-7	0.088	0.0002	3.339E-9	4.45E-7	0.0561	0.0002	3.406E-9
XIV	5	35	4	4.67E-7	0.081	0.0002	2.918E-9	1.96E-7	0.0293	0.0001	3.527E-9
XV	5	35	6	4.77E-7	0.080	0.0002	2.380E-9	1.65E-7	0.0176	0.0001	3.171E-9

(b) For sugar as osmotic agent

NO	Conc (°B)	Temp (°C)	R	Moisture Ratio				Solute Gain Ratio			
				Resi Square	E%	RMSE	D (m^2/S)	Resi. Square	E%	RMSE	D (m^2/S)
I	50	35	5	3.07E-7	0.06	0.0001	1.6680E-9	4.83E-7	0.07	0.0002	1.2217E-9
II	50	45	4	4.03E-7	0.06	0.0002	1.10996E-9	3.02E-7	0.05	0.0001	1.0223E-9
III	50	45	5	4.54E-6	0.12	0.0007	1.32166E-9	4.20E-7	0.07	0.0002	1.1719E-9
IV	50	45	6	3.91E-7	0.05	0.0002	9.611E-10	4.41E-7	0.06	0.0002	1.0353E-9
V	50	55	5	4.55E-7	0.06	0.0002	1.05251E-9	3.52E-7	0.05	0.0001	1.0909E-9
VI	55	55	4	3.50E-7	0.04	0.0002	8.3818E-10	2.94E-7	0.04	0.0001	6.308E-10
VII	55	55	6	3.92E-7	0.05	0.0002	9.7044E-10	2.68E-7	0.04	0.0001	7.113E-10
VIII	55	45	5	3.72E-7	0.05	0.0002	1.9271E-9	4.32E-7	0.06	0.0002	1.2454E-9
IX	55	35	4	4.66E-7	0.07	0.0002	1.12386E-9	3.46E-7	0.05	0.0001	2.2032E-9
X	55	35	6	4.73E-7	0.08	0.0002	1.37098E-9	2.86E-7	0.04	0.0001	1.1728E-9
XI	45	45	5	3.65E-7	0.06	0.0002	1.02441E-9	4.62E-7	0.07	0.0002	1.1489E-9
XII	45	55	4	3.72E-7	0.05	0.0002	9.3112E-10	0.00028	0.27	0.0056	8.216E-10
XIII	45	55	6	4.49E-7	0.06	0.0002	1.00975E-9	2.68E-7	0.04	0.0001	7.925E-10
XIV	45	35	4	4.76E-7	0.07	0.0002	1.18529E-9	1.39E-7	0.02	0.0001	1.9683E-9
XV	45	35	6	1.72E-5	0.12	0.0014	1.08208E-9	4.39E-7	0.06	0.0002	1.0765E-9

(c) For Sugar and salt mixture as osmotic agent

NO	Conc (50°B+ Salt%)	Temp (°C)	R	Moisture Ratio				Solute Gain Ratio			
				Resi. Sq.	E(%)	RMSE	D (m^2/S)	Resi. Sq.	E(%)	RMSE	D (m^2/S)
I	10	45	4	0.0008	0.6222	0.0094	1.5941E-9	3.31E-7	0.0462	0.0001	1.2861E-9
II	10	45	5	2E-06	0.1184	0.0004	1.7685E-9	4.56E-7	0.0661	0.0002	1.1747E-9
III	10	35	5	3E-07	0.0500	0.0002	1.6798E-9	6.45E-7	0.0815	0.0002	1.572E-9
IV	10	55	5	2E-07	0.0472	0.0001	2.0782E-9	3.49E-7	0.0489	0.0002	1.5762E-9
V	10	45	6	4E-07	0.0603	0.0002	1.6119E-9	3.87E-7	0.0522	0.0002	1.3077E-9
VI	15	45	5	3E-07	0.0509	0.0002	1.9772E-9	3.04E-7	0.0446	0.0002	3.2192E-9
VII	5	45	5	0.0035	1.0467	0.0189	1.7215E-9	2.05E-6	0.1017	0.0004	1.2172E-9
VIII	15	45	4	2E-07	0.0370	0.0001	1.9811E-9	2.65E-7	0.0378	0.0001	2.3728E-9
IX	15	55	6	3E-07	0.0395	0.0001	2.1338E-9	5.45E-7	0.0473	0.0002	3.2771E-9
X	15	35	4	2E-07	0.0345	0.0001	1.9756E-9	3.59E-7	0.0465	0.0001	1.5393E-9
XI	15	35	6	3E-07	0.0482	0.0002	2.3086E-9	3.09E-7	0.0436	0.0001	1.7707E-9
XII	5	55	4	3E-07	0.0536	0.0002	3.0226E-9	3.89E-7	0.0478	0.0001	1.4486E-9
XIII	5	55	6	3E-07	0.0462	0.0001	1.7992E-9	4.22E-7	0.0598	0.0002	1.4900E-9
XIV	5	35	4	3E-07	0.0536	0.0002	1.5447E-9	5.22E-7	0.0850	0.0002	1.4683E-9
XV	5	35	6	3E-07	0.0526	0.0002	1.8039E-9	4.53E-7	0.0525	0.0002	9.5015E-10

APPENDIX - H (i)

Various regression coefficients and statistical parameters of various osmotic dehydration models with salt as an osmotic agent

(a) Page Model

Expt No	Conc (%)	Temp (°C)	R	Moisture Ratio						Solute Gain Ratio					
				K	N	R^2	χ^2	E%	RMSE	K	N	R^2		E%	RMSE
I	10	45	4	0.4674	0.3263	0.759	0.0032	33.32	0.0508	0.2702	0.5055	0.973	0.0005	42.523	0.02
II	10	45	5	0.1733	0.6931	0.976	0.0004	61.728	0.0195	0.2045	0.4832	0.99	0.0002	6.004	0.015
III	10	45	6	0.3195	0.3873	0.794	0.0043	31.524	0.0589	0.132	0.7315	0.949	0.0013	556.31	0.033
IV	10	55	5	0.6988	0.1728	0.507	0.0038	23.402	0.0557	0.4121	0.3431	0.481	0.012	101.08	0.098
V	10	35	5	0.1744	0.6392	0.961	0.0009	197.28	0.028	0.104	0.6534	0.944	0.0025	50.376	0.045
VI	15	35	4	0.3083	0.4127	0.857	0.0028	32.486	0.048	0.1289	0.5703	0.986	0.0005	12.423	0.021
VII	15	35	6	0.1836	0.5768	0.941	0.0017	59.024	0.0368	0.1258	0.5356	0.971	0.0011	17.8	0.03
VIII	15	45	5	0.3717	0.361	0.778	0.0039	38.657	0.0563	0.148	0.6047	0.965	0.0012	42.809	0.031
IX	15	55	4	0.9269	0.0975	0.153	0.0071	33.269	0.0757	0.5377	0.2471	0.347	0.0138	97.35	0.105
X	15	55	6	0.8779	0.1118	0.202	0.0067	33.324	0.0732	0.8262	0.1131	0.073	0.0223	183.38	0.133
XI	5	45	5	0.2111	0.4216	0.852	0.0042	23.269	0.0582	1.5122	0.0129	0.003	0.005	36.633	0.064
XII	5	55	4	0.663	0.1721	0.513	0.0039	22.173	0.0562	2350.3	-1.426	0.373	0.0099	50.628	0.089
XIII	5	55	6	0.4552	0.2625	0.703	0.004	25.698	0.0566	0.5329	0.2157	0.375	0.0109	55.358	0.094
XIV	5	35	4	0.3586	0.3178	0.774	0.004	27.058	0.0567	0.2379	0.4566	0.831	0.0046	79.029	0.061
XV	5	35	6	0.1756	0.4619	0.917	0.0026	19.484	0.0459	0.0529	0.7898	0.887	0.0072	214.01	0.076

For Page Model

For MR “K”=0.103683*(Conc)$^{0.100579}$ * (Temp)$^{0.101897}$*(Ratio)$^{0.100249}$

E% = 41.7062; χ^2= 0.1350; RMSE=0.3146; R^2=0.879

For MR “N”=0.087019*(Conc)$^{0.097471}$ * (Temp)$^{0.096689}$ *(Ratio)$^{0.099293}$

E%=53.0704; χ^2= 0.0867; RMSE=0.2521; R^2=0.898

For SGR “K”=0.069674*(Conc)$^{-0.15432}$ * (Temp)$^{1.5199}$ *(Ratio)$^{-2.88795}$

E%=42.2385; χ^2= 501992.9; RMSE=606.7356 R^2= 0.8542

For SGR “N”=0.006418*(Conc)$^{0.101567}$ * (Temp)$^{0.098403}$ *(Ratio)$^{0.099432}$

E%=76.5663; χ^2=0.4910; RMSE=0.6001; R^2=0.901

(b) GEM

Expt No	Conc (%)	Temp (°C)	R	Moisture Ratio						Sulute Gain Ratio					
				A	K	R^2	χ^2	E%	RMSE	A	K	R^2	χ^2	E%	RMSE
I	10	45	4	0.3523	0.0102	0.484	0.0069	43.963	0.0744	0.5229	0.0255	0.961	0.0007	49.504	0.025
II	10	45	5	0.6684	0.0462	0.978	0.0004	48.677	0.0187	0.5563	0.0129	0.956	0.0012	21.588	0.032
III	10	45	6	0.4608	0.0114	0.568	0.0091	44.434	0.0855	0.7321	0.0411	0.9511	0.0013	340.05	0.032
IV	10	55	5	0.289	0.0022	0.174	0.0065	26.357	0.0721	0.6276	0.0281	0.311	0.016	65.231	0.113
V	10	35	5	0.6318	0.0332	0.973	0.0006	75.068	0.0234	0.7348	0.0197	0.945	0.0024	47.887	0.044
VI	15	35	4	0.5186	0.017	0.689	0.0062	47.352	0.0709	0.6694	0.0141	0.953	0.0018	26.004	0.039
VII	15	35	6	0.6076	0.024	0.952	0.0014	32.964	0.0335	0.6528	0.0099	0.972	0.0011	15.254	0.03
VIII	15	45	5	0.4349	0.0117	0.566	0.0077	46.062	0.0787	0.6656	0.0225	0.964	0.0012	41.748	0.031
IX	15	55	4	0.2473	0.0001	0.001	0.0084	31.608	0.0822	0.2967	0.0032	0.095	0.0192	106.75	0.124
X	15	55	6	0.254	0.0005	0.01	0.0083	34.013	0.0815	0.2315	-0.001	0.015	0.0236	167.25	0.138
XI	5	45	5	0.5622	0.0084	0.696	0.0086	31.217	0.0833	0.175	-0.001	0.072	0.0047	35.076	0.061
XII	5	55	4	0.3108	0.0021	0.19	0.0065	26.113	0.0725	0.057	-0.008	0.636	0.005	56.312	0.068
XIII	5	55	6	0.379	0.0045	0.424	0.0077	33.599	0.0789	0.3542	0.0031	0.164	0.0146	63.224	0.108
XIV	5	35	4	0.4322	0.0061	0.543	0.0081	36.722	0.0806	0.5631	0.0153	0.778	0.006	68.605	0.07
XV	5	35	6	0.6013	0.0092	0.789	0.0067	28.098	0.0732	0.8371	0.019	0.897	0.0065	190.37	0.072

(C) Power Model

Expt. No	Conc (%)	Temp (°C)	R	Moisture Ratio						Solute Gain Ratio					
				N	N	R^2	χ^2	E%	RMSE	K	N	R^2	χ^2	E%	RMSE
I	10	45	4	1.5207	-0.5602	0.862	0.0018	26.309	0.0385	2.5626	-0.7687	0.946	0.001	47.347	0.029
II	10	45	5	4.783	-1.0463	0.957	0.0008	241.4	0.0262	2.1064	-0.5709	0.947	0.0014	21.355	0.034
III	10	45	6	1.9462	-0.5704	0.897	0.0021	23.588	0.0415	4.6954	-0.9741	0.929	0.0019	1434.7	0.039
IV	10	55	5	0.7156	-0.2707	0.592	0.0032	22.274	0.0507	1.6599	-0.5564	0.572	0.0099	91.232	0.089
V	10	35	5	3.6581	-0.8899	0.911	0.0022	569.98	0.0423	2.9622	-0.6598	0.877	0.0054	62.693	0.066
VI	15	35	4	2.0375	-0.6079	0.932	0.0013	23.653	0.0332	2.5685	-0.5877	0.946	0.0021	21.137	0.041
VII	15	35	6	2.8176	-0.7442	0.879	0.0035	142.97	0.053	2.0292	-0.4783	0.884	0.0045	32.471	0.06
VIII	15	45	5	1.6576	-0.5442	0.855	0.0025	33.201	0.0455	2.9724	-0.7165	0.914	0.0029	60.041	0.048
IX	15	55	4	0.4885	-0.1638	0.192	0.0068	32.94	0.0739	1.1739	-0.416	0.443	0.0118	91.338	0.097
X	15	55	6	0.525	-0.1836	0.248	0.0063	32.77	0.071	0.6313	-0.2104	0.11	0.0213	181.24	0.131
XI	5	45	5	1.8169	-0.4582	0.897	0.0029	20.869	0.0484	0.2236	-0.0234	0.004	0.005	36.587	0.064
XII	5	55	4	0.7165	-0.2516	0.589	0.0033	20.585	0.0516	4.0E-05	1.6769	0.408	0.0094	51.779	0.087
XIII	5	55	6	1.0663	-0.3534	0.774	0.003	22.371	0.0494	0.8672	-0.288	0.417	0.0102	53.414	0.09
XIV	5	35	4	1.325	-0.4067	0.837	0.0028	23.024	0.0481	1.9444	-0.562	0.819	0.0049	83.513	0.063
XV	5	35	6	2.0345	-0.4835	0.956	0.0013	14.443	0.0334	3.1879	-0.638	0.791	0.0132	325.85	0.103

(d) Penetration Model

Expt No	Conc (%)	Temp (°C)	R	Water Loss					Solute Gain				
				A	R^2	χ^2	E%	RMSE	A	R^2	χ^2	E%	RMSE
I	10	45	4	1.4367	N	26.84	28.991	4.914	0.4573	N	2.101	25.872	1.375
II	10	45	5	1.3248	N	19.87	27.236	4.228	0.4284	N	1.073	21.22	0.982
III	10	45	6	1.3253	N	20.17	27.105	4.26	0.4019	N	1.723	26.36	1.245
IV	10	55	5	1.0004	N	17.42	30.907	3.96	0.3034	N	1.319	31.986	1.089
V	10	35	5	1.3518	N	17.12	25.988	3.925	0.4536	0.203	1.088	20.943	0.989
VI	15	35	4	1.3757	N	20.39	27.114	4.283	0.6971	0.161	2.25	19.308	1.423
VII	15	35	6	1.3791	N	14.39	24	3.599	0.5382	0.536	0.895	16.315	0.897
VIII	15	45	5	1.368	N	21.17	28.551	4.364	0.5468	N	1.988	23.171	1.337
IX	15	55	4	0.979	N	23.46	33.112	4.594	0.3554	N	2.399	31.389	1.469
X	15	55	6	1.0878	N	24.94	33.042	4.737	0.3619	N	3.636	37.02	1.809
XI	5	45	5	1.1486	N	9.603	23.979	2.939	0.0919	N	0.219	34.643	0.444
XII	5	55	4	1.0358	N	16.96	31.039	3.906	0.0565	N	0.188	41.638	0.411
XIII	5	55	6	1.3056	N	22.3	28.955	4.479	0.1036	N	0.147	32.641	0.364
XIV	5	35	4	1.3533	N	19.47	27.753	3.186	0.0992	N	0.082	25.828	0.272
XV	5	35	6	1.3627	N	11.02	21.58	3.148	0.1643	0.312	0.153	17.329	0.371

For Penetration Model

For water loss "A" $=0.0160916*(\mathrm{Conc})^{0.0196}*(\mathrm{Temp})^{-0.14844}*(\mathrm{Ratio})^{0.519256}$
E%=9.4346; $\chi^2=0.0353$; RMSE=0.160916; $R^2=0.5236$
For Solute gain "A" $=1.073604*(\mathrm{Conc})^{1.597483}*(\mathrm{Temp})^{-0.887927}*(\mathrm{Ratio})^{1.289315}$
E%=20.9626; $\chi^2=0.28383$; RMSE=0.1401; $R^2=0.45137$

(e) Magee Model

Expt No	Conc (%)	Temp (°C)	R	Water Loss					Solute Gain				
				K	A	R^2	E%	RMSE	K	A	R^2	E%	RMSE
I	10	45	4	0.3432	12.641	0.467	8.4029	1.4555	0.1605	3.5544	0.7562	6.0732	0.362
II	10	45	5	0.4055	10.821	0.606	8.3085	1.3095	0.2102	2.5423	0.9038	5.9777	0.2807
III	10	45	6	0.4502	10.512	0.538	10.56	1.6675	0.1476	3.0748	0.6014	9.1031	0.4755
IV	10	55	5	0.1623	10.19	0.278	7.5088	1.0373	0.0655	2.6269	0.2261	14.078	0.4795
V	10	35	5	0.4892	9.9671	0.673	8.5315	1.3552	0.2462	2.251	0.7749	10.433	0.526
VI	15	35	4	0.4544	10.84	0.581	9.4136	1.5358	0.364	3.1131	0.8687	8.762	0.5631
VII	15	35	6	0.5698	9.1316	0.75	8.6371	1.3105	0.3219	2.2053	0.9432	5.2314	0.3144
VIII	15	45	5	0.3903	11.05	0.507	9.4556	1.5357	0.2546	3.3092	0.7731	8.8248	0.5521
IX	15	55	4	0.0604	11.596	0.033	9.3299	1.3034	0.0688	3.5308	0.1537	13.611	0.6423
X	15	55	6	0.0861	12.135	0.06	8.818	1.359	0.0122	4.2891	0.0035	16.305	0.8247
XI	5	45	5	0.5052	6.852	0.664	11.487	1.4314	-0.0022	1.556	0.0091	36.105	0.4102
XII	5	55	4	0.1715	10.129	0.29	7.7669	1.0673	-0.0155	0.9914	0.2929	10.23	0.096
XIII	5	55	6	0.3584	11.377	0.483	9.0709	1.4743	0.0203	0.8694	0.223	11.354	0.1505
XIV	5	35	4	0.4451	10.527	0.563	9.3304	1.5602	0.0386	0.6637	0.6365	9.5184	0.116
XV	5	35	6	0.6585	7.1764	0.754	11.276	1.5205	0.0964	0.5708	0.7348	13.526	0.2359

(f) Azuara Model

Expt No.	Conc (%)	Temp (°C)	R	Water Loss						Solute Gain					
				WL_∞	β_1	R^2 of Line	E%	RMSE	R^2	SG_∞	β_2	R^2 of Line	E%	RMSE	R^2
I	10	45	4	16.86	0.9737	0.996	7.846	1.6294	0.926	5.84	0.1389	0.998	2.188	0.143	0.964
II	10	45	5	16.26	0.2371	0.998	4.5644	0.8049	0.961	5.8	0.0622	0.999	3.248	0.179	0.976
III	10	45	6	16.42	0.2533	0.997	7.5172	1.2476	0.933	5.09	0.1678	0.997	5.552	0.277	0.935
IV	10	55	5	11.83	-0.481	0.995	11.881	2.1488	0.82	3.19	-0.191	0.976	34.46	1.546	0.606
V	10	35	5	16.61	0.1746	0.996	5.7251	0.867	0.938	5.87	0.0658	0.992	5.932	0.313	0.927
VI	15	35	4	16.83	0.2479	0.997	6.348	1.1327	0.951	8.73	0.0516	0.999	2.955	0.199	0.983
VII	15	35	6	17.15	0.1166	0.992	4.7029	0.8319	0.914	7.45	0.0384	0.992	6.034	0.348	0.946
VIII	15	45	5	15.85	0.7371	0.993	10.174	1.7687	0.885	6.97	0.0912	0.996	4.324	0.285	0.949
IX	15	55	4	11.6	-0.195	0.995	21.516	4.7417	0.532	3.17	-0.322	0.991	20.67	1.199	0.576
X	15	55	6	12.42	-0.197	0.994	22.651	5.0333	0.534	3.83	-0.086	0.978	111.9	8.79	0.356
XI	5	45	5	13.7	0.1304	0.988	9.1514	1.0418	0.908	1.04	-0.132	0.986	39.23	1.024	0.065
XII	5	55	4	11.89	-0.499	0.994	12.838	2.1538	0.776	0.65	-0.058	0.963	44.98	0.663	0.082
XIII	5	55	6	15.8	0.7447	0.995	9.3068	1.6575	0.822	1.04	-0.189	0.965	32.53	0.487	0.405
XIV	5	35	4	16.29	0.2977	0.993	8.7	1.4111	0.862	1.19	0.1788	0.978	9.861	0.105	0.815
XV	5	35	6	16.64	0.0825	0.994	5.4146	0.7303	0.965	1.99	0.0511	0.971	10.69	0.176	0.86

(g) General Model

$WL\,\% = 21.03952 * (\text{Time})^{0.135739} * (\text{Conc})^{0.05881} * (\text{Temp})^{-0.30314} * (\text{Ratio})^{-0.00103}$

E%=10.5980; $\chi^2=3.2148$; RMSE=1.7628; $R^2=0.52694$

$SG\% = 0.296756 * (\text{Time})^{0.144263} * (\text{Conc})^{1.455103} * (\text{Temp})^{-0.58346} * (\text{Ratio})^{0.357103}$

E%=21.8248; $\chi^2=1.2641$; RMSE=1.1054; $R^2=0.7199$

$MR = 0.00238 * (\text{Time})^{-1.52764} * (\text{Conc})^{0.840232} * (\text{Temp})^{1.872023} * (\text{Ratio})^{-0.07618}$

E%=81.0 ; $\chi^2=0.0365$; RMSE=0.1880; $R^2=$

$SGR = 0.000118 * (\text{Time})^{0.603051} * (\text{Conc})^{0.825633} * (\text{Temp})^{-0.92616} (\text{Ratio})^{-0.05675}$

E%=98.8534; $\chi^2=0.0685$; RMSE=0.2567; $R^2=0.658$

APPENDIX- H (ii)

Various regression coefficients and statistical parameters of various osmotic dehydration models with sugar as an osmotic agent

(a) Page Model

Expt No.	Conc (°B)	Temp (°C)	R	Moisture Ratio						Solute Gain Ratio					
				K	N	R^2	χ^2	E%	RMSE	K	N	R^2	χ^2	E%	RMSE
I	50	35	5	0.0711	0.6217	0.989	0.0005	7.6669	0.0196	0.0511	0.6424	0.99	0.0004	4.5396	0.019
II	50	45	4	0.0523	0.6173	0.995	0.0002	2.6428	0.0127	0.0403	0.6626	0.971	0.0013	8.4471	0.0328
III	50	45	5	0.0594	0.6178	0.992	0.0003	3.8476	0.016	0.052	0.627	0.993	0.0002	3.8664	0.0149
IV	50	45	6	0.031	0.7055	0.99	0.0005	4.8894	0.019	0.0366	0.6784	0.962	0.0017	7.8171	0.0373
V	50	55	5	0.0343	0.7041	0.992	0.0004	4.4542	0.0179	0.0392	0.6758	0.984	0.0007	6.8089	0.024
VI	55	55	4	0.0249	0.7364	0.993	0.0004	3.3638	0.0165	0.0148	0.7956	0.978	0.0009	4.9205	0.0273
VII	55	55	6	0.0319	0.6928	0.96	0.0018	7.5011	0.0375	0.0175	0.7714	0.948	0.0023	7.2297	0.0423
VIII	55	45	5	2.4725	0.7001	0.995	0.0002	3.1688	0.0129	0.0412	0.6826	0.931	0.0036	18.7	0.053
IX	55	35	4	2.7202	0.7127	0.956	0.0023	11.222	0.0427	0.0481	0.6518	0.964	0.0017	11.556	0.037
X	55	35	6	2.6709	0.6333	0.991	0.0004	4.5046	0.0172	0.0509	0.6127	0.887	0.0048	16.075	0.0612
XI	45	45	5	2.5484	0.5848	0.994	0.0003	3.1986	0.0147	0.0408	0.6774	0.99	0.0005	3.1303	0.0197
XII	45	55	4	2.5091	0.7149	0.992	0.0004	3.9979	0.0178	0.0249	0.734	0.992	0.0003	3.7052	0.0171
XIII	45	55	6	2.6852	0.7084	0.994	0.0003	4.045	0.0156	0.023	0.7334	0.957	0.0019	8.3666	0.0389
XIV	45	35	4	2.6744	0.6904	0.987	0.0006	5.5564	0.0224	0.0881	0.5859	0.944	0.0022	15.726	0.0422
XV	45	35	6	2.8324	0.6979	0.992	0.0004	4.7583	0.018	0.0385	0.6792	0.992	0.0003	4.0371	0.0175

Page Model

For Water Loss “K”=0.017287*(Conc) $^{2.447701}$*(Temp) $^{-2.25548}$*(Ratio) $^{-0.08809}$

E%=61.6070; χ^2=4.8777; RMSE=1.8913; R^2=0.599

For Water Loss “N”=0.327993*(Conc) $^{0.09938}$*(Temp) $^{0.127379}$*(Ratio) $^{-0.07895}$

E%=4.0461; χ^2=0.0019; RMSE=0.0369; R^2=0.064891

For Solute Gain “K”=0.140115*(Conc) $^{0.781738}$*(Temp) $^{-1.19102}$*(Ratio) $^{0.051179}$

E%=24.4145; χ^2=0.0003; RMSE=0.0142; R^2=0.31583

For Solute Gain “N”=0.332694*(Conc) $^{-0.13748}$*(Temp) $^{0.316344}$*(Ratio) $^{0.025763}$

E%=3.1727; χ^2=0.0020; RMSE=0.0381; R^2=0.52829

(b) GEM

Expt No.	Conc (°B)	Temp (°C)	R	Moisture Ratio						Solute Gain Ratio					
				A	K	R^2	χ^2	E%	RMSE	A	K	R^2	χ^2	E%	RMSE
I	50	35	5	0.7923	0.0069	0.962	0.0017	14.564	0.0364	0.7923	0.0069	0.971	0.0013	8.3597	0.0321
II	50	45	4	0.8235	0.006	0.99	0.0004	4.4705	0.0177	0.8235	0.006	0.954	0.0021	7.4866	0.0409
III	50	45	5	0.7863	0.0063	0.975	0.0011	6.3927	0.0293	0.7863	0.0063	0.984	0.0006	4.0074	0.023
IV	50	45	6	0.8297	0.0059	0.989	0.0005	4.0148	0.0202	0.8297	0.0059	0.963	0.0017	7.1569	0.0371
V	50	55	5	0.8221	0.0063	0.976	0.0011	7.7594	0.0304	0.8221	0.0063	0.982	0.0008	6.9318	0.026
VI	55	55	4	0.9059	0.0045	0.983	0.0008	5.8922	0.0254	0.9059	0.0045	0.991	0.0003	3.4183	0.0172
VII	55	55	6	0.8826	0.0046	0.985	0.0006	3.8567	0.0232	0.8827	0.0046	0.977	0.001	5.2571	0.028
VIII	55	45	5	0.8187	0.007	0.988	0.0005	3.3474	0.0206	0.8187	0.007	0.925	0.002	18.46	0.0552
IX	55	35	4	0.8002	0.0069	0.946	0.0028	12.963	0.0474	0.8002	0.0069	0.943	0.0027	10.165	0.0464
X	55	35	6	0.7749	0.0055	0.98	0.0009	6.3216	0.0265	0.7749	0.0055	0.94	0.0025	11.605	0.0445
XI	45	45	5	0.8278	0.0068	0.984	0.0007	4.6323	0.0244	0.8278	0.0068	0.967	0.0016	8.3125	0.0358
XII	45	55	4	0.8757	0.0056	0.985	0.0007	5.9162	0.0239	0.8757	0.0056	0.988	0.0005	4.5129	0.0213
XIII	45	55	6	0.8655	0.005	0.977	0.0011	7.1941	0.0296	0.8655	0.0049	0.98	0.0008	5.5432	0.0264
XIV	45	35	4	0.6984	0.0088	0.98	0.0009	8.1186	0.0278	0.6984	0.0088	0.953	0.0019	18.798	0.039
XV	45	35	6	0.8313	0.0064	0.968	0.0016	9.3811	0.0358	0.8313	0.0064	0.975	0.0012	6.2797	0.0306

(c)Power Model

Expt No.	Conc (°B)	Temp (°C)	R	Moisture Ratio						Solute Gain Ratio					
				N	N	R^2	χ^2	E%	RMSE	K	N	R^2	χ^2	E%	RMSE
I	50	35	5	3.1642	-0.5388	0.968	0.0014	12.062	0.0335	2.6956	-0.4473	0.953	0.0021	10.243	0.041
II	50	45	4	2.281	-0.3898	0.927	0.0029	11.771	0.0481	2.5645	-0.4084	0.939	0.0028	13.159	0.0473
III	50	45	5	2.6486	-0.4514	0.957	0.0018	12.805	0.0383	2.4606	-0.4154	0.942	0.0024	12.231	0.044
IV	50	45	6	2.4449	-0.3863	0.914	0.0041	14.214	0.0564	2.4488	-0.394	0.899	0.0048	15.596	0.0612
V	50	55	5	2.731	-0.4283	0.946	0.0027	11.774	0.0462	2.5161	-0.41	0.916	0.004	14.337	0.0558
VI	55	55	4	2.4764	-0.3766	0.928	0.0035	11.323	0.0524	2.0684	-0.3023	0.846	0.0068	14.395	0.0727
VII	55	55	6	2.1791	-0.355	0.842	0.0071	17.357	0.0747	1.9857	-0.3003	0.794	0.0091	16.954	0.0842
VIII	55	45	5	2.4725	-0.3886	0.931	0.0032	12.129	0.0504	2.6921	-0.4409	0.868	0.0069	21.892	0.0734
IX	55	35	4	2.7202	-0.4326	0.893	0.0057	12.723	0.0666	2.7711	-0.4508	0.935	0.0031	17.112	0.0497
X	55	35	6	2.6709	-0.4547	0.94	0.0026	14.71	0.0457	1.9756	-0.3487	0.763	0.01	26.243	0.0885
XI	45	45	5	2.5484	-0.4043	0.943	0.0027	12.098	0.0461	2.8094	-0.4444	0.964	0.0017	9.2766	0.037
XII	45	55	4	2.5091	-0.3945	0.918	0.004	12.243	0.0558	2.4139	-0.3694	0.918	0.0039	11.697	0.0556
XIII	45	55	6	2.6852	-0.4164	0.952	0.0024	10.168	0.0433	2.103	-0.3261	0.832	0.0076	16.388	0.0769
XIV	45	35	4	2.6744	-0.4348	0.919	0.004	13.83	0.0561	2.6572	-0.5096	0.868	0.0054	24.854	0.0649
XV	45	35	6	2.8324	-0.4398	0.966	0.0017	8.5656	0.0367	2.6666	-0.4231	0.954	0.0022	10.931	0.0416

(d) Penetration Model

Expt No.	Conc (°B)	Temp (°C)	R	Water Loss					Solute Gain				
				A	R^2	χ^2	E%	RMSE	A	R^2	χ^2	E%	RMSE
I	50	35	5	2.187	0.764	9.791	11.396	2.9502	0.7118	0.909	0.5106	7.398	0.6737
II	50	45	4	2.1815	0.933	3.465	6.9925	1.755	0.6728	0.956	0.2876	6.963	0.5056
III	50	45	5	2.4132	0.91	5.566	8.0894	2.2244	0.7101	0.932	0.3787	6.538	0.5802
IV	50	45	6	2.3166	0.987	1.048	2.9735	0.9653	0.6575	0.957	0.2666	5.949	0.4868
V	50	55	5	3.448	0.943	9.16	5.4527	2.8534	0.802	0.954	0.3742	4.835	0.5767
VI	55	55	4	4.0423	0.98	5.632	5.5652	2.2374	0.6457	0.971	0.2536	5.637	0.4748
VII	55	55	6	3.137	0.979	5.259	5.4664	2.1622	0.5031	0.962	0.1697	7.064	0.3884
VIII	55	45	5	3.4247	0.988	2.182	3.0783	1.3928	0.387	0.89	0.2195	8.107	0.4417
IX	55	35	4	2.8999	0.969	3.68	3.9955	1.8087	0.2803	0.812	0.1533	10.39	0.3691
X	55	35	6	2.9648	0.923	7.575	7.6116	2.595	0.3923	0.916	0.1612	10.1	0.3785
XI	45	45	5	2.6689	0.981	1.965	5.0602	1.3219	0.5964	0.936	0.2935	7.418	0.5108
XII	45	55	4	3.6804	0.966	6.636	4.2154	2.4288	0.6863	0.986	0.1155	4.287	0.3204
XIII	45	55	6	3.9267	0.954	9.985	5.7342	2.9792	0.617	0.979	0.1362	5.411	0.348
XIV	45	35	4	3.4281	0.922	11.29	5.3761	3.169	0.3123	0.648	0.2577	12.95	0.4786
XV	45	35	6	3.4055	0.941	4.839	7.2721	2.074	0.29	0.967	0.0387	6.604	0.1855

Penetration model

For Water loss “A”$=0.333717*(\text{Conc})^{0.132773}*(\text{Temp})^{0.585786}*(\text{Ratio})^{-0.32648}$
E%=16.9462; $\chi^2=0.4733$; RMSE=0.5891; $R^2=0.1855$
For Solute gain “A”$=0.039416*(\text{Conc})^{-0.85877}*(\text{Temp})^{1.638697}*(\text{Ratio})^{-0.30533}$
E%=18.5131; $\chi^2=0.0413$; RMSE=0.1741; $R^2=0.457$

(e) Magee Model

Expt No.	Conc (°B)	Temp (°C)	Ratio	WATER LOSS					SOLUTE GAIN				
				K	A	R^2	E%	RMSE	K	A	R^2	E%	RMSE
I	50	35	5	1.5424	6.3499	0.934	7.713	1.6085	0.5784	1.2346	0.965	6.3207	3.46
II	50	45	4	1.7753	3.8201	0.988	3.501	0.7371	0.6229	0.6458	0.965	7.4151	0.718
III	50	45	5	1.9266	5.1933	0.973	5.401	1.2246	0.5801	1.213	0.984	4.6386	2.47
IV	50	45	6	2.2647	0.5059	0.993	3.078	0.9137	0.6311	0.2794	0.978	6.5514	1.337
V	50	55	5	3.1954	1.2942	0.98	5.967	2.2585	0.7354	0.4175	0.987	4.5312	7.754
VI	55	55	4	4.0847	-0.3367	0.988	5.446	2.2236	0.6987	0.3947	0.988	15.964	7.143
VII	55	55	6	3.9922	1.2365	0.99	5.085	1.9908	0.5061	0.1584	0.98	8.9406	6.234
VIII	55	45	5	3.3961	0.781	0.994	3.657	1.2482	0.3558	0.2583	0.949	7.2612	2.562
IX	55	35	4	2.8309	1.3706	0.956	4.644	2.0248	0.2641	0.2283	0.968	10.6	9.092
X	55	35	6	2.7	3.014	0.977	3.929	1.8477	0.364	0.3209	0.96	8.3848	6.066
XI	45	45	5	2.593	1.0276	0.991	5.061	1.171	0.5468	0.3443	0.976	7.5209	1.732
XII	45	55	4	3.4983	0.7759	0.987	4.564	2.013	0.6958	-0.049	0.992	3.1799	5.988
XIII	45	55	6	3.6902	1.0223	0.983	6.656	2.408	0.6248	-0.0624	0.988	5.6484	8.381
XIV	45	35	4	3.0819	1.991	0.978	4.04	2.211	0.2472	0.5528	0.928	7.8657	7.834
XV	45	35	6	3.183	1.4507	0.975	7.632	2.535	0.276	0.1407	0.984	6.6192	8.3308

(f) Azuara Model

Expt No.	Conc (°B)	Temp (°C)	Ratio	Water Loss						Solute Gain					
				WL_∞	β_1	R^2 of Line	E%	RMSE	R^2	SG_∞	β_2	R^2 of Line	E%	RMSE	R^2
I	50	35	5	32.57	0.0266	0.997	2.57	0.58	0.991	11.83	0.0178	0.992	4.243	0.277	0.987
II	50	45	4	38.17	0.015	0.996	5.042	1.157	0.987	12.58	0.0143	0.967	6.053	0.466	0.965
III	50	45	5	40.32	0.0189	0.992	4.341	1.031	0.986	12.15	0.0163	0.989	5.53	0.346	0.984
IV	50	45	6	44.05	0.0132	0.98	5.502	1.244	0.979	12.25	0.014	0.967	7.887	0.548	0.949
V	50	55	5	60.24	0.0151	0.995	2.78	1.036	0.992	14.02	0.0153	0.98	6.379	0.457	0.973
VI	55	55	4	80.64	0.0116	0.989	3.189	1.437	0.991	15.06	0.0085	0.919	9.433	0.562	0.96
VII	55	55	6	79.36	0.0127	0.94	11.16	3.981	0.935	10.8	0.0092	0.871	13.46	0.578	0.92
VIII	55	45	5	66.22	0.0132	0.988	4.047	1.435	0.988	6.61	0.017	0.954	8.537	0.368	0.924
IX	55	35	4	52.91	0.0157	0.967	8.25	2.415	0.963	4.93	0.0172	0.974	7.202	0.259	0.952
X	55	35	6	49.75	0.0199	0.99	3.15	1.304	0.983	7.19	0.0146	0.892	14.06	0.551	0.85
XI	45	45	5	50	0.0142	0.99	3.901	1.118	0.987	10.27	0.0162	0.996	2.249	0.172	0.993
XII	45	55	4	67.57	0.0135	0.987	5.087	1.503	0.987	13.81	0.0116	0.983	5.277	0.32	0.986
XIII	45	55	6	70.42	0.0141	0.996	2.218	0.993	0.995	12.9	0.0105	0.914	12.32	0.651	0.932
XIV	45	35	4	57.47	0.0166	0.989	4.851	1.56	0.981	4.5	0.0295	0.987	6.999	0.229	0.924
XV	45	35	6	59.88	0.0154	0.999	0.995	0.406	0.999	5.26	0.0151	0.992	3.321	0.107	0.99

(g) General Model

$WL\% = 0.684632 * (Time)^{0.48145} * (Conc)^{0.051443} * (Temp)^{0.399002} * (Ratio)^{-0.07267}$
$E\% = 17.0928$; $\chi^2 = 43.9814$; RMSE=6.5079; $R^2 = 0.778$
$SG\% = 0.108804 * (Time)^{0.470177} * (Conc)^{-0.90456} * (Temp)^{1.497112} * (Ratio)^{-0.37463}$
$E\% = 20.7927$; $\chi^2 = 3.2153$; RMSE= 1.7596; $R^2 = 0.57206$
$MR = 0.062717 * (Time)^{-0.4761} * (Conc)^{0.560851} * (Temp)^{0.483521} * (Ratio)^{-0.05166}$
$E\% = 13.4561$; $\chi^2 = 0.0055$; RMSE=0.0731; $R^2 = 0.82241$
$SGR = 0.05028 * (Time)^{-0.47472} * (Conc)^{0.429284} * (Temp)^{0.638663} * (Ratio)^{0.037538}$
$E\% = 17.5886$; $\chi^2 = 0.0079$; RMSE=0.0875; $R^2 = 0.8076$

APPENDIX- H (iii)

Various regression coefficients and statistical parameters of various osmotic dehydration models with mixture of sugar-salt as an osmotic agent

(a) page model

Expt No.	Conc (50°B+ salt%)	Temp (°C)	Ratio	Moisture Ratio						Solute Gain Ratio					
				K	N	R^2	χ^2	E%	RMSE	K	N	R^2	χ^2	E%	RMSE
I	10	45	4	0.0704	0.6068	0.992	0.0004	5.1792	0.0179	0.0401	0.6913	0.98	0.00102	3.1522	0.0286
II	10	45	5	0.072	0.6167	0.997	0.0002	2.7492	0.0111	0.0368	0.7027	0.985	0.00077	3.7755	0.0248
III	10	35	5	0.0717	0.6063	0.998	0.0001	3.5224	0.0095	0.809	0.1318	0.753	0.05738	26.752	0.2142
IV	10	55	5	0.1026	0.5633	0.997	0.0003	4.4736	0.0164	0.0585	0.6432	0.986	0.00068	5.7645	0.0234
V	10	45	6	0.0733	0.6053	0.996	0.0002	2.8587	0.012	0.0367	0.7107	0.972	0.00134	6.3654	0.0328
VI	15	45	5	0.1691	0.4576	0.932	0.0032	8.0549	0.0508	0.0412	0.6761	0.987	0.00066	4.7713	0.023
VII	5	45	5	0.0693	0.6184	0.993	0.0003	5.9519	0.0159	0.0386	0.6911	0.991	0.00046	2.3624	0.0193
VIII	15	45	4	0.1174	0.5352	0.976	0.0012	4.8542	0.0306	0.1083	0.5659	0.992	0.00031	3.8382	0.0157
IX	15	55	6	0.0914	0.5919	0.997	0.0001	4.2231	0.0103	1.0586	0.1419	0.001	0.03404	38.559	0.165
X	15	35	4	0.0961	0.5759	0.992	0.0004	4.5031	0.0175	0.0723	0.5876	0.966	0.00155	9.4619	0.0352
XI	15	35	6	0.1032	0.5801	0.997	0.0001	4.9303	0.0108	0.0613	0.6404	0.955	0.00194	11.655	0.0394
XII	5	55	4	0.1163	0.5092	0.953	0.0025	7.9449	0.0446	0.0436	0.6886	0.968	0.00151	4.9394	0.0347
XIII	5	55	6	0.0806	0.5934	0.994	0.0003	3.9112	0.015	0.0481	0.6648	0.975	0.00119	6.1621	0.0308
XIV	5	35	4	0.064	0.622	0.995	0.0002	3.2775	0.0139	0.069	0.5937	0.958	0.00253	10.416	0.045
XV	5	35	6	0.0767	0.601	0.997	0.0001	3.2491	0.0099	0.0245	0.7544	0.989	0.00057	3.0447	0.0214

Page Model

For Water Loss "K"$=-1.04588*(\text{Conc})^{-9.66623}*(\text{Temp})^{0.030754}*(\text{Ratio})^{-3.86455}$

E%=17.5891; $\chi^2=0.0011$; RMSE=0.0284; $R^2=0.789$

For Water Loss "N"$=-0.26436*(\text{Conc})^{-2.07046}*(\text{Temp})^{-0.05098}*(\text{Ratio})^{-2.79969}$

E%=5.6677; $\chi^2=0.0027$; RMSE=0.0448; $R^2=0.854$

For solute gain "K"$= -1.90864*(\text{Conc})^{0.008495}*(\text{Temp})^{-0.02446}*(\text{Ratio})^{-2.36388}$

E%=33.4184; $\chi^2=0.1478$; RMSE=0.3292; $R^2=0.775$

For solute gain “N”= $-1.43096*(\text{Conc})^{-0.40649}*(\text{Temp})^{0.061904}*(\text{Ratio})^{-0.82603}$
E%=48.2709; χ^2=0.049; RMSE=0.1895; R^2=0.802

(b) GEM

Expt No.	Conc (50°B+ Salt%)	Temp (°C)	Ratio	Moisture Ratio						Solute Gain Ratio					
				A	K	R^2	χ^2	E%	RMSE	A	K	R^2	χ^2	E%	RMSE
I	10	45	4	0.7287	0.0079	0.965	0.0018	9.7943	0.0386	0.812	0.0067	0.995	0.0002	2.3584	0.0136
II	10	45	5	0.6607	0.0073	0.952	0.0023	5.6164	0.0431	0.8296	0.0066	0.994	0.0002	2.9663	0.0154
III	10	35	5	0.67	0.0073	0.946	0.0026	5.6146	0.0462	0.6802	0.0068	0.912	0.0048	13.034	0.0625
IV	10	55	5	0.6344	0.0085	0.95	0.0023	9.4993	0.043	0.7134	0.0071	0.968	0.0015	3.9673	0.0352
V	10	45	6	0.6528	0.0071	0.935	0.0031	5.9685	0.0505	0.7987	0.0067	0.994	0.0002	3.6885	0.0147
VI	15	45	5	0.6725	0.0081	0.959	0.0019	9.2188	0.0395	0.8131	0.0066	0.985	0.0007	4.4559	0.0247
VII	5	45	5	0.7024	0.0081	0.961	0.0019	8.1844	0.039	0.8196	0.0066	0.992	0.0004	3.5	0.0182
VIII	15	45	4	0.5163	0.0069	0.782	0.0237	11.641	0.1378	0.5794	0.0082	0.966	0.0012	5.4186	0.0321
IX	15	55	6	0.6148	0.0088	0.933	0.0031	8.8615	0.05	0.5094	0.0086	0.918	0.0027	8.2485	0.0472
X	15	35	4	0.5593	0.0072	0.861	0.0068	11.115	0.0739	0.748	0.0071	0.988	0.0005	4.409	0.0209
XI	15	35	6	0.589	0.0087	0.93	0.0031	11.787	0.0498	0.7292	0.0075	0.983	0.0007	8.0436	0.0239
XII	5	55	4	0.6735	0.0072	0.933	0.0035	8.9044	0.053	0.776	0.0071	0.998	0.0001	2.1394	0.0092
XIII	5	55	6	0.617	0.0074	0.894	0.0054	9.4726	0.066	0.7757	0.0074	0.995	0.0002	3.6302	0.0137
XIV	5	35	4	0.6986	0.0069	0.94	0.0031	8.177	0.0505	0.7322	0.0075	0.93	0.004	13.059	0.0565
XV	5	35	6	0.6435	0.0074	0.938	0.0029	5.4637	0.0485	0.8566	0.0059	0.994	0.0003	2.4985	0.0164

(C) Power Model

Expt No.	Conc (50°B+ salt%)	Temp (°C)	Ratio	Moisture Ratio						Solute Gain Ratio					
				K	N	R^2	χ^2	E%	RMSE	K	N	R^2	χ^2	E%	RMSE
I	10	45	4	4.922	-0.6351	0.645	0.0189	10.1367	0.1232	4.0022	-0.547	0.56	0.0221	16.7672	0.1331
II	10	45	5	4.0908	-0.6024	0.761	0.0115	13.6244	0.0961	3.8776	-0.533	0.619	0.0196	16.1385	0.1254
III	10	35	5	3.8455	-0.5726	0.787	0.0104	13.4694	0.0916	4.282	-0.589	0.687	0.0173	12.5695	0.1177
IV	10	55	5	4.5722	-0.6677	0.746	0.0116	12.7694	0.0964	3.623	-0.56	0.794	0.0099	16.9935	0.0894
V	10	45	6	3.1008	-0.6028	0.782	0.0106	12.1321	0.0922	3.4753	-0.501	0.63	0.018	18.32	0.1202
VI	15	45	5	4.4741	-0.6477	0.75	0.0118	11.3826	0.0973	3.9513	-0.543	0.644	0.0186	14.9654	0.1222
VII	5	45	5	3.3311	-0.5309	0.83	0.0083	16.0732	0.0816	3.9388	-0.53	0.599	0.0209	13.692	0.1293
VIII	15	45	4	5.7593	-0.7042	0.552	0.0221	8.6504	0.1331	3.1888	-0.659	0.685	0.0119	16.0842	0.0977
IX	15	55	6	5.3888	-0.7072	0.641	0.0166	12.4469	0.1155	3.5443	-0.67	0.866	0.0045	17.4756	0.0604
X	15	35	4	5.1741	-0.6797	0.638	0.0177	10.8826	0.1191	3.9938	-0.561	0.501	0.0229	20.063	0.1355
XI	15	35	6	5.2754	-0.7144	0.653	0.0153	10.0991	0.1107	3.4955	-0.539	0.621	0.0164	24.0879	0.1146
XII	5	55	4	4.5144	-0.6158	0.725	0.0145	11.1089	0.1077	4.0968	-0.572	0.524	0.0226	18.1253	0.1346
XIII	5	55	6	4.7651	-0.6514	0.753	0.0126	10.0597	0.1006	3.7173	-0.546	0.621	0.0182	16.4876	0.1208
XIV	5	35	4	3.1198	-0.5808	0.777	0.0119	10.24	0.0977	2.1268	-0.449	0.79	0.0119	13.5968	0.0979
XV	5	35	6	3.1621	-0.6051	0.748	0.012	13.7214	0.098	3.3908	-0.466	0.658	0.0179	13.7162	0.1199

(d)Penetration Model

Expt No.	Conc (50°B+ salt%)	Temp (°C)	Ratio	Water LOSS					Solute Gain				
				A	R^2	χ^2	E%	RMSE	A	R^2	χ^2	E%	RMSE
I	10	45	4	4.3723	0.814	36.32	9.4241	5.717	0.7645	0.97	0.2301	6.0266	0.4551
II	10	45	5	4.4946	0.809	35.98	11.414	5.69	0.8537	0.982	0.187	4.8751	0.4103
III	10	35	5	4.0966	0.859	24.23	10.832	4.669	0.7593	0.863	0.9296	10.496	0.9147
IV	10	55	5	5.1134	0.661	69.64	14.097	7.916	0.9019	0.907	0.8543	9.6878	0.8768
V	10	45	6	4.8346	0.836	37.97	10.794	5.845	0.9128	0.968	0.3457	6.9756	0.5578
VI	15	45	5	5.1433	0.707	64.72	13.553	7.632	0.8937	0.97	0.3342	5.6472	0.5484
VII	5	45	5	3.1226	0.824	28.86	11.684	5.096	0.7814	0.97	0.251	5.3137	0.4753
VIII	15	45	4	4.9164	0.653	69.66	13.596	7.917	1.1069	0.51	3.8323	16.658	1.8572
IX	15	55	6	5.1008	0.669	68.83	14.285	7.87	1.1836	0.168	6.0401	19.229	2.3315
X	15	35	4	4.5237	0.708	51.02	13.448	6.776	0.8875	0.914	0.752	10.153	0.8227
XI	15	35	6	4.7983	0.51	78.25	15.861	8.392	0.9709	0.843	1.3727	12.105	1.1115
XII	5	55	4	4.7989	0.835	39.32	9.0179	5.948	0.7231	0.944	0.3448	7.9961	0.5571
XIII	5	55	6	4.9492	0.779	51.41	11.132	6.801	0.8682	0.916	0.6926	8.5237	0.7895
XIV	5	35	4	3.1852	0.813	33.96	8.7501	5.528	0.735	0.839	1.0318	11.003	0.9636
XV	5	35	6	4.2073	0.816	30.9	12.24	5.273	0.6706	0.991	0.0707	3.6661	0.2522

Penetration Model

For Water loss "A"=0.910734*(Conc) $^{0.076298}$*(Temp) $^{0.361865}$*(Ratio) $^{0.064182}$

E%=: 3.4697; χ^2=0.05676; RMSE=0.2038; R^2=0.6905

For Solute Gain "A"=0.318378*(Conc) $^{0.189105}$*(Temp) $^{0.051504}$*(Ratio) $^{0.234299}$

E%=6.5532; χ^2=0.0106; RMSE=0.0884; R^2=0.5803

(e) Magee Model

Expt No.	Conc (50°B+ salt%)	Temp (°C)	Ratio	Water Loss					Solute Gain				
				K	A	R^2	RMSE	E%	K	A	R^2	RMSE	E%
I	10	45	4	3.5779	5.2268	0.951	3.2486	6.621	0.7011	0.589	0.993	0.2704	3.385
II	10	45	5	3.2175	11.615	0.966	2.3827	6.236	0.7704	0.8611	0.994	0.2382	2.647
III	10	35	5	3.0712	9.8693	0.967	2.2623	6.674	0.6002	1.477	0.93	0.6545	9.08
IV	10	55	5	3.3248	16.184	0.945	3.1732	6.519	0.7144	2.0644	0.98	0.4044	5.188
V	10	45	6	3.5718	11.952	0.96	2.87	6.893	0.7889	1.3356	0.996	0.196	2.175
VI	15	45	5	3.4494	15.277	0.945	3.307	6.614	0.7985	1.0001	0.985	0.3913	4.571
VII	5	45	5	2.9996	10.143	0.965	2.2807	6.371	0.6906	0.8492	0.988	0.3056	3.783
VIII	15	45	4	3.5079	12.622	0.92	4.0159	9.073	0.6509	4.4599	0.967	0.4819	4.495
IX	15	55	6	3.3288	16.695	0.937	3.4226	7.614	0.6211	5.5071	0.934	0.6538	5.583
X	15	35	4	3.0479	13.354	0.935	3.1785	7.767	0.7037	2.0535	0.99	0.2851	3.051
XI	15	35	6	2.9006	16.939	0.927	3.2344	7.44	0.7025	2.7146	0.989	0.3	2.632
XII	5	55	4	3.6076	9.9172	0.955	3.115	7.65	0.5905	1.4055	0.996	0.147	1.603
XIII	5	55	6	3.532	12.46	0.941	3.5072	8.411	0.6844	1.6852	0.99	0.2715	2.432
XIV	5	35	4	3.1403	7.868	0.954	2.7369	8.231	0.5814	1.174	0.924	0.665	9.939
XV	5	35	6	3.0287	11.549	0.961	2.4125	6.734	0.6619	0.1664	0.992	0.2365	3.856

(f) Azuara Model

Expt No.	Conc (50°B+ salt%)	Temp (°C)	Ratio	Water Loss						Solute Gain					
				$WL_{\propto}$	β_1	R^2 of Line	P%	RMSE	R^2	$SG_{\propto}$	β_2	$R^2$of Line	P%	RMSE	R^2
I	10	45	4	63.1	0.0244	0.998	3.47	1.182	0.992	13.21	0.0173	0.977	8.2	0.546	0.964
II	10	45	5	66.22	0.0265	0.996	4.316	1.678	0.987	15.13	0.0163	0.978	7.806	0.543	0.973
III	10	35	5	62.5	0.0249	0.996	3.719	1.38	0.99	11.76	0.0229	0.989	6.552	0.423	0.971
IV	10	55	5	70.92	0.0323	0.997	3.827	1.864	0.984	14.58	0.0225	0.988	6.253	0.514	0.975
V	10	45	6	72.99	0.0255	0.995	4.077	1.683	0.989	15.85	0.0175	0.974	7.855	0.696	0.96
VI	15	45	5	72.46	0.0307	0.998	3.252	1.541	0.99	15.62	0.017	0.981	7.104	0.539	0.974
VII	5	45	5	61.35	0.0254	0.993	4.374	1.621	0.985	13.51	0.0169	0.984	6.717	0.438	0.977
VIII	15	45	4	67.57	0.032	0.998	2.836	1.255	0.991	15.22	0.0375	0.996	4.904	0.566	0.973
IX	15	55	6	70.92	0.0336	0.998	2.928	1.375	0.991	15.48	0.0458	0.997	4.707	0.538	0.976
X	15	35	4	63.29	0.0313	0.998	3.344	1.28	0.99	14.66	0.0211	0.977	7.929	0.77	0.942
XI	15	35	6	63.69	0.0376	0.999	3.108	1.334	0.989	15.08	0.0241	0.979	7.883	0.763	0.94
XII	5	55	4	71.43	0.0241	0.997	3.211	1.47	0.99	12.06	0.0198	0.978	8.684	0.58	0.95
XIII	5	55	6	71.43	0.0275	0.999	2.211	0.937	0.996	13.95	0.0203	0.981	7.855	0.651	0.954
XIV	5	35	4	61.73	0.0231	0.998	2.556	0.841	0.996	11.25	0.0211	0.983	8.287	0.456	0.964
XV	5	35	6	62.89	0.0272	0.996	3.529	1.413	0.991	12.89	0.0134	0.973	7.486	0.409	0.977

(g) General Model

WL g/ 100 FF=1.543556*$(\text{Time})^{0.36622}$*$(\text{Conc})^{0.08643}$*$(\text{Temp})^{0.31215}$*$(\text{Ratio})^{0.200804}$

E%=6.2737; χ^2=10.2214; RMSE=3.1433; R^2=0.94775

MR=7.608194*$(\text{Time})^{-0.60935}$*$(\text{Conc})^{-0.12012}$*$(\text{Temp})^{-0.05519}$*$(\text{Ratio})^{-0.11166}$

E%=13.9932; χ^2= 0.0077; RMSE= 0.0866; R^2= 0.81198

SG g/ 100 g FF = 0.149738*$(\text{Time})^{0.403692}$*$(\text{Conc})^{0.253484}$*$(\text{Temp})^{0.314946}$*$(\text{Ratio})^{0.271357}$

E%=: 7.7376; χ^2=0.6418; RMSE=0.7876; R^2=0.9345

SGR=20.82346*$(\text{Time})^{-0.52348}$*$(\text{Conc})^{-0.23639}$*$(\text{Temp})^{-0.42181}$*$(\text{Ratio})^{0.144419}$

E%= 21.6271; χ^2=0.0125; RMSE= 0.1102; R^2=0.71161

APPENDIX-I

The values of experimental data for all responses for optimization of osmotic dehydration of carrot cubes in solutions of different osmotic agents

(a) Salt solution

Coded process variables			Un-coded process variables			Responses				
Time (x_1)	Temp (x_2)	Conc. (x_3)	Time (min) (X_1)	Temp (°C) (X_2)	Conc.(%) (X_3)	Water loss (Y_1)	Solute gain (Y_2)	Rehydration ratio (Y_3)	Shrinkage% (Y_4)	Acceptance% (Y_5)
-1.6818	0	0	69.5462	40	10	18.2021	2.4179	3.4689	17	80
1	-1	-1	150	30	5	15.9422	0.9451	4.1509	21	70
0	1.6818	0	120	56.8179	10	18.237	3.1819	2.8479	25	60
0	0	0	120	40	10	18.7215	2.3894	3.142	20	73
-1	1	-1	90	50	5	17.5456	2.6499	4.2019	25	65
0	0	0	120	40	10	18.7301	2.391	3.148	21	72
-1	-1	-1	90	30	5	16.0124	0.9152	4.606	16	84
0	0	0	120	40	10	18.7214	2.3892	3.148	19	72
0	0	-1.6818	120	40	1.591036	15.9084	1.1379	5.3573	32	53
0	0	0	120	40	10	18.7197	2.3735	3.145	20	74
-1	-1	1	90	30	15	18.5188	4.5014	3.1699	8	95
0	0	1.6818	120	40	18.4089	19.895	5.4929	2.8919	24	72
0	0	0	120	40	10	18.7185	2.3725	3.145	23	67
0	0	0	120	40	10	18.7343	2.3863	3.147	20	75
1	-1	1	150	30	15	19.1801	5.3143	2.7212	13	85
0	-1.6818	0	120	23.18207	10	16.7451	2.8681	3.3859	7	88
1	1	-1	150	50	5	17.2343	2.3595	3.9825	35	50
1	1	1	150	50	15	19.458	3.9717	2.48774	39	52
1.6818	0	0	170.4538	40	10	18.4867	2.8139	2.9099	35	53
-1	1	1	90	50	15	19.01	3.5201	2.69798	26	58

(b) Sugar solution

Coded process variables			Un-coded process variables			Responses				
Time (x_1)	Temp (x_2)	Conc. (x_3)	Time (min) (X_1)	Temp (°C) (X_2)	Conc. (%) (X_3)	Water loss (Y_1)	Solute gain (Y_2)	Rehydration ratio (Y_3)	Shrinkage% (Y_4)	Acceptance% (Y_5)
0	0	0	180	45	55	38.692	10.6	3.3	5	82
0	0	0	180	45	55	38.691	10.632	3.28	6	83
0	0	0	180	45	55	38.051	9.987	3.31	5	83
1.6818	0	0	280.9075	45	55	41.1213	12.374	3.0087	0	82
0	-1.6818	0	180	28.18207	55	38.4263	8.5165	3.465	12	78
1	-1	1	240	35	60	38.7693	9.2471	3.3113	4	81
1	-1	-1	240	35	50	36.8137	10.414	3.1972	3	79
-1	-1	1	120	35	60	29.4589	7.7482	3.6352	16	78
0	0	0	180	45	55	38.0064	9.0283	3.341	5	82
0	0	-1.6818	180	45	46.591	37.331	11.406	3.1758	6	79
1	1	1	240	55	60	51.867	16.119	2.8992	0	85
0	1.6818	0	180	61.8179	55	61.3691	16.39	2.7208	3	83
1	1	-1	240	55	50	49.9785	15.397	2.9195	0	82
-1	-1	-1	120	35	50	27.9922	8.0164	3.5725	13	79
0	0	0	180	45	55	38.6828	10.622	3.2491	5	83
-1	1	1	120	55	60	43.386	12.26	3.0622	7	82
0	0	1.6818	180	45	63.40896	41.0889	9.6128	3.2959	7	81
-1	1	-1	120	55	50	41.5236	12.898	3.0415	6	81
0	0	0	180	45	55	38.9851	10.053	3.2097	5	82
-1.6818	0	0	79.0924	45	55	26.1625	6.7602	3.4434	14	79

(c)Sugar-salt mixture solution

Coded process variables			Un-coded process variables			Responses				
Time (x_1)	Temp (x_2)	Conc. (x_3)	Time (min) (X_1)	Temp (°C) (X_2)	Conc(salt%) (X_3)	Water loss (Y_1)	Solute gain (Y_2)	Rehydration Ratio (Y_3)	Shrinkage% (Y_4)	Acceptance% (Y_5)
0	0	0	180	45	50°B+10	45.1987	13.475	2.93254	0	99
1	1	-1	240	55	50°B+5	55.3466	16.22	2.7401	0	88
0	0	0	180	45	50°B+10	45.2014	13.481	2.9511	0	99
0	0	0	180	45	50°B+10	45.1792	13.453	2.965	0	99
1.6818	0	0	280.9076	45	50°B+10	46.3632	16.115	2.678	0	95
0	0	-1.6818	180	45	50°B+1.59	40.519	12.345	3.07697	0	89
-1	1	-1	120	55	50°B+5	47.081	13.582	3.0361	2	90
0	0	1.6818	180	45	50°B+18.4	45.067	14.847	2.781	0	92
0	0	0	180	45	50°B+10	45.1587	13.449	2.9458	0	97
-1.6818	0	0	79.0924	45	50°B+10	35.2662	11.654	3.21534	3	85
0	0	0	180	45	50°B+10	45.2035	13.49	2.94235	0	98
-1	-1	1	120	35	50°B+15	44.3001	12.01	3.15979	1	84
-1	-1	-1	120	35	50°B+5	34.9035	10.038	3.2731	4	81
0	1.6818	0	180	61.8179	50°B+10	60.3769	16.484	2.75101	1	94
0	-1.6818	0	180	28.182	50°B+10	48.3881	11.453	3.117	2	90
1	-1	-1	240	35	50°B+5	41.301	12.626	3.0081	0	95
1	-1	1	240	35	50°B+15	49.2564	14.619	2.83197	0	95
1	1	1	240	55	50°B+15	51.3239	17.102	2.6154	2	94
-1	1	1	120	55	50°B+15	44.5389	14.533	2.8801	0	96
0	0	0	180	45	50°B+10	45.1693	13.448	2.9765	0	98

APPENDIX-J

Analysis of variance for overall effect of the process variables on the five responses

Osmotic solution	Process variable	d.f.	Sum of squares and (F values in parenthesis)				
			Water Loss	Solute Gain	Rehydration Ratio	Shrinkage (%)	Overall Acceptability (%)
Salt	TIME	4	0.6705 (2501.79)	0.6502 (1152.82)	0.4105 (8552.1)	362.685 (17.95)	652.3143 (7.988)
	TEMP	4	6.02287 (22473.4)	4.6776 (8293.7)	0.38075 (7932.29)	811.9128 (40.19)	1925.058 (23.57)
	CONC	4	21.09369 (78707.8)	28.7002 (50886.8)	9.07704 (189105)	191.4589 (9.47)	467.282 **(5.72)***
	RESIDUAL	10	0.00067	0.00141	0.00012	50.5079	204.141
Sugar	TIME	4	318.4339 (233.35)	29.2685 (14.313)	0.2398 (40.37)	265.5091 (199)	18.4756 (14.7)
	TEMP	4	811.3163 (594.55)	101.0326 (49.4)	0.7586 (127.7)	123.9097 (92.87)	39.4129 (31.38)
	CONC	4	11.7573 (8.61)	2.6712 **(1.306)***	0.01609 **(2.7)***	7.5929 **(5.69)***	17.3029 (13.77)
	RESIDUAL	10	3.4115	5.1122	0.01485	3.3355	3.1395
Sugar-salt Mixture	TIME	4	186.2764 (66527)	23.7983 (7627.6)	0.3101 (149.08)	20.9023 (55.67)	336.135 (96.68)
	TEMP	4	398.4193 (142292)	32.1142 (10293)	0.1918 (92.21)	9.04 (24.07)	216.054 (62.14)
	CONC	4	107.9681 (38560)	7.9295 (2541.5)	0.0842 (40.48)	7.9117 (21.07)	151.262 (43.5)
	RESIDUAL	10	0.007	0.0078	0.0052	0.9387	8.6917

F_{table} (4,10) 5% level= 3.48; F_{table} (4,10) 1% level= 5.99; * Non significant at 1% level

APPENDIX-K

Convective drying kinetics of osmosed and un-osmosed carrot cubes

(a) Un-osmosed (Blanched)

55°C					65°C					75°C				
Time (min)	M.C% (d.b.)	M.C. % (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)	Time (min)	M.C% (d.b.)	M.C.% (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)	Time (min)	M.C% (d.b.)	M.C. % (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)
0	1426.23	93.44	-	-	0	1283.89	92.77	-	-	0	1284.99	92.77	-	-
20	1308.29	92.89	5.8968	-	25	1035.17	91.19	9.9488	4.9470	35	982.80	90.76	8.6338	5.2042
45	1147.88	91.98	6.4165	2.7861	50	859.50	89.57	7.0267	7.1968	50	836.74	89.32	9.7373	8.0159
70	981.05	90.74	6.6731	4.5808	75	733.63	88.00	5.035	8.0688	70	697.07	87.45	6.9838	9.8597
100	801.39	88.90	5.9887	6.3188	105	568.50	85.04	5.5042	9.8069	100	503.38	83.42	6.4561	13.2636
125	705.14	87.57	3.8499	6.7512	115	512.05	83.66	5.6455	10.4941	137	318.91	76.12	4.9858	14.7208
155	538.31	84.33	5.5609	8.3862	160	328.87	76.68	4.0706	12.2667	200	119.70	54.48	3.1620	18.5276
185	409.98	80.39	4.2776	9.5360	200	206.14	67.33	3.0681	13.8232	260	40.41	28.78	1.3214	21.7606
230	288.07	74.23	2.7091	10.2945	230	134.30	57.32	2.3947	15.2323	320	16.84	14.41	0.3927	23.178
260	191.82	65.73	3.2082	11.7966	290	49.25	33.00	1.4174	18.2386	380	8.99	8.250	0.1309	23.7183
315	91.46	47.77	1.8246	14.2773	350	20.18	16.79	0.4846	20.0746	440	7.39	6.887	0.0265	21.9621
380	44.24	30.67	0.7265	14.909	413	11.57	10.37	0.1365	20.1131	500	6.04	5.702	0.0225	21.0376
425	17.67	15.02	0.5903	17.6183	483	7.82	7.25	0.0536	19.5911	560	5.18	4.932	0.0143	20.4256
485	11.13	10.01	0.1090	17.7055	543	6.24	5.88	0.0262	19.0766	-	-	-	-	-
545	8.31	7.67	0.0470	17.317	598	5.52	5.23	0.0132	18.4248	-	-	-	-	-
605	6.64	6.22	0.0278	16.9656	650	5.03	4.79	0.0093	17.5961	-	-	-	-	-
665	5.87	5.54	0.0128	16.3088	-	-	-	-	-	-	-	-	-	-
725	5.23	4.97	0.0106	15.9356	-	-	-	-	-	-	-	-	-	-

(b) Salt osmosed

55°C					65°C					75°C				
Time (min)	**M.C% (d.b.)**	**M.C.% (w.b)**	**Drying Rate**	**D_{ew}x10^{-10} (m^2/s)**	**Time (min)**	**M.C% (d.b.)**	**M.C. % (w.b)**	**Drying Rate**	**D_{ew}x10^{-10} (m^2/s)**	**Time (min)**	**M.C% (d.b.)**	**M.C.% (w.b)**	**Drying Rate**	**D_{ew}x10^{-10} (m^2/s)**
0	547.22	84.54	-	-	0	575.33	85.19	-	-	0	489.21	83.02	-	-
35	418.31	80.70	3.6830	5.2651	38	408.83	80.34	4.3815	7.3203	53	273.62	73.23	4.0677	12.1991
60	355.62	78.05	2.5076	6.7897	63	331.94	76.84	3.0754	9.4370	75	220.59	68.80	2.4101	13.4581
85	289.94	74.35	2.6271	8.6453	86	272.95	73.18	2.5647	10.7021	95	182.40	64.58	1.9096	14.0659
115	224.26	69.16	2.1892	10.1812	118	194.64	66.06	2.4473	12.7142	125	131.18	56.74	1.7072	15.2662
140	188.44	65.33	1.4329	10.5063	128	161.76	61.79	3.2883	14.2212	161	86.26	46.31	1.2478	16.4275
170	134.70	57.39	1.7912	12.0765	173	93.85	48.41	1.5090	16.0222	225	43.85	30.48	0.6626	16.8848
200	95.89	48.95	1.2936	13.2425	213	59.18	37.18	0.8666	16.865	285	29.84	22.98	0.2334	16.1303
245	63.05	38.67	0.7297	13.8607	243	42.11	29.63	0.5688	17.354	345	22.18	18.15	0.1276	15.0111
275	45.14	31.10	0.5970	14.5554	303	24.87	19.91	0.2874	17.2736	405	16.66	14.28	0.0921	14.3268
330	30.51	23.38	0.2659	14.3774	363	19.22	16.12	0.0941	15.8866	465	13.04	11.54	0.0601	13.6977
395	21.26	17.53	0.1423	13.8464	426	15.47	13.40	0.0594	14.6567	525	10.42	9.43	0.0437	13.2349
440	16.84	14.41	0.0981	13.5648	486	12.03	10.73	0.0574	14.0886	575	8.61	7.93	0.0361	12.8304
500	13.56	11.94	0.0547	12.9340	546	9.94	9.04	0.0346	13.4683	605	7.08	6.61	0.0510	12.6927
560	12.07	10.77	0.0248	12.0600	601	8.40	7.75	0.0281	13.0813	620	5.27	5.01	0.1203	13.7205
620	9.14	8.37	0.0487	12.1193	666	6.97	6.52	0.0219	12.7978	-	-	-	-	-
680	7.65	7.10	0.0248	11.9007	726	5.96	5.62	0.0168	12.7053	-	-	-	-	-
740	6.51	6.11	0.0189	11.7850	765	5.19	4.93	0.0198	12.8091	-	-	-	-	-
800	5.20	4.94	0.0218	12.4583	-	-	-	-	-	-	-	-	-	-

(c) Sugar osmosed

55°C					65°C					75°C				
Time (min)	M.C% (d.b.)	M.C.% (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)	Time (min)	M.C% (d.b.)	M.C.% (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)	Time (min)	M.C% (d.b.)	M.C.% (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)
0	354.51	77.99	-	-	0	362.69	78.38	-	-	0	334.76	76.99	-	-
20	317.73	76.06	1.8393	-	3	352.42	77.89	3.4238	-	15	295.48	74.71	2.6183	-
45	274.62	73.30	1.7243	3.7811	21	297.92	74.86	3.0278	-	30	254.28	71.77	2.7471	6.4604
70	231.51	69.83	1.7243	5.7600	41	259.22	72.16	1.9347	6.6465	50	217.65	68.51	1.8311	8.2061
100	193.19	65.89	1.2773	6.9425	76	212.65	68.01	1.3306	7.5355	80	170.02	62.96	1.5877	10.1669
125	171.63	63.18	0.8621	7.1559	86	189.24	65.42	2.3404	8.9131	117	126.88	55.92	1.1659	11.2710
155	142.89	58.83	0.9579	7.8046	131	145.06	59.19	0.9818	9.3322	180	72.06	41.88	0.8702	12.8741
185	118.94	54.32	0.7983	8.2682	171	113.40	53.14	0.7914	9.6616	240	40.42	28.78	0.5272	14.0588
230	94.99	48.71	0.5322	8.3676	201	94.64	48.62	0.6253	9.8016	300	24.11	19.42	0.2718	14.5785
260	78.23	43.89	0.5588	8.7260	261	60.21	37.58	0.5737	10.6422	360	14.49	12.66	0.1602	15.1989
315	60.51	37.69	0.3222	8.6662	321	39.11	28.11	0.3517	11.1205	420	11.39	10.23	0.0516	14.4350
380	42.30	29.73	0.2800	8.9131	384	24.85	19.90	0.2263	11.5871	480	8.83	8.11	0.04269	14.1259
425	30.43	23.33	0.2639	9.4362	444	16.41	14.09	0.1407	11.9948	540	7.44	6.92	0.0232	13.6189
485	22.28	18.22	0.1357	9.5511	504	12.00	10.71	0.0734	12.0373	600	6.45	6.06	0.0164	13.2091
545	16.77	14.36	0.0918	9.6102	559	9.51	8.69	0.0451	11.9765	660	5.69	5.38	0.0127	12.9623
605	12.08	10.78	0.0782	9.935	624	7.78	7.22	0.0266	11.7509	690	5.10	4.85	0.0194	12.8761
665	9.54	8.71	0.0423	9.9955	684	6.65	6.24	0.0187	11.5923	-	-	-	-	-
725	7.77	7.21	0.0295	10.064	744	5.90	5.57	0.0125	11.4108	-	-	-	-	-
785	5.76	5.44	0.0335	10.9339	795	5.29	5.02	0.0119	11.3690	-	-	-	-	-
830	5.13	4.88	0.0138	11.2276	-	-	-	-	-	-	-	-	-	-

(d) Sugar-salt mixture

55°C					65°C					75°C				
Time (min)	M.C% (d.b.)	M.C.% (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)	Time (min)	M.C% (d.b.)	M.C. % (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)	Time (min)	M.C% (d.b.)	M.C.% (w.b)	Drying Rate	D_{ew}x10^{-10} (m^2/s)
0	249.52	71.38	-	-	0	245.81	71.08	-	-	0	259.39	72.17	-	-
35	179.85	64.26	1.9906	7.5360	15	204.67	67.17	2.7426	-	33	171.43	63.15	2.6652	11.7725
60	149.29	59.88	1.2221	9.0967	40	160.03	61.54	1.7856	10.2956	55	132.87	57.05	1.7526	14.6378
85	121.56	54.86	1.1090	10.498	62	127.13	55.97	1.4956	12.7387	75	108.29	51.99	1.2289	15.4502
115	94.68	48.63	0.8963	11.5539	95	90.45	47.49	1.1113	14.5642	105	77.90	43.79	1.0130	16.5809
140	80.25	44.52	0.5768	11.5819	105	70.44	41.32	2.0011	17.4155	141	53.87	35.01	0.6675	17.0618
170	58.90	37.07	0.7117	12.8044	150	46.46	31.72	0.5327	17.2348	205	29.69	22.89	0.3779	17.1885
300	46.95	31.95	0.0919	8.6389	190	33.57	25.13	0.3223	16.825	265	19.87	16.57	0.1636	16.3643
345	35.00	25.92	0.2655	9.1094	220	26.53	20.97	0.2347	16.6036	325	14.84	12.92	0.0837	15.3212
375	24.88	19.92	0.3372	10.1512	280	17.68	15.02	0.1475	16.0544	385	11.86	10.60	0.0497	14.3442
430	18.75	15.79	0.1115	10.2184	340	15.45	13.38	0.0372	14.1057	445	10.17	9.23	0.028	13.327
495	12.93	11.45	0.0894	10.5868	403	11.41	10.24	0.0641	13.7241	505	8.88	8.15	0.0215	12.5311
540	11.30	10.15	0.0362	10.3357	463	9.10	8.34	0.0384	13.3074	565	8.05	7.45	0.0137	11.7533
600	9.58	8.752	0.0285	10.0545	523	7.90	7.32	0.0198	12.6409	625	6.41	6.02	0.0273	12.0261
660	8.59	7.91	0.0165	9.6424	578	7.02	6.56	0.0160	12.1882	671	5.58	5.28	0.0180	11.7569
720	7.47	6.95	0.0185	9.4912	643	6.33	5.95	0.0106	11.6393	700	5.15	4.89	0.0148	11.6904
780	6.60	6.19	0.0146	9.3896	703	5.71	5.40	0.0102	11.3830	-	-	-	-	-
840	5.96	5.62	0.0106	9.2838	763	5.33	5.06	0.0064	11.0501	-	-	-	-	-
900	5.48	5.20	0.0079	9.1880	815	5.29	5.02	0.0007	10.3047	-	-	-	-	-

APPENDIX-L

Analysis of Variance for average total convective dehydration time

Source of Variation	SS	df	MS	F	P-value	F crit
Drying air temp.	60762.5	2	30381.25	97.43653	2.66E-05	5.143249
Osmotic treatment	43091.67	3	14363.89	46.06682	0.000155	4.757055
Error	1870.833	6	311.8056			
Total	105725	11				

APPENDIX-M

Analysis of Variance for Shrinkage constants 'A' and 'B' during convective dehydration

For 'A'

Source of Variation	SS	d.f.	MS	F	P-value	F crit
TREATMENT	0.067027	3	0.022342	122.2848	9.06E-06	4.757055
TEMPERATURE	0.006499	2	0.003249	17.78518	0.003007	5.143249
Error	0.001096	6	0.000183			
Total	0.074622	11				

For 'B'

Source of Variation	SS	d.f.	MS	F	P-value	F crit
TREATMENT	13.43736	3	4.47912	132.7538	7.11E-06	4.757055
TEMPERATURE	0.082886	2	0.041443	1.228296	0.357164	5.143249
Error	0.20244	6	0.03374			
Total	13.72269	11				

APPENDIX-N

ANOVA for Average effective moisture diffusivity during convective dehydration

Source of Variation	SS	d.f.	MS	F	P-value	F crit
TEMPERATURE	2.82E-19	2	1.41E-19	28.74673	0.000844	5.143249
TREATMENT	1.52E-19	3	5.06E-20	10.30685	0.008796	4.757055
Error	2.94E-20	6	4.91E-21			
Total	4.63E-19	11				

APPENDIX- O

Regression summary and statistical parameters for various empirical models for convective dehydration of carrot cubes

(a) Page Model

Expt No.	Temp (°C)	Osmotic treatment	K	N	E%	χ^2	RMSE	R^2
I	55	Un-osmosed	0.006591	0.97562	6.122	3.5E-05	0.00561	0.999
II	55	Salt	0.021056	0.796039	15.659	0.000195	0.01321	0.998
III	55	Sugar	0.004976	1.096047	31.057	0.000148	0.01150	0.998
IV	55	Sugar-Salt	0.002417	1.181917	5.594	6.46E-05	0.00758	0.999
V	65	Un-osmosed	0.010575	0.919519	11.945	0.000104	0.00966	0.999
VI	65	Salt	0.015472	0.919913	39.583	0.000466	0.02042	0.995
VII	65	Sugar	0.0055	1.115179	39.771	0.000187	0.01290	0.998
VIII	65	Sugar-Salt	0.001778	1.283433	18.130	6.01E-05	0.00683	0.999
IX	75	Un-osmosed	0.009088	0.986531	22.440	8.58E-05	0.00866	0.999
X	75	Salt	0.023126	0.842234	32.370	0.000259	0.01504	0.997
XI	75	Sugar	0.014181	0.936274	31.421	0.000134	0.01077	0.998
XII	75	Sugar-Salt	0.003651	1.211926	22.954	8.09E-05	0.00827	0.999

(b) Log Model

Expt No.	Temp (°C)	Osmotic treatment	A	K	C	E%	χ^2	RMSE	R^2
I	55	Un-osmosed	0.992009	0.00594	0.00879	2.97	3.16E-5	2.69E-5	0.999
II	55	Salt	0.940609	0.008491	0.03857	19.78	0.00031	0.00026	0.996
III	55	Sugar	1.018546	0.008186	0.00172	23.09	0.00027	0.00023	0.997
IV	55	Sugar-Salt	1.061981	0.006012	-0.02752	54.33	0.00037	0.00031	0.997
V	65	Un-osmosed	0.970501	0.007056	0.00946	5.347	0.00016	0.00013	0.998
VI	65	Salt	0.970007	0.011531	0.02847	10.49	0.00014	0.00012	0.998
VII	65	Sugar	1.016823	0.00979	0.00385	25.86	0.00034	0.00028	0.996
VIII	65	Sugar-Salt	1.078998	0.007093	-0.03244	105.83	0.00092	0.00074	0.993
IX	75	Un-osmosed	0.990588	0.008744	0.00970	9.20	5.57E-5	4.53E-5	0.999
X	75	Salt	0.959833	0.012216	0.03122	12.33	6.26E-5	5.09E-5	0.999
XI	75	Sugar	0.983071	0.010984	0.01668	10.70	3.91E-5	3.13E-5	0.999
XII	75	Sugar-Salt	1.058335	0.009531	-0.02374	116.80	0.00072	0.00055	0.995

(C) Generalised Exponential Model

Expt No.	Temp (°C)	Osmotic treatment	A	K	E%	χ^2	RMSE	R^2
I	55	Un-osmosed	0.997014	0.005785	9.0633	4.96E-5	0.00667	0.999
II	55	Salt	0.953773	0.007342	42.310	0.00096	0.02941	0.982
III	55	Sugar	1.019577	0.008147	26.426	0.00026	0.01533	0.997
IV	55	Sugar-Salt	1.043739	0.006452	43.275	0.00052	0.00046	0.995
V	65	Un-osmosed	0.977057	0.00686	14.879	0.00017	0.01265	0.998
VI	65	Salt	0.987758	0.010576	44.580	0.00054	0.02216	0.994
VII	65	Sugar	1.019322	0.009688	36.046	0.00032	0.01708	0.996
VIII	65	Sugar-Salt	1.056647	0.007675	62.793	0.00114	0.03159	0.991
IX	75	Un-osmosed	0.996597	0.008485	23.129	8.85E-5	0.00879	0.999
X	75	Salt	0.977747	0.011089	46.257	0.00058	0.02270	0.993
XI	75	Sugar	0.994009	0.010471	37.125	0.00017	0.01240	0.997
XII	75	Sugar-Salt	1.042087	0.01011	62.179	0.00086	0.02707	0.993

(d) Two Term Exponential Model

Expt No.	Temp (°C)	Osmotic treatment	A	K_0	B	K_1	E%	χ^2	RMSE	R^2
I	55	Un-osmosed	0.99701	0.00578	3E-13	3E-13	9.0633	5.58E-5	0.0066	0.999
II	55	Salt	0.33528	0.00344	0.66447	0.012413	8.2249	5.96E-5	0.0068	0.999
III	55	Sugar	1.02092	0.00819	0.00258	-0.00277	16.371	0.0002	0.0150	0.997
IV	55	Sugar-Salt	0.52194	0.00645	0.52179	0.006452	43.275	0.0006	0.0214	0.995
V	65	Un-osmosed	0.97917	0.00695	0.00270	-0.00489	3.9382	0.0002	0.0116	0.998
VI	65	Salt	0.98775	0.01057	-2.3E-13	-2.3E-13	44.580	0.00062	0.0221	0.994
VII	65	Sugar	1.02088	0.00976	-0.00774	0.001412	16.703	0.00035	0.0165	0.996
VIII	65	Sugar-Salt	0.50082	0.00767	0.55582	0.007675	62.793	0.00133	0.0315	0.991
IX	75	Un-osmosed	0.99955	0.00863	-0.0173	0.001027	5.9305	5.12E-5	0.0061	0.999
X	75	Salt	0.97774	0.01108	2.36E-13	2.36E-13	46.257	0.0007	0.0227	0.993
XI	75	Sugar	0.99776	0.01068	0.00747	-0.00385	16.370	5.91E-5	0.0065	0.999
XII	75	Sugar-Salt	0.51835	0.01009	0.518342	0.010095	50.392	0.0009	0.0253	0.994

(e) Midilli Model

Expt No.	Temp (°C)	Osmotic treatment	A	K	N	C	E (%)	χ^2	RMSE	R^2
I	55	Un-osmosed	1.00536	0.00660	0.97768	6.69E-6	1.9916	3.05E-5	0.0049	0.999
II	55	Salt	1.00547	0.01815	0.83185	2.38E-5	6.1815	0.00013	0.0101	0.998
III	55	Sugar	0.99287	0.00423	1.12976	1.94E-5	12.750	0.00010	0.0089	0.999
IV	55	Sugar-Salt	0.99722	0.00233	1.18806	7.3E-7	5.2528	7.31E-5	0.0075	0.999
V	65	Un-osmosed	0.99342	0.00997	0.92977	2.22E-6	9.9757	0.00010	0.0091	0.999
VI	65	Salt	0.99982	0.01275	0.96503	3.94E-5	14.093	0.00010	0.0090	0.998
VII	65	Sugar	0.99498	0.00481	1.14449	2.11E-5	18.432	0.00012	0.0100	0.998
VIII	65	Sugar-Salt	0.98886	0.00153	1.31067	3.4E-6	8.3443	7.95E-5	0.0077	0.999
IX	75	Un-osmosed	0.99648	0.00809	1.01290	1.96E-5	5.3431	4.89E-5	0.0060	0.999
X	75	Salt	1.00176	0.01850	0.89702	3.95E-5	12.924	5.25E-5	0.0062	0.999
XI	75	Sugar	0.99994	0.01177	0.97932	2.66E-5	14.466	5.46E-5	0.0063	0.999
XII	75	Sugar-Salt	0.99400	0.00343	1.22378	3.34E-6	16.927	9.83E-5	0.0082	0.999

(f) Modified Midilli Model

Expt No.	Temp (°C)	Osmotic treatment	A	K	N	C	E (%)	χ^2	RMS E	R^2
I	55	Un-osmosed	0.99919	0.00653	0.98127	0.00584	2.1714	3E-05	0.0049	0.999
II	55	Salt	0.98171	0.01689	0.85421	0.02260	6.9837	0.00011	0.0094	0.998
III	55	Sugar	0.97918	0.00403	1.14319	0.01271	9.2810	0.00010	0.0089	0.999
IV	55	Sugar-Salt	0.99705	0.00234	1.18760	0.00023	5.5793	7.32E-5	0.0075	0.994
V	65	Un-osmosed	0.99418	0.01015	0.92572	-0.00023	10.021	0.00010	0.0091	0.999
VI	65	Salt	0.96829	0.01113	1.00448	0.02773	8.8013	5.88E-5	0.0068	0.998
VII	65	Sugar	0.98046	0.00449	1.16315	0.01343	10.236	0.00012	0.0097	0.998
VIII	65	Sugar-Salt	0.98760	0.00153	1.31054	0.00132	10.025	8.02E-5	0.0077	0.999
IX	75	Un-osmosed	0.98434	0.00795	1.01985	0.01160	7.0602	5.57E-5	0.0064	0.999
X	75	Salt	0.97376	0.01654	0.93168	0.02663	8.3305	1.99E-5	0.0038	0.999
XI	75	Sugar	0.98249	0.01080	1.00363	0.01694	9.998	4.25E-5	0.0055	0.999
XII	75	Sugar-Salt	0.99474	0.00348	1.22007	-0.00048	18.513	7.42E-5	0.0074	0.999

APPENDIX-P

Average ambient temperature (°C) and relative humidity (%) during year 2004

Month	Average Temperature (°C)		Average relative humidity (%)	
	Maximum	Minimum	Maximum	Minimum
January	17.3	7.8	98	76
February	22.9	8.7	95	51
March	30.9	13.9	88	36
April	37	20.4	55	24
May	39.4	23.3	58	39
June	35.9	25.1	69	46
July	35.8	27.2	78	59
August	32.9	26	89	72
September	34.3	23.7	88	53
October	29.7	17.1	92	52
November	26.7	11.8	87	45

VITA

Name of the student : Bahadur Singh

Father's name : S. Dewan Singh

Mother's name : Smt. Bachan Kaur

Nationality : Indian

Date of birth : 27-12-1965

Permanent home address : V.P.O.:- Hathan
Tehsil :- Malerkotla
Distt:- Sangrur (Pb)
Pin Code :- 148023

EDUCATIONAL QUALIFICATIONS

Bachelor Degree : B. Sc. (Non medical)
- University : Punjabi University, Patiala.
- Year of award : 1986
- Percentage of marks : 60.00%

Bachelor Degree : B. Tech. (Agril. Engineering)
- University : Punjab Agricultural University, Ludhiana.
- Year of award : 1991
- OGPA/OCPA : 2.73/4.00

Master's Degree : M. Tech. (Agro Industrial Processing)
- University : Punjab Agricultural University, Ludhiana.
- Year of award : 1997
- OCPA : 7.78/10.00

Ph.D.
- OCPA : 8.12/10.00

Title of Master's Thesis : Quality improvement of Raisins by osmo-mechanical dehydration of grapes grown in Punjab