COMPARATIVE PERFORMANCE OF SOLAR CABINET, VACUUM ASSISTED SOLAR AND OPEN SUN DRYING METHODS

By

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ABSTRACT

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Tomato (*Lycopersicon esculentum L.var*) is one of the most important vegetables in our diet and dried tomato products are becoming popular for the preparation of various food items. Though sun drying has been used for the preservation, it is a slow process and the quality of the dried product is often inferior due to contaminations. Therefore, a lab model solar cabinet and vacuum assisted solar dryers were developed to study the drying kinetics of tomato slices (4, 6 and 8 mm thicknesses) and the results were compared individually with open sun drying under the weather conditions of Montreal, Canada. The drying kinetics using thin layer drying models and the influence of weather parameters such as ambient air temperature, relative humidity, solar insolation and wind velocity on drying of tomato slices were evaluated.

During drying, it was observed that the temperatures inside the solar cabinet and vacuum chamber were increased to 63 and 48^{o}C when the maximum ambient temperature was only 30^{o}C. The tomato slices of 4, 6 and 8 mm thicknesses could be dried from 94.0 to 11.5% wet basis moisture content, respectively in 300, 420 and 570 min using solar cabinet, in 360, 480 and 600 min using vacuum assisted solar dryer and it took 435, 615 and 735 min under open sun drying method.

The quality of tomato slices in terms of physicochemical parameters such as colour retention, water activity, rehydration capacity and ascorbic acid retention were evaluated and the overall study concluded that good quality dehydrated tomato slices could be produced by using vacuum assisted solar dryer compared to solar cabinet and open sun drying methods. The Page model was found to be better in describing the drying kinetics of tomato slices in all the drying methods studied.

RÉSUMÉ

RAJKUMAR PERUMAL

M.Sc. **Bioresource Engineering**

ANALYSE COMPARATIVE DE LA PERFORMANCE DU SÉCHAGE AVEC UN SÉCHOIR SOLAIRE, UN SÉCHOIR SOLAIRE SOUS-VIDE ET PAR SÉCHAGE NATUREL

La tomate (*Lycopersicon esculentum L. var*) est une importante source nutritive de notre alimentation et les tomates séchées gagnent en popularité dans de nombreuses préparations alimentaires. Le séchage naturel est la méthode traditionnelle utilisée pour la production de tomates séchées, cependant c'est un processus lent et la qualité du produit séché est variable et sujette à la contamination. Un séchoir solaire et un séchoir solaire sous-vide furent donc développés afin d'étudier le séchage solaire de tranches de tomates (4, 6 et 8 mm d'épaisseur) en comparaison au séchage naturel sous les conditions météorologiques de Montréal, Canada. La cinétique du séchage des tranches de tomates suivant des modèles en couches minces a été établie en fonction de l'influence des conditions météorologiques telles que la température ambiante, l'humidité relative, le rayonnement solaire et la vitesse du vent.

Lors du séchage dans le séchoir solaire et le séchoir solaire sous-vide, la température interne des deux séchoirs a atteint 63° et 48°C respectivement alors que la température ambiante était de 30°C. Les tranches de tomates de 4, 6 et 8 mm d'épaisseur ont pu être séchées d'un taux d'humidité de 94% à 11.5% (état humide) et ce après 300, 420 et 570 minutes en utilisant le séchoir solaire, en 360, 480 et 600 minutes grâce au séchoir solaire sous-vide, alors qu'il en a pris 435, 615 et 735 minutes par séchage naturel.

La qualité des tranches de tomates a été évaluée en fonction de certains paramètres physico-chimiques tels que la stabilité de la couleur, l'activité de l'eau, la capacité de réhydratation, et la conservation de l'acide ascorbique. Des tranches de tomates séchées de meilleure qualité peuvent être produites par séchage solaire sous-vide en comparaison avec le séchage solaire et le séchage naturel. La modélisation de Page offre une très bonne représentation de la cinétique du séchage des tranches de tomates et ce pour les trois méthodes de séchage étudiées.

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(P.RAJKUMAR)

CONTRIBUTIONS OF AUTHORS

The authors for both the articles in this thesis are P.Rajkumar, G.S.V.Raghavan and Y.Gariepy. The research work submitted here was performed by the candidate and supervised by Dr.G.S.V.Raghavan of the Department of Bioresource Engineering, Macdonald campus of McGill University, Montreal, Canada. The entire fabrication and experimental study were carried out in the post harvest technology lab, Department of Bioresource Engineering, McGill University. Mr. Y.Gariepy provided technical assistance in the design and fabrication of solar dryers which was used to collect the data during the entire experimental period.

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NOMENCLATURE

a & b	Drying constants in Wang and Singh model
a*	Red - green axis
a_w	Water activity
b*	Yellow - blue axis
CV	Coefficient of variance, %
D_{eff}	Effective moisture diffusivity (m^2/s)
DM	Dry matter
k	Drying rate constant (min^{-1})
L	Slice thickness, (m)
L*	Neutral gray axis (white = 100; black = 0)
LSD	Least significant difference
M_e	Equilibrium moisture content in decimal, (d.b)
M_i	Initial moisture content in decimal, (w.b)
M_t	Moisture content, dry basis (decimal) at ts time, (d.b)
MR	Moisture ratio
MR_{exp}	Experimental moisture ratio
MR_{pre}	Predicted moisture ratio
M_θ	Moisture content, dry basis (decimal) at θ time
NS	Non-significant
P	Probability
q & n	Drying constants in Page model
R^2	Coefficient of determination
RMSE	Root mean square error
SCD	Solar cabinet dryer
SEd	Standard error difference,
t	Drying time, min
VSD	Vacuum assisted solar dryer
W_D	Initial mass of the sample before rehydration, g
Wr	Rehydrated sample mass, g
χ^2	Chi-square

I. GENERAL INTRODUCTION

1.1 Introduction

Vegetables and their products are of great nutritional importance since they make a significant contribution in supplying wealth of essential vitamins, minerals, antioxidants, fibers and carbohydrates that improve the quality of the diet. Many vegetables are highly seasonal in nature. They are available in plenty at a particular period of time in specific regions that many times result in market glut. Due to perishable nature, huge quantity of vegetables is spoiled within a short period. The post harvest loss in vegetables has been estimated to be about 30-40% due to inadequate post harvest handling, lack of infrastructure, processing, marketing and storage facilities (Karim and Hawlader, 2005). Therefore, the food processing sector can play a vital role in reducing the post harvest losses by processing and value addition of vegetables which will ensure better remuneration to the growers.

Tomato (*Lycopersicon esculentum L.var*) is one the most important fruits/vegetables grown in a wide range of climates, mostly in open - field but also under protection in plastic green houses and heated glass houses. It is a commercially important crop both for fresh fruit market and for the food processing industries. The annual world wide production of tomatoes has been estimated at 125 million tonnes in an area of about 4.2 million hectares. The global production of tomatoes (fresh and processed) has been increased by 300% in the last four decades (FAO, 2005) and the leading tomato producers are in both tropical and temperate regions. Canada is also an important producer of tomato (USDA, 2004) with an annual production of about 0.6 million tonnes both for processing and fresh fruit consumption (Statistics-Canada, 2006).

Tomatoes are one of the important vegetables/fruits in our diet, since they are rich in health valued food components such as carotenoids (Lycopene), ascorbic acid (Vitamin C), vitamin E, folate and dietary fiber (Davies and Hobson, 1981). It is a versatile commodity that can be eaten fresh or processed to use in a wide array of products to improve these flavour. There is a rapid development of tomato processing industries in recent decades with a series of interlinked activities. Various foods prepared from tomatoes are: i) tomato preserves such as whole peeled tomatoes, tomato paste, tomato juice, tomato pulp, tomato puree and pickled tomatoes, ii) dried tomatoes such as tomato flakes and tomato powder and iii) tomato based foods such as tomato soup, tomato sauce and ketchup.

To increase the shelf life of tomatoes, different preservation techniques are being employed that comprise of manipulation of storage temperature and relative humidity, addition of chemical preservatives, protection against air / germ pollution through waxing, dehydration and processing into other products. However, the success of these methods depends on how it meets certain requirements of the product quality for consumption. Therefore, it is essential to preserve the tomatoes by using any of the food preservation techniques and to be made available in an acceptable form throughout the year at relatively minimum cost.

Drying is a common technique for preservation of food and other products; including fruits and vegetables. The major advantage of drying food products is the reduction of moisture content to a safe level that allows to extend the shelf life of dried products. The removal of water from foods provides microbiological stability and reduces deteriorative chemical reactions. Also, the process allows a substantial reduction in terms of mass, volume, packaging requirement, storage and transportation costs with more convenience (Okos et al., 1992). Therefore, the drying processes offer an alternative way of using tomato for consumption. The dehydration of tomato has been practiced for many years as a means of preserving tomato. Dried tomato in the form of slice or powder helps to develop new food materials for ready to eat products. Recently, there is a great demand for natural sun / solar dried organic or bio-cultivated tomato in the international markets. Fresh tomatoes are dried into halves, quarters, slices and powdered for making different products.

Sun drying is a well known traditional method of drying agricultural commodities immediately after harvest. However, it is plagued with in-built problems, since the product is unprotected from rain, storm, windborne dirt, dust, and infestation by insects, rodents, and other animals. It may result in physical and structural changes in the product such as shrinkage, case hardening, loss of volatiles and nutrient components and lower water reabsorption during rehydration. Therefore, the quality of sun dried product is degraded and sometimes become not suitable for human consumption.

Though different mechanical drying methods are available, they are expensive, need technical skill and many of them lead to poorer quality final product. Also, it is an energy consuming process in the post harvest processing of food products. The dryers are fueled mainly through petroleum products, biomass or electricity for their drying applications. Of the world's total energy requirements, 80% comes from fossil fuels and only 2-3% is through renewable energy sources (WEA, 2000). The escalation of fuel cost, fossil fuel depletion and high pollution potential of conventional fuels to the environment has resulted in a search for a safe alternative fuel for dryers. Future energy systems are likely to have significant shares of renewable energy as it is the transition from existing fossil fuel driven energy systems to a sustainable energy systems based on renewable energy (Banerjee, 2005).

Solar energy is one of the most promising renewable energy sources in the world because of its abundance, inexhaustible and non-pollutant in nature compared with higher prices and shortage of fossil fuels (Basunia and Abe, 2001). The concept of a dryer powered by solar energy is becoming increasingly feasible because of the gradual reduction in price of solar collectors coupled with the increasing concern about atmospheric pollution caused by conventional fossil fuels used for drying crops. However, conversion technologies differ from region to region, due to the variation in the solar intensities (Bahnasawy and Shenana, 2003). Solar drying can be considered as an elaboration of sun drying and is an efficient system of utilizing solar energy. The introduction of solar drying system seems to be one of the most promising alternatives to reduce post harvest losses (Muhlbauer et al., 1993). The solar dried products have much better colour and texture as compared to open sun dried products. The justification for solar dryers is that they dry products rapidly, uniformly and hygienically, the traits inevitable for industrial food drying processes. Since, they are more effective than sun drying, but have lower operating costs than mechanized dryers (Diamente and Munro, 1993; Condori et al., 2001), more importance is given now-a-days to use solar dryers.

Different types of solar dryers for drying of biological materials have been reviewed by Ekechukwa and Norton (1998) and Farkas (2004). Although for commercial production of agricultural products, forced convection solar dryer provides a better control of drying air, they require additional energy for drying operation. Hence, natural convection solar dryer is highly preferred for drying food products especially when in thin layers (Pangavhane, et al., 2002). Therefore, a research study was undertaken to evaluate a natural convection solar cabinet dryer for drying sliced tomatoes.

However, it is a serious concern that drying at higher temperatures may cause damage to the flavour, color and nutrients of the dehydrated product (Prakash et al., 2004; Praveenkumar et al., 2006). Further, undesirable quality changes in the dehydrated products may also be due to the presence of oxygen in the drying medium. Dehydration of food materials containing antioxidants is a difficult food process operation, mainly because of undesirable changes that occur in the quality of dehydrated products. Vacuum drying is one of the efficient means of drying food materials having oxidative and heat sensitivity properties. Since, the lower pressure (vacuum) in the system allows the use of lower drying temperature in order to achieve similar moisture content of the end product. Generally, processing of tomatoes to a final moisture content of < 15% often involves high temperature in the presence of oxygen and therefore, the product show oxidative damage (Zanoni et al., 1998). It is reported that the quality of vacuum dried coconut was superior to the conventionally dried products (Fernando and Thangavel, 1987). Therefore, a vacuum assisted solar dryer could be a better alternative for drying food materials susceptible for oxidation and heat sensitivity, since solar radiation can pass through vacuum and the moisture in the product can be driven out at lower temperatures (Kiranoudis et al., 1992).

Drying kinetics is generally affected by air temperature, relative humidity, air velocity and material size (Kiranoudis et al., 1992). Generally, the drying phenomena can be described using thin layer drying models mainly to estimate the drying times and moisture content of the food materials at any time after they are subjected to a known temperature and relative humidity (Torgul and Pehlivan, 2004). Many research studies have been reported on mathematical modelling and experimental studies conducted on thin layer drying process of various food products such as onion and pepper (Kiranoudis, 1992), chilli (Hussain and Bala, 2002), carrot (Doymaz, 2004) and tomato (Sacilik et al., 2006). In modelling, the investigators have tested various models and reported the best model that fit the experimental data. Although considerable literature is available on drying kinetics of various food products using thin layer drying models, no information is available on vacuum assisted solar drying of tomato slices. Since, solar energy is sustainable and any research work in this line will help to produce quality dried products.

1.2 Hypothesis

This research work is focused on the development and evaluation of a natural convection solar dryer and a vacuum assisted solar dryer for drying tomato slices in relation to weather parameters. The hypothesis is that during solar cabinet and open sun drying of tomato slices, they might be subjected to oxidative heat damages. The oxidative heat damage can be controlled by vacuum application in solar drying. Therefore, the final vacuum dried slices should be better in terms of physicochemical qualities such as colour retention, rehydration capacity, nutrient content and lower water activity.

1.2 Objectives

Based on the hypothesis, three objectives were formulated as follows:

- To develop and evaluate a natural convection solar cabinet dryer for drying sliced tomatoes in relation to weather parameters such as ambient air temperature, relative humidity, wind velocity and solar insolation and compare its performance in terms of product quality *vis a vis* open sun drying.
- To develop and evaluate a vacuum assisted solar dryer for drying sliced tomatoes in relation to weather parameters and compare its performance with open sun drying.
- To evaluate the drying kinetics of both solar and vacuum assisted solar drying of tomato slices in relation to open sun drying using thin layer drying models and also to evaluate their physicochemical quality.

II. REVIEW OF LITERATURE

This chapter deals with the review of research works carried out on general information about tomatoes, open sun drying, solar drying, vacuum application in drying, thin layer drying models and biochemical quality.

2.1 General Introduction on Tomatoes

Tomatoes (*Lycopersicon esculentum L.var*) are the world's most commercially produced and used vegetable crop (Ensminger et al., 1994). The annual world wide production of tomatoes has been estimated at 125 million tonnes in an area of about 4.2 million hectares. It is very important in the economic point of view and hence the global production of tomatoes (fresh and processed) has been increased by 300% in the last four decades (FAO, 2005) and the leading tomato producers are in both tropical and temperate regions (Dhaliwal et al., 2003). India's contribution is around 7.6 million tonnes (http://faostat.fao.org). Canada is also an important producer of tomato (USDA, 2004) with an annual production of about 0.6 million tonnes both for processing and fresh fruit consumption (Statistics-Canada, 2006).

Over the last few years, tomato products have aroused new scientific interest due to their antioxidant activity. Tomatoes and tomato products are rich in health-related food components as they are good sources of carotenoids (in particular, lycopene), ascorbic acid (vitamin C), vitamin E, folate and flavanoids (Davies and Hobson, 1981). They also provide potassium, iron, phosphorous and some B vitamins and are a good source of dietary fiber. They have around 90% water and the large amount of water also makes the fruit perishable. In a ripe fruit, solids form about 5.7% of the fruit, mainly sugars in the form of glucose and a small portion of acid in the form of citric acid (Wills, 1981). The chemical composition of the tomato fruit depends on factors such as cultivar, maturity and environmental conditions, in which they are grown (Davies and Hobson, 1981).

It is a short duration crop, giving high yield. But the excess production results in a glut in the market and reduction in tomato prices. Also, it is highly perishable in the fresh state leading to wastage and losses during the peak harvesting period. The prevention of these losses and wastage is very much important especially due to subsequent imbalance in supply and demand at the harvesting off season and economic consideration (Karim and Hawlader, 2005). Therefore, there is a need to increase the shelf life of tomatoes either in fresh or in processed form using food preservation techniques.

2.2 Drying Methods

Drying is one of the oldest methods of food preservation technique and it represents a very important aspect of food processing. During drying two processes take place simultaneously such as heat transfer to the product from the heating source and mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air. The basic essence of drying is to reduce the moisture content of the product to a level that prevents deterioration within a certain period of time, normally regarded as the "safe storage period" as reported by Ekechukwu (1998).

The drying of fruit and vegetables is a subject of great importance. Dried fruit and vegetables have gained commercial importance and their growth on a commercial scale has become an important sector of agricultural industry (Karim and Hawlader, 2005). The advantages of dried foods are illustrated by Somogyi and Luh (1986):

- Extended shelf life because of inhibition of microbial and enzymatic reactions.
- Providing consistent product and the seasonal variations are diminished.
- Substantially lower cost of handling, transportation and storage.
- The dried products size, shape and form are modified and the price is constant throughout the year.
- Dried foods can be packed in recyclable packages; this is not always done with fresh foods.
- The dried foods can be used as snacks and other processed foods.

But during drying, the changes associated with physical and biochemical structure are inevitable because the food is subjected with thermal, chemical and other treatments.

Drying is one of the most energy intensive unit operations and consequently many research works have been carried out to explore the possible energy utilization. It is obvious that in many rural locations, grid-connected electricity and supplies of other non-renewable sources of energy are either unavailable, unreliable or, for many farmers, too expensive. Thus, in such areas, food drying systems that employ motorised fans and/or electrical heating are inappropriate (Ekechukwu and Norton, 1997). The large initial and running costs of fossil fuel powered dryers present such barriers that they are rarely adopted by small scale farmers. The optimization of dryers necessitates complete knowledge of the whole drying process, thus leading to energy savings and avoiding environmental pollution by using renewable sources of energy (Icerman and Morgan, 1984).

Usage of renewable energy technologies has received considerable attention within the past five years for their potential to help meet basic needs in many countries (Banerjee, 2005). Also, use of renewable energy today is much more desirable because most of the other alternative sources of energy have adverse effect on the environment and are in most cases more expensive (Basunia and Abe, 2001). As the sun is the cheapest source of renewable energy and sun drying is still the most common method used to preserve agricultural products in most tropical and sub tropical countries despite the problems and the risk of contamination involved; high food losses ensue from inadequate drying, fungal attacks, insects, birds and rodents encroachment, unexpected down pour of rain and other weathering effects (Ong, 1999). However, at present, a large proportion of the world's supply of dried fruits and vegetables continue to be "sun dried" in the open under primitive conditions. Therefore, the quality of the dried product is often degraded seriously, sometimes beyond edibility. In such conditions, solar-energy dryers appear to be increasingly attractive as commercial propositions (Ekechukwu, 1998).

2.2.2 Solar dryers

Various investigations have shown that solar drying can be an effective means of food preservation since the product is completely protected during drying against rain, dust, insects and animals (El-Sebaii et al., 2002; Farkas, 2004). But still some obstacles have to be overcome that solar drying will become a technology with a broad dissemination. Although a lot of research work has been conducted during the last decades, only a small number of appropriate solar dryers which can be used by farmers or small scale industries in developing countries are commercially available. Furthermore, there is still a lack of knowledge on how to process fruits, vegetable, fish, etc. in a proper way to ensure a high quality product and to minimize post-harvest losses (Esper and Muhlbauer, 1988).

In solar drying, solar-energy is used as either the sole source of the required heat or as a supplemental source. The air flow can be generated by either natural or forced-convection. The heating procedure could involve the passage of preheated air through the product or by directly exposing the product to solar radiation or a combination of both (Ekechukwu and Norton, 1998). The major requirement is the transfer of heat to the moist product by convection and conduction from the surrounding air mass at temperatures above that of the product or by radiation, mainly from the sun and to a little extent from surrounding hot surfaces (McLean, 1980).

In direct radiation drying, part of the solar radiation may penetrate the material and be absorbed within the product itself, thereby generating heat in the interior of the product as well as at its surface, and thereby enhancing heat transfer (Basunia and Abe, 2001). During drying, there is a tendency of the food to form dry surface layers which are impervious to subsequent moisture transfer, if the drying rate is very rapid. To avoid this effect, the heat transfer and evaporation rates must be closely controlled to guarantee optimum drying rates (Arinze et al., 1979).

2.2.3 Classification of drying systems

All drying systems can be classified primarily according to their operating temperature ranges into two main groups of high temperature dryers and low temperature dryers. However, dryers are more commonly classified broadly according to their heating sources into fossil fuel dryers (more commonly known as conventional dryers) and solar-energy dryers. Further, solar-energy drying systems are classified primarily according to their heating modes and the manner in which the solar heat is utilized (El-Sebaii et al., 2002).

- passive solar-energy drying systems (conventionally termed natural-convection solar drying systems); and
- active solar-energy drying systems (most types of which are often termed hybrid solar dryers).

Although, for commercial production of dried agricultural products, forced convection solar dryer might provide a better control of drying air; natural convection solar dryer does not require any other energy during drying operation. Hence, natural convection solar dryer is highly preferred for drying food products especially when in thin layers of drying (Pangavhane, 2002).

2.2.3.1 Natural convection and other solar dryers

Natural convection solar dryer depends for its operation entirely on solar-energy in which, solar-heated air is circulated through the product by bouyancy forces or as a result of wind pressure, acting either singly or in combination. It is reported that the dryer is superior operationally and competitive economically to natural open sun drying. The advantages of natural convection solar dryer over open sun drying are reported by Ekechukwu and Norton (1998) as follows:

- It requires a smaller area of land in order to dry similar quantities of product.
- It yields a relatively high quantity and quality of dry food because fungi; insects and rodents are unlikely to infest the food during drying.
- The drying period is shortened compared with open air drying, thus attaining higher rates of product throughput.
- Protection from sudden down pours of rain; and
- Commercial viability, i.e. it is relatively low capital and maintenance costs because of the use of readily available indigenous labour and materials for construction.

Many researchers worked on the natural convection solar drying of agricultural produce. Among them, Pangavhane et al. (2002) developed a natural convection solar dryer consisting of a solar air heater and a drying chamber for drying various agricultural products like fruits and vegetables. They reported that the drying airflow rate increased with increase in ambient temperature by the thermal buoyancy in the collector. In this study, grapes were dried and the qualitative analysis showed that the traditional drying of grapes, i.e. shade drying and open sun drying required 15 and 7 days, respectively, while the natural convection solar dryer took only 4 days and produced better quality raisins. The developed natural convection solar dryer could produce the average temperature between 50 and 55^{o}C, which was optimum for dehydration of the grapes as well as for most of the fruits and vegetables.

The control of the drying process in natural-convection solar dryers presents a major problem, because they are designed to minimise capital and running costs. Thus, special control mechanisms are inappropriate. The best approach is to incorporate chimneys, which regulates the residency period of the drying air within the drying chamber (Ekechukwu and Norton, 1997). Based on this approach, they designed a solar chimney for natural-convection solar dryers. The results showed that the solar chimneys, if designed properly could maintain chimney air temperatures consistently above the ambient temperature which would enhance the desired buoyancy-induced air flow through the chimney and drying rate.

Das and Kumar (1999) described the performance of a natural convection solar dryer coupled with a vertical flat plate collector chimney for drying paddy. The experiments during the winter months showed an average rise of air temperatures of 27.1^{o}C with an average air flow rate of 0.67 m^3/min (0.22m/s) through the chimney. They observed that the dryer took only 9 h to dry the paddy from 31 to 13% moisture content (d.b.) when compared to 16 h in open sun drying.

El-Sebaii et al. (2002) developed a natural convection solar dryer, consisting of a flat-plate solar air heater connected to a drying chamber. They dried tomatoes, grapes, figs, green peas and onions and reported that the quality of the dried products was better when compared to open sun drying method. Similarly, Gbaha et al. (2006) designed a direct type natural convection solar dryer using local materials and then tested experimentally by drying cassava, bananas and mango slices. They reported that the thermal performance of the newly developed dryer in terms of heat and mass transfers influenced by solar incident radiation were found to be higher when compared to open sun drying for the selected food materials.

It is reported that the orientation of solar dryer also plays an important role for maximizing the performance of solar dryers. Walker and Duncan (1974) proposed that the east-west arrangement would be preferable in the winter periods above 40 to 45^{o} latitude. But in summer periods, north-south would be better to get maximum solar radiation.

Karsli (2006) presented a performance analysis of four types of air heating flat plate solar collectors: a finned collector with an angle of 75°, a finned collector with an angle of 70°, a collector with tubes, and a base collector. The results showed that the efficiency depends on the solar radiation and the construction of the solar air collectors and orientation. The highest collector efficiency and air temperature rise were achieved by the finned collector with angle of 75°, whereas the lowest values were obtained for the base collector. For drying fruits, Umarov et al. (1989) designed and fabricated a simple solar dryer, consisting of a polyethylene stretched over metal hoops that covered a black heat absorbent material inclined 20- 25^{o}C towards the south. The results indicated that the drying rates under tunnel were found to be 3 times higher than sun drying.

Lahsasni et al. (2004) presented the thin layer convective solar drying of prickly pear peel. They recorded the drying parameters such as ambient air temperature (32 to 36^{o}C), drying air temperature (50 to 60^{o}C), relative humidity (23 to 34%), drying air flow rate (0.0277 to 0.0833 m^3/s) and daily solar radiation (200 to 950 W/m^2) during drying. They concluded that the experimental drying curves showed only a falling drying rate period with the main factor in controlling the drying rate was found to be the drying air temperature. Ali et al. (1988) designed and fabricated a solar tray dryer, which could be used for both direct and indirect drying. The maximum temperature attained was 65^{o}C in direct conditions and 60^{o}C in indirect condition.

Tiris et al. (1995) investigated the construction and performance of a solar powered drying system consisting of a solar air heater and a drying chamber and discussed the thermal efficiencies of both the solar air heater and the drying section. The results of this study showed that the drying periods of solar dried sultana grapes, green beans, sweet peppers and chillies were 1.8, 2.2, 1.9 and 2.0 times shorter than the natural sun dried products (drying period: 6-10 days).

Yaldiz and Ertekin (2001) used a solar cabinet dryer to dry pumpkin, green pepper, stuffed pepper, green bean, and onion in thin layers and the results were compared with natural sun drying method. The results revealed that drying air temperature could increase up to 46°C and the drying air velocity had an impact on the drying process. They reported that the drying time was reduced (30.29-90.43 h) in solar drying as compared to open sun drying (48.59 and 121.81 h) for different vegetables.

Pande and Thanvi (1991) designed, developed and tested a solar dryer cum heater for dehydrating fruit and vegetables. Experiments revealed that 10-15 kg of fruit/vegetables could be dehydrated in 3-5 days. Based on the principles of psychrometry, Madhlopa et al. (2002) designed a solar air heater, comprising two absorber systems in a single flat-plate collector. The heater was integrated to a drying chamber for food dehydration. This collector design offered flexibility in manual adjustment of the thermal characteristics of the solar dryer. The performance of the dryer was evaluated by drying fresh samples of mango slices. The air heater converted up to 21.3% of solar radiation to thermal power, and raised the temperature of the drying air from about 31.7 to 40.1^{o}C around noon. The dryer reduced the wet basis moisture content of sliced fresh mangoes from 85% to 13% (w.b.) in 3-5 days depending on the weather conditions.

Field level performance of the solar tunnel dryer for drying of fish was reported by Bala and Mondol (2001). The dryer consists of a transparent plastic covered flat plate collector and a drying tunnel connected in series to supply hot air directly into the drying tunnel using four fans, operated by two 40 Watt solar modules. The temperature of the drying air at the collector outlet varied from 35.1 to 52.2°C during drying. The fish was dried to a wet basis moisture content of 16.78% from 67% in 5 days of drying in solar tunnel dryer as compared to 5 days of drying in the traditional method for comparable samples to a final moisture content of 32.8% only. In addition, the fish dried in the solar tunnel dryer was completely protected and the dried fish was better in quality.

Singh et al. (2005) studied the performance of solar tunnel dryer for drying unripe peeled mango. They reported that air temperature inside the dryer could be maintained in the range of 50-75°C on typical sunny days. Cut mango pieces with initial moisture content of 79% were dried in four and half days to a moisture level of 4.2% as compared to ten days in open drying to a moisture content of 4.7%. They observed the average drying temperature in the tunnel was 60°C and quality of the product dried in the tunnel dryer was found to be superior to the sun-dried product in terms of microbial load, appearance and acceptability.

Bala et al. (2003) conducted field level experiments on solar drying of pineapple using solar tunnel drier. They found that in all the cases the use of the solar tunnel drier lead to considerable reduction of drying time in comparison to sun drying. Proximate analysis also indicated that good quality dried pineapple slices could be produced using solar tunnel drier.

In recent times, multi purpose solar dryers are becoming popular for drying agricultural commodities. In this concept, Lutz et al. (2003) developed a multi purpose solar dryer consisting of a small fan, a solar air heater and a tunnel dryer for drying various agricultural products such as fruits, vegetables, medicinal plants etc. They reported that the dryer could handle 100 - 1000 kg of fresh material and could be dried within 1 - 7 days to safe storage levels. The developed solar dryer was successfully tested in Greece, Yugoslavia, Egypt, Ethiopia and Saudia Arabia for drying grapes, tomato, dates, onions, peppers and several medicinal plants.

For humid weather conditions, Amir et al. (1991) developed a multi-purpose solar tunnel dryer, since open-air sun drying and smoke drying are the traditional drying methods in these regions, which lead to insufficient product quality. To prevent penetration of water into the construction and subsequent flooding, the solar dryer was installed on a wooden substructure. To heat the drying air during cloudy and rainy days, particularly in the rainy season, a biomass furnace with heat exchanger was integrated into the solar drying system. Results showed that compared to natural sun drying, the drying time of cocoa, coffee and coconut could be reduced up to 40%.

Similarly for hot and humid weather conditions of Thailand, Schirmer et al. (1996) developed a mu1ti-purpose solar tunnel dryer to dry bananas. The dryer comprised a plastic sheet-covered flat plate collector and a drying tunnel. The dryer was arranged to supply hot air directly to the drying tunnel using three fans powered by a 53 W solar cell module. The products to be dried were spread in one layer on a plastic net in the drying tunnel to receive energy from both the hot air supplied by the collector and incident solar radiation. This dryer could be used to dry up to 300 kg of ripe bananas in each drying batch. They concluded that the temperature of the drying air from the collector varied between 40 and 65°C during drying and the bananas could be dried within 3-5 days, compared to the 5-7 days needed for open sun drying.

Sacilik et al. (2006) reported on the thin layer solar drying experiments of organic tomato using multi-purpose solar tunnel dryer under the ecological conditions of Ankara, Turkey. They reported that organic tomatoes could be dried to the final wet basis moisture content of 11.5 from 93.3% in four days of drying in the solar tunnel dryer as compared to five days of drying in the open sun drying.

Using the photovoltaic (PV) system technique, an experimental closed-type dryer was developed by Chen et al. (2005). They designed the transparent drying cabinet with high transmittance glass to decrease the reflection of direct sunlight and to offer extra direct solar heating on the raw material during drying. Lemon slices were dried and results were compared with hot air drying at 60^{o}C. They indicated that the dried lemon slices had retained better levels of quality similar to hot air dried in terms of sensory parameters.

2.3 Vacuum Application in Drying

The main aim of creating vacuum during drying is to enable the removal of moisture at lower temperature than the boiling point under ambient condition. Water boils at 100^{o}C under standard atmospheric pressure (1.013 bar), but if the pressure is reduced or the vacuum is created to 40 mbar, the boiling temperature will be reduced to 29^{o}C (Moran and Shapiro, 1996). The important feature of vacuum drying is the exclusion of air during drying, which makes this process more attractive for drying food materials that may deteriorate or chemically modified due to air or exposure to high temperature. The lower pressure (vacuum) in the system allows the use of lower drying temperature in order to achieve similar moisture content of the end product with other drying methods.

The drying system that has vacuum application consists of four main components such as vacuum chamber, vacuum pump, heat supply and a device to collect condensed water vapour. Vacuum treatment is useful in combination with other processes to get a good final end product. Obvious advantages of combining vacuum with other drying processes have guided many scientists to work on food drying experiments. Since, the product temperature is lower compared to other drying methods; drying time will be reduced as a result the final quality of the product will be better.

Many scientists have contributed in the vacuum application to food drying and combining with other systems like microwave and freeze drying. Among them, Fernando and Thangavel (1987) reported that the quality of vacuum dried coconut was superior to the conventionally dried products. Similarly, the vacuum dried celery was better in quality compared to hot air dried ones Madamba and Liboon (2001). Vacuum drying of mango pulp at varying conditions of pulp thickness (2, 3, and 4 mm) and vacuum chamber plate temperature (65, 70, and 75°C) under 30-50 mm of mercury absolute pressure was reported by Jaya and Das (2003). They predicted the moisture content of the pulp at different times of drying with correlation coefficient varying between 0.98 and

0.99 for pure mango pulp. They concluded that the vacuum dried mango pulp was better in quality and to achieve a lower color change, vacuum drying should be carried at maximum pulp thickness of 2.6 mm and vacuum chamber plate temperature of 72.3°C.

Combination of microwave heating and vacuum drying resulted in the accelerated drying rate of model fruit gels (Drouzas et al., 1999). Further, they reported that the experimental pectin gel with 38.4% moisture content was dried to less than 3% moisture in four minutes and the colour of the dried gel was better compared to air drying. Similar combination method was used by Mousa and Farid (2002) for drying banana slices with microwave under vacuum. They concluded that thermal and drying efficiencies were almost 100% at the beginning of the drying process, but decreased with reduction in the moisture content and the effect of vacuum was particularly important to attain low moisture values in food products. Also Sunjka et al. (2004) and Geyer et al. (2006) reported that the combination method could increase the drying rate of cranberries and guava fruit, respectively.

Cui et al. (2003) also studied the combination of microwave-vacuum drying method and compared with those dried by freeze drying and conventional hot-air drying of garlic slices. The comparison showed that the quality of garlic slices dried by the combination method was close to that of freeze dried garlic slices and much better than that of conventional hot-air dried ones. Similarly, the carotenoid retention of carrot slices and chlorophyll retention of chive leaves, dried by the combination of microwave-vacuum drying was also close to that of freeze dried and much better than that of conventional hot-air dried ones (Cui et al., 2004).

2.4 Moisture Diffusivity

Drying in the context of food dehydration is the removal of moisture from the material by thermal means. In the drying process of food materials, water is frequently brought to the material surface by means of liquid diffusion, involving a concentration gradient. However, in certain situations vaporization may occur internally and the water vapour diffuses to the surface of the material. The drying technique used determines how the water vapour is removed from the material surface based on thermal properties (Hansen et al., 1993).

Several researchers have presented the various numerical models for moisture migration considering diffusion as the primary transport mechanism. Diffusivity kinetic models are used to interpret the phenomenon of drying and thus the estimated values will be optimized by the model hypothesis such as boundary conditions, geometry, constant or variable physical and transport properties of isothermal and non isothermal drying. They found that the effective water diffusivity in both isothermal and non isothermal models followed Fick's law with temperature, which increases linearly with initial moisture content (Gaston et al., 2004).

The solution of Fick's model for moisture diffusion in thin layer drying is as follows.

$$\text{Moisture ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} = A\, e^{\left(\frac{-D_{eff}\, t}{4L^2}\right)} \tag{2.1}$$

Where,

M_i	=	initial moisture content, dry basis (decimal)
M_t	=	Moisture content, dry basis (decimal) at t time
M_e	=	equilibrium moisture content, dry basis (decimal)
A	=	constant
D_{eff}	=	effective moisture diffusivity, m^2/s
t	=	time, s
L	=	thickness of the slice, m

Diamante and Munro (1993) derived a mathematical model for the solar drying of sweet potato slices based on Fick's diffusion equation. The model could satisfactorily describe the solar drying of sweet potato slices to a moisture content below 20% on dry weight basis. They concluded that mean effective drying chamber temperature and sample thickness were the main factors that affected the solar drying process for sweet potato slices. Victor and Luis (1997) developed a simple drying model for water evaporation and validated it by applying open air solar drying of red pepper. Herman et al. (2001) dried carrot slabs (0.1 -1.0 cm) with air temperature of 50-60°C. They reported that the water transport in carrot slabs during drying was controlled by internal diffusion and they also reported that interfacial conditions might be in steady state during drying.

The effective moisture diffusivity for meat, vegetables, fruits and food gels at a temperature of 25°C was found to be in the range of 1.2 - 2 x 10^{-10} m^2/s (Lomanro et al.,

1985) and the effective moisture diffusivity of vegetable waste (mixture of lettuce and cauliflower) varied from 6.03 x 10^{-9} to 3.15 x 10^{-8} m^2/s as the temperature increased from 50 to 150°C.

The drying behaviour of tomato slices at 45, 60 and 75°C was investigated by Akanbi et al. (2006). They observed that three falling rate periods with effective moisture diffusivity in the range of 3.72-12.27 x 10^{-9} m^2/s during drying. Similarly, Giovanelli et al. (2002) reported that the effective water diffusivity values ranged from 2.3 - 9.1×10^{-9} m^2/s based on the size of the tomato slices during hot air drying.

A non-linear regression procedure was used to fit 10 different thin layer drying mathematical models to the experimental drying curves of tomato using solar tunnel dryer (Sacilik et al., 2006). The models were compared using the coefficient of determination, mean relative percent error, root mean square error and the reduced chi-square. They reported that the approximation of diffusion model had shown a better fit to the experimental drying data as compared to other models. Hawlader et al. (1991) also used diffusion model to investigate the drying characteristics of tomato under various operating conditions with different air temperatures and flow velocities. They observed shrinkage during drying and this effect was incorporated in the basic diffusion model through the use of a power law expression that related apparent shrinkage to moisture content. Analysis of experimental data yielded a better correlations between the effective diffusivity and both temperature and air velocity.

Singh et al. (2006) investigated the effect of air temperature and pretreatments (KMS: citric acid) on drying kinetics of sweet potato slices using a tray dryer. They described the moisture transfer from sweet potato slices in falling rate period by applying the unsteady-state Fickian diffusion model. They determined the drying rate constant (k) and found to be affected by pretreatments. Raisin samples (Lomanro et al., 1985) and Corn pasta (Andrieu et al., 1986) have been modeled using Fick's law for the thin layer drying.

2.5 Thin Layer Drying Models

Thin layer drying models have gained wide acceptance to design new or simulate the existing system or for the analytical drying solutions. Many researchers have used the exponential drying model in describing the drying behaviour of the food materials. The solution of the Fick's equation, with the assumptions of diffusion based moisture migration, negligible shrinkage, constant diffusion coefficients and temperature, is simplified to get the single exponential model (Lewis, 1921) as:

$$\text{Moisture Ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} = e^{-kt} \tag{2.2}$$

Where,

M_i	=	initial moisture content, dry basis (decimal)
M_t	=	Moisture content, dry basis (decimal) at 't' time
M_e	=	equilibrium moisture content, dry basis (decimal)
k	=	constant
t	=	drying time, min

The Henderson and Pabis (1961) model is also the general series solution of Fick's second law. The following thin layer drying equation (Henderson and Pabis model) was successfully used by (Doymaz, 2004; Sacilik et al., 2006) for the prediction of drying time and for generalization of drying curves.

$$\frac{M_t - M_e}{M_i - M_e} = Ae^{-kt} \tag{2.3}$$

If the constant 'A' in the above equation is equal to unity, the equation is reduced to the same form as Newton's law of cooling for highly conductive materials.

Another model which has been widely used to fit the thin layer drying data is the Page equation (Hossain and Bala, 2002; Prabhanjan et al. 1994; Wang, 2002). It is a simple modification of the exponential law using moisture ratio with additional drying parameter. Page (1949) proposed a thin layer drying equation:

$$\frac{M_t - M_e}{M_i - M_e} = e^{-qt^n} \tag{2.4}$$

Where, 'q' and 'n' are drying constants that depend on the air temperature and type of material.

The empirical equation proposed by Wang and Singh (1978) has also been used to describe the thin layer drying characteristics of food materials (Akpinar et al., 2003; Doymaz, 2004; Goyal et al., 2006):

$$\frac{M_t - M_e}{M_i - M_e} = 1 + at + bt^2 \tag{2.5}$$

Where, 'a' and 'b' are drying constants.

A mathematical model for drying kinetics is normally based on the physical mechanisms of internal heat and mass transfer and on the heat transfer conditions external to the material being dried that control the process resistance, as well as on the structural and thermodynamic assumptions. Modeling of drying is usually complicated by the fact that more than one mechanism may contribute to the total mass transfer rate and the contribution from the different mechanisms may change during the drying process (Cui et al, 2004). The effect of air conditions (air temperature, air humidity and air velocity) and characteristic sample size on drying kinetics of various food materials such as tomato, potato, carrot, pepper, garlic, mushroom, onion, leek, pea, corn, celery, pumpkin during air drying was examined by Krokida et al. (2003). They found that the parameters of the model considered were greatly affected by the air conditions and sample size during drying and also in particular the temperature increment increased the drying constant and decreased the equilibrium moisture content of the dehydrated products.

Sodha et al. (1985) presented a simple analytical model based on heat and mass transfer at the product surface and included the effects of wind speed, relative humidity, product thickness and heat conducted to the ground for open sun drying and cabinet type solar drier. They proposed an analytical model to predict the hourly variation of product temperature and moisture content under constant rate and falling rate periods of drying of apples, peaches, cherries and mango slices.

In order to simulate the functioning of solar collector, Chemkhi et al. (2004) reported a simple model based on the evaluation of different heat transfer coefficients in the collector. By using the model, they calculated the output energy and thermal efficiency as a function of ambient temperature, incident solar radiation, wind speed and air mass flow rate for drying of fruits and vegetables in Mediterranean countries. Simate (2001) presented a mathematical model for natural convection solar drying of maize grain. The results showed that temperatures at the top and bottom of the bed were higher than that in the middle resulting in two drying fronts one at the top and the other at the bottom of the bed and moving in opposite directions. The results were verified against experimental data from a prototype natural convection maize solar dryer and obtained a good agreement between theoretical and experimental values.

Raghavan and Silveira (2001) studied the shrinkage of strawberries as a function of the moisture ratio during microwave-convective drying. The drying results showed that the shrinkage had a linear relation with moisture ratio and the change in volume was bigger for the fruits osmotically dehydrated than for the not osmotically dehydrated ones. They concluded that the power level influenced on shrinkage and equivalent diameter for pre-treated and osmotically dehydrated samples.

Gbaha et al. (2006) reported that the Lewis single exponential model could satisfactorily describe the thin layer drying characteristics of cassava, bananas and mango slices dried in natural convection solar dryer. They also reported that the drying effectiveness for modeling was performed by the determination of parameters, like ambient temperature, drying chamber temperature, drying air mass flow and incident heat fluxes. El-Sebaii et al. (2002) presented a linear correlation between drying constant k and product temperature to describe the drying curves of the materials such as tomatoes, grapes, figs, green peas and onions under natural convection solar dryer. Furthermore, the characteristics constants c and n of Henderson's equation were determined and also they achieved a good agreement between experimental and theoretical results.

Midilli and Kucuk (2003) optimised a mathematical model on thin layer forced and natural solar drying of shelled and unshelled pistachio samples. In order to estimate and select the suitable form of solar drying curves, eight different mathematical models, which are semi-theoretical and/or empirical, were applied to the experimental data and compared according to their coefficients of determination (R^2, χ^2). It was deduced that the logarithmic and two term models could sufficiently describe thin layer solar and open sun drying of shelled and unshelled pistachio, respectively.

Hossain and Bala (2002) conducted thin-layer drying experiments under overflow, underflow and through flow conditions of green chillies with air temperature ranging from 40 to 65°C, relative humidity ranging from 10 to 60% and air velocity ranging from 0.10 to 1.0 m/s. The single exponential equation and the Page equation were used to determine the thin-layer drying characteristics for green chilli. Both the equations fitted well to the experimental data. But the Page equation was found to describe the thin-layer drying of chilli better than the single exponential equation. Similarly for thin layer drying (50-70°C) of coconut strips, Page model gave better predictions than the single or double term exponential model (Madamba, 2003). Further, he showed that the drying air temperature and slab thickness significantly affected the average drying rate.

Wang (2002) also concluded that Page model was found to give the best results in describing single-layer far-infrared radiation drying of onion when compared to other mathematical models such as exponential and an approximation of the diffusion model. The conclusion was arrived by conducting experiments using three levels of far-infrared radiation intensities (0.50, 0.80 and 1.00 kW/kg of initial mass of onion), three initial thicknesses of onion slices (2, 4 and 6 mm), three air velocities (0.10, 0.20 and 0.35 m/s) and three inlet air relative humidities (28.6, 36.8 and 43.1%). The performance of these models was evaluated by comparing the coefficient of determination (r^2), the residuals of moisture ratios, and the root mean square errors between the observed and predicted moisture ratios.

2.6 Biochemical Quality

Food quality is the sum of all desirable attributes which make a food acceptable for consumption. Quality attributes of a product may be divided into three major categories such as sensory, hidden and quantitative (Salunkhe et al., 1991). The sensory attributes are color, glossiness, size, shape, defects, odour and taste. The hidden attributes are nutritive values, presence of dangerous contaminants and poisonous materials. The quantitative parameters are those which contribute to the overall food quality such as yield of a dried product. In order to determine the quality of the dried product, several parameters have to be examined through quality evaluation. For tomato the parameters such as colour, water activity, rehydration ratio and nutrient content in terms of ascorbic acid are considered to be appropriate for evaluation.

2.6.1 Colour

Colour has been considered to have a key role in food choice, food preference acceptability, and may even influence taste thresholds, sweetness perception and pleasantness as reported by Clydesdale (1993). Hence, it is a very important quality factor in processed tomato products to influence consumer acceptability. There are many reactions that take place during thermal processing which affect colour. Among them, the most common are pigment degradation, chlorophyll and browning reactions such as Maillard reaction and oxidation of ascorbic acid (Barreiro et al., 1997).

Colour is the human perception of light waves reflected from the surface of any material. It is one of the first noticed characteristics of food and in early periods, it was evaluated only by subjectively or with the use of colour comparing charts. The most common technique to assess the food colour is by colorimeter. There are several colour scales in which the surface colour can be represented. It is usually defined by three coordinates. The L*, a* and b* scale is recognized to show a better discrimination between small colour differences in the darker region of the colour space, providing good discrimination for saturated colours as in the case of tomato products (Barreiro et al., 1997).

The three dimensional L*, a* and b* can be used in Minolta chromameter. The L* is the lightness coefficient, ranging from 0 (black) to 100 (white) on a vertical axis. The a* is the purple red (positive a* value) and blue-green (negative a* value) on horizontal axis. Second horizontal axis is b*, which represents yellow (positive b* value) and blue (negative b* value) as reported by McGuire, (1992). The 3D colour system is shown in Fig.2.1.

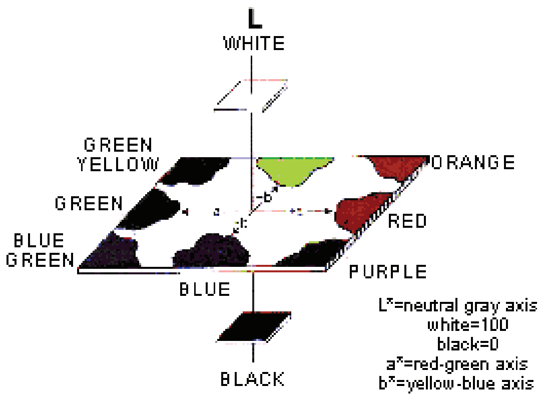


Figure 2.1. 3D - colour coordinates system

Olorunda (1990) reported that an increase in drying time and temperature resulted in tissue darkening, while other study reported that an increase in darkness (L*) and decrease in ratio (a*/b* value) of tomatoes after air drying (Kerkhofs, 2003).

Ahmed et al. (2000) described that the colour degradation during thermal processing of green chilli puree followed a first order reaction kinetics. They concluded that the colour retention was higher in chilli pureed through a 14 mesh screen and the hunter colour L, a and b values could be used to predict the variation of total colour in green chilli puree.

Sacilik et al. (2006) reported on thin layer solar tunnel dried tomato slice colour values; L, a and a/b varied from 33.8 to 37.44, 23.54 to 27.2 and 1.44 to 1.51, respectively. Corresponding values for samples of open sun drying varied from 30.54 to 34.90, 20.20 to 24.87 and 1.49 to 1.60, respectively. They concluded that the tomato slices dried under solar tunnel drier retained better colour than open sun dried due to the exposure of the tomato slices to solar radiations for a longer drying time. Bolin and Huxoll (1991) reported that browning of fresh fruits and vegetables reduced the quality and often it is the limiting factor for shelf life and marketability of the dried products.

Heredia et al. (2007) studied the combination of osmotic dehydration and microwave drying to improve the quality of dried tomatoes. They used various osmotic solutions formulated with salt, sugar and calcium lactate in an osmotic treatment prior to microwave assisted air drying. The results showed that osmotic dehydration with ternary solutions (27.5% sucrose, 10% salt and water (w/w)) with the addition of 2% of calcium lactate combined with microwave assisted air drying makes it possible to obtain dried and intermediate moisture tomato products with better colour that are shelf stable and have better quality than the traditional product.

Shi et al. (1999) reported that the colour (L* and a*/b* values) of tomatoes was retained best under conditions of osmotic dehydration at 25^{o}C. The colour retention was better in vacuum dried Thomson grapes when compared to microwave and hot air dried grapes (Clary and Ostrom, 1995).

2.6.2 Water activity

Water activity is the main factor of numerous important food processing operations, such as microbial growth, toxin formation, enzymatic and non-enzymatic reactions (Leung, 1986). It is the availability of water for microbial, enzymic or chemical activity that determines the shelf life of food and this is measured by the water activity of a food also known as the relative vapour pressure (Fellows, 2000).

Water activity (a_w) is defined as the ratio of vapour pressure of water (P) in a food to the saturated vapour pressure of water (P_s) at the same temperature (Kaminski and Kudra, 2000).

$$a_w = \frac{P}{P_s} \tag{2.6}$$

The water activity is a function of moisture content in food and temperature and water connections in food can be defined by water activity (Barbosa-Canovas and Vega-Mercado, 1996) as follows:

Free water $a_w = 1.0$

Loosely bound water $a_w > 0.7$

Moderately bound water $0.3 < a_w < 0.7$

Tightly bound water $a_w < 0.3$

Measurement of water activity implies cognition of many factors such as vapour pressure, osmotic pressure, freezing points depression, boiling point elevation, psychrometric assessments (dew point and wet bulb depression) and suction potential (Leung, 1986).

Salunkhe et al. (1991) proposed the following water activity values:

Table 2.1. Food classification according to moisture contents

a_w	Moisture content	Food	Characteristics
>0.7	> 30%	High moisture	Soft, must be heated to prevent microbial growth
0.85	20-30%	Intermediate	Semi-moist, firm, prone to Maillard reactions, less susceptible to fat oxidation than low moisture foods
<0.7	< 20%	Low moisture	Hard, firm, resistant to microbial growth and less prone to Maillard reactions, prone to fat oxidation.

It is also reported that almost all microbial activity is inhibited below $a_w = 0.6$, most fungi are inhibited below $a_w = 0.7$, most yeasts are inhibited below $a_w = 0.8$ and most bacteria below a_w = 0.9. The interaction of a_w with temperature, pH, oxygen and carbon dioxide, or chemical preservatives has an important effect on the inhibition of microbial growth (Fellows, 2000, Wang, 1991).

Water activity isotherm is used to display the hysteresis often encountered depending on whether the water is being added to the dry material or removed (drying) from the wet material (Seiler, 1976). This hysteresis is due to non-reversible structural changes and non-equilibrium effects in food products (Fig.2.2).

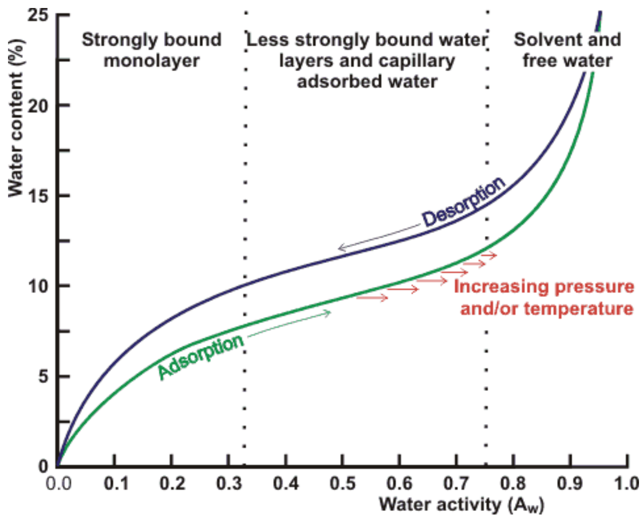


Figure 2.2. Water activity isotherm

The water activity must be measured at constant temperature to compare the results. Akanbi et al. (2006) observed the water vapour sorption isotherm of dehydrated tomato slices in the water activity (a_W) range of 0.08-0.85 at three temperature levels, i.e., 25, 30 and 40^{o}C. Beaudry et al. (2004) dried partially dehydrated cranberries (osmotically dehydrated) to low water contents using four methods: hot air drying; microwave-assisted convective drying; freeze-drying; and vacuum drying. They reported that there was no significant difference in water activity of the dried cranberries.

2.6.3 Rehydration capacity

In dried products, rehydration behaviour must be known to assure the acceptable properties of the rehydrated samples. In the rehydration process, two main cross-current mass fluxes are involved, a water flux from the rehydrating solution to the product and a flux of solutes from the food product to the solution. The pre-drying treatments, drying conditions and rehydrations itself, induce structural and compositional changes in the food which affect the product quality. Rehydration behaviour has been considered as a measure of the induced damage in the material during drying (Lewicki, 1998).

Before consumption of dried foods, they have to be rehydrated by adding water. Various factors that influence the rehydration are drying temperature, soaking time, air displacement, pH and ionic strength (Salunkhe, 1991). The rehydration characteristics of the dried product are also influenced by the method of processing, sample constitution, preparation of the sample prior to rehydration and extent of the structural and chemical changes induced by drying (Krokida and Maroulis, 2000). It is obvious that the dehydration processes that change product composition in lesser extent are expected to offer better rehydration ratio of the finished product such as freeze and vacuum drying methods.

Generally, the rehydration phenomenon can be explained by physical shrinkage and changes in physiochemical composition during drying at colloidal level (Potter and Hotchkiss, 1995). Also, if proteins are denatured and when they can not reabsorb water completely leads to lower rehydration of the product.

Prakash et al. (2004) analyzed the drying characteristics of carrots using a solar cabinet dryer, fluidized bed dryer (at temperatures 50, 60, 70^{o}C) and microwave oven dryer (at power levels 2, 3, 4). They reported that carrots dried by fluidized bed drying showed better rehydration properties than those dried by microwave oven and solar methods. Tomatoes dried at lower temperature (60^{o}C) have been reported to imbibe more water on rehydration than those dried at 70 or 80^{o}C (Olorunda et al., 1990). Sacilik et al. (2006) reported that the rehydration ratio of the thin layer solar tunnel dried organic tomato was little higher (3.15) than the open sun dried tomato (3.10).

Madamba and Liboon (2001) mentioned that the rehydration ratio of vacuum dried celery was influenced by the temperature, vacuum pressure and slice thickness. The rehydration characteristics of microwave-vacuum and convective hot air dried mushrooms were reported by Giri and Prasad (2005). The rehydration was stabilized in 10 min at 100^{o}C and in 3 h at 30^{o}C and the rehydration was in the range of 2.3 -3.4. They suggested that the rehydration ratio could be improved by maintaining lower pressure (higher vacuum) and higher microwave power.

The effect of temperature on rehydration kinetics was investigated for fruits and vegetables dehydrated by convective, vacuum, freeze, and osmotic drying methods (Krokida and Philippopoulos, 2005). The results showed that the water temperature influences the rehydration kinetics and the equilibrium moisture content of the rehydrated product. The shrinkage that takes place during dehydration prevents rehydration and produces products with lower apparent density and higher porosity. Flavor losses seem to have lower rates during rehydration compared to those observed during drying. Rehydration ratio and flavour retention were significantly higher in freeze and vacuum dried fruits and vegetables. However, Beaudry et al. (2004) reported that the freeze-dried cranberries had the highest rehydration ratio compared to vacuum drying, microwave-assisted convective drying and hot air drying methods.

2.6.4 Ascorbic acid

Consumption of tomato and tomato based products has been associated with decreased risk of some cancers due to the presence of antioxidants (Takeoka et al., 2001). Zanoni et al. (1998) reported that processing of tomatoes to a final moisture content of < 15% often involves high temperature in the presence of oxygen and therefore the product showed oxidative damage. Giovanelli et al. (2002) also reported that considerable losses of ascorbic acid during the production of dried tomato halves and tomato pulp using high temperatures. Further, Zanoni et al. (1998) mentioned that the loss of ascorbic acid was dependent on the drying temperature used and the moisture content in the final product since, the tomatoes dried at 80^{o}C contained 10% ascorbic acid and at 110^{o}C contained none.

Abushita et al. (1997) conducted an experiment to investigate the antioxidant vitamin (vitamin E, vitamin C and β-carotene) content of tomato. They reported that paired-ion liquid chromatography provided excellent separation of ascorbic acid (36-48 mg per 100 g) with high peak purity.

Chang et al. (2006) studied the effects of drying processes such as freeze-dried (FD) and hot-air-dried (AD) on the antioxidant properties of two tomatoes varieties I-Tien-Hung (ITH) and Sheng-Neu (SN). The results showed a significant decrease in ascorbic acid content of dried tomatoes (223 mg/100 g DM) when compared to fresh tomatoes (284 mg/100 g DM).

Goula and Adamopoulos (2006) determined a mathematical model for the reaction kinetics of ascorbic acid degradation to describe the rate of vitamin C loss in a drying process of tomato halves or tomato pulp. They reported that the kinetics of ascorbic acid degradation followed a first-order reaction with a reaction rate constant dependent on the product moisture content, in addition to temperature. Furthermore, there was a maximum drying rate constant when the moisture content of tomato samples was between 65 and 70%. They concluded that a close agreement between the experimental and predicted values of ascorbic acid loss during the tomato pulp concentration was observed, confirming the validity of their proposed model.

III. DRYING KINETICS OF TOMATO SLICES IN SOLAR CABINET DRYER COMPARED WITH OPEN SUN DRYING

3.1 Abstract

A solar cabinet dryer was developed to dry tomato slices. Its drying performance was compared with open sun drying under the climatic conditions of Montreal, Canada. The tomato slices of 4, 6 and 8 mm thicknesses could be dried from 94.0 to 11.5% wet basis moisture content, respectively in 300, 420 and 570 min in solar cabinet and it took 435, 615 and 735 min in open sun drying method. Four thin layer drying models were used to optimize the goodness of fit to the experimental data. The models were compared using coefficient of determination, chi-square and root mean square error. The Page model was found to fit the experimental data better as compared to other models. The moisture diffusivity of tomato slices ranged from 4.25 to 7.67 x 10^{-7} m^2/s in the case of solar cabinet drying and from 3.09 to 9.28 x 10^{-9} m^2/s for open sun drying. The influence of air temperature, relative humidity, solar insolation and wind velocity on drying kinetics of tomato slices was discussed. The analysis on colour, water activity, rehydration ratio and ascorbic acid was also performed.

3.2 Introduction

Tomato (*Lycopersicon esculentum L.var*) is one of the most widely used and versatile vegetable crops. It is highly seasonal and available in large quantities at a particular season of the year in most of the tropical countries. Due to market glut during peak season large quantity of tomato gets spoiled. Processing, preservation and storage of tomato during peak season can prevent the huge post harvest losses in tomato and make them available in the off season at comparatively lesser cost. Tomato and tomato products are rich in health valued food components such as carotenoids (Lycopene), ascorbic acid (Vitamin C), vitamin E, folate and dietary fiber (Davies and Hobson, 1981).

Dehydration processes offer an alternative way of using tomato for consumption and the dehydration of tomato has been practiced for many years as a means of preservation. Dried tomato in the form of slice or powder helps to develop new food materials for ready to eat products. Recently, there is a great demand for natural sun /

solar dried organic or bio-cultivated tomato in the international markets. Fresh tomatoes are dried as halves, quarters, slices and powdered for making different products. Though different mechanical drying methods are available, they are expensive and many of them lead to poorer quality final product.

Among all the drying methods, sun drying is a well known method for drying agricultural commodities immediately after harvest especially in developing countries. However, sun drying is plagued with in-built problems since the product during drying is unprotected from rain, storm, windborne dirt, dust, and infestation by insects, rodents, and other animals. This may result in physical and structural changes in the product such as shrinkage, case hardening, loss of volatiles and nutrient components and lower water reabsorption during rehydration. Therefore, the quality of sun dried product is degraded and sometimes become not suitable for human consumption. Further the required drying time is too long in sun drying.

Mechanical drying is an energy consuming process in the post harvest processing of food products; hence more importance is given now-a-days to use solar energy. Solar energy is considered as an important alternative source of energy because of its abundant, inexhaustible and non-pollutant in nature compared with higher prices and shortage of fossil fuels (Basunia and Abe, 2001). Solar dryers are now becoming increasingly popular due to the fact that they dry products rapidly, uniformly, hygienically, the traits inevitable for industrial food drying processes (Diamente and Munro, 1993; Condori et al., 2001). Different solar dryers like direct, indirect and natural convection for tomato have been reviewed by Ekechukwa and Norton (1998) and Farkas (2004). Although for commercial production of agricultural products, forced convection solar dryer provides a better control of drying air, they require additional energy for drying operation. Hence, natural convection solar dryer is highly preferred for drying food products especially when in thin layers.

The drying phenomena can be described using thin layer drying models mainly to estimate the drying times and moisture content of the food materials at any time after they are subjected to a known temperature and relative humidity (Torgul and Pehlivan, 2004). Many research studies have been reported on mathematical modelling and experimental studies conducted on thin layer drying process of various food products such as onion and pepper (Kiranoudis, 1992), chilli (Hussain and Bala, 2002), carrot (Doymaz, 2004) and tomato (Sacilik et al., 2006). In modelling, generally, the investigators have reported the best model that fit the experimental data. However, little information is available on solar drying of tomato slices under Canadian climatic conditions. Therefore, a research study was undertaken to fabricate and evaluate a solar cabinet dryer for drying sliced tomatoes and compare its performance in terms of product quality *vis a vis* open sun drying in relation to weather parameters such as ambient air temperature, relative humidity, wind velocity and solar insolation. Also, it was desired to study the drying kinetics of tomato slices of different thicknesses using thin layer drying models.

3.3 Materials and Methods

Fresh Olympian Gold (#4799) green house grown, herbicide and insecticide free tomatoes of Canada were procured from local market and stored in a refrigerator maintained at 4^{o}C until the drying experiments. Before the start of the experiment, tomatoes (size 65-75 g) were allowed to equilibrate with room temperature (20 ± 1ºC) for one hour. The tomatoes were washed with potable water and sliced into circular discs of 4, 6 and 8 mm thicknesses using a hand operated adjustable mechanical slicer. The sliced tomatoes were dried using both Solar Cabinet Dryer (SCD) and open sun drying methods.

3.3.1 Drying in solar cabinet dryer

Figure 3.1 shows the schematic diagram of solar cabinet dryer developed at the Department of Bioresource Engineering, McGill University, Canada. The dryer has a drying chamber, converged with an angle of inclination of 25^{o} towards centre. At the converged section, a channel was fitted to drain the condensate collected from the inner sloping surface of drying chamber. Two chimneys of each 3.5 cm diameter and 50 cm height were fixed at both the sides for natural convection of air during drying. 100 g of sliced tomatoes were spread on a black surface coated tray and the samples were kept in the drying chamber of the solar cabinet dryer. The drying tray rested on a digital electronic balance with an accuracy of ± 0.01 g. Provisions were made to record the reduction of mass, product temperature, air temperature and relative humidity inside the drying chamber using a data logger (Agilent 34970A, USA) connected to a personnel computer (PC). Experiments were carried out between 9.00 and 17.00 h on bright sunny days.

3.3.2 Open Sun Drying

Sun drying experiments were carried out simultaneously with the SCD experiments between 9:00 and 17:00 h. Tomato slices in a single layer was kept in a black painted tray, which was placed on a digital electronic weighing platform of ± 0.01g accuracy (Fig. 3.1). Using appropriate sensors, the data on the reduction in product mass, product temperature, ambient air temperature, relative humidity, wind velocity and solar insolation were recorded in the computer using a data logger (Agilent 34970A, USA).

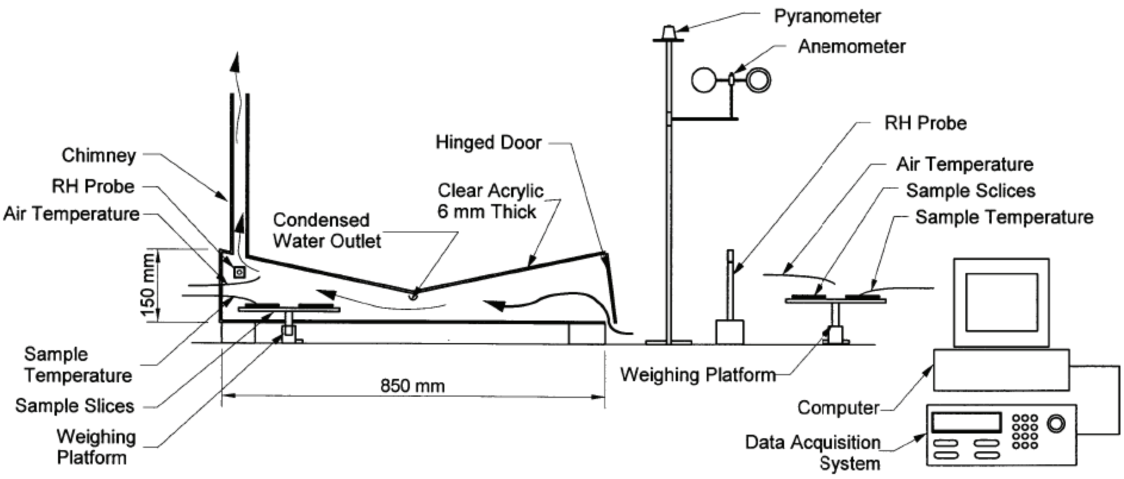


Figure 3.1. Schematic view of solar cabinet and open drying setup

3.3.3 Moisture content

The moisture content of the tomato samples was determined by using vacuum oven at 70°C for 24 h (AOAC, 1980). Triplicate samples were used for the determination of moisture content and the average values were reported.

3.3.4 Equilibrium Moisture content

The equilibrium moisture content of the dried tomato samples was determined by drying at 60°C in a batch type cabinet dryer until it reached the constant mass (Prabhanjan et al., 1995). The moisture at this condition was reported as the equilibrium moisture content of dried tomatoes.

3.3.5 Mathematical modelling

The moisture ratio of tomato slices dried under solar cabinet dryer and by open sun drying at a given time, t was calculated using a relationship:

$$\text{Moisture Ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} = e^{-kt} \tag{3.1}$$

Where,

M_i and M_e are the initial and equilibrium dry basis moisture contents, %

M_t is dry basis moisture content at any time 't'

k is the drying rate constant per minute

t is the drying time, min.

Since, the well known thin layer drying models related dimensionless moisture ratio as the dry basis moisture content versus drying time into a dimensionless moisture ratio versus drying time. The experimental moisture ratio versus drying time data were fitted in four thin layer drying models (Table 3.1) widely used to describe the drying characteristics of most food products and the best model was selected to describe the solar cabinet and open sun drying processes of tomato slices.

Table 3.1. Thin layer drying models based on moisture ratio

Model Name	Model	References
Lewis	MR = $\exp(-kt)$	Lewis (1921), Akpinar et al., (2006)
Page	MR = $\exp(-kt^n)$	Page (1949), Diamente and Munro (1993)
Henderson-Pabis	MR = $A \exp(-kt)$	Henderson - Pabis (1961), Doymaz (2004)
Wang and Singh	MR = $1 + at + bt^2$	Wang and Singh (1978), Sasilik et al. (2006)

The regression analysis was performed using Excel software. The coefficient of determination (R^2) was used as primary criteria for selecting the model that best fit the experimental data. In addition to the coefficient of determination, the best fit of the experimental data was also selected based on various statistical parameters such as the reduced chi-square (χ^2) as the mean square of the deviations between the experimental and predicted values for the models and root mean square error analysis (RMSE). To get the best fit of the experimental data, the coefficient of determination should be higher and the χ^2 and RMSE should be lower (Akpinar et al., 2006).

The statistical parameters were calculated by using the following relationships:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(MR_{pre,i} - \overline{MR}_{pre,i}\right)^2\right]}{\left[\sum_{i=1}^{n}\left(MR_{\exp,i} - \overline{MR}_{\exp,i}\right)^2\right]} \tag{3.2}$$

$$\chi^2 = \frac{\left[\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)^2\right]}{N - n} \tag{3.3}$$

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]} \tag{3.4}$$

Where, $MR_{exp,i}$ is the i^{th} experimentally observed moisture ratio values,

$MR_{pre,i}$ is the i^{th} predicted moisture ratio values,

N is the total number of observations, and

n is the number of constants in the model.

3.3.6 Effective moisture diffusivities

Fick's equation is widely used for explaining drying mechanism of solid food material involving diffusion of vapour (Sankat and Castaigne, 2004). When a material dries mainly in the falling rate period, then it could be assumed that the internal moisture diffusion occurs. Therefore, moisture diffusivity in tomato slices can be calculated from the experimental drying data using Fick's second law for a slab shaped material. The solution to this equation developed by Crank (1975) can be applied for tomato slices of different thicknesses by assuming uniform initial moisture distribution as:

$$\frac{M_\theta}{M_\infty} = 1 - \sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}e^{\left(\frac{-D(2n+1)^2\pi^2 t}{4L^2}\right)} \tag{3.5}$$

Where, D is the diffusivity (m^2/s)

L is the thickness of the sample (m).

For long drying periods, Eqn. (3.5) can be simplified to only first term of the series (Tutuncu and Labuza, 1996) as:

$$\text{Moisture ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} = \frac{8}{\pi^2} e^{\left(\frac{-D\pi^2 t}{4L^2}\right)} = A\ e^{\left(\frac{-D_{eff} t}{4L^2}\right)} \qquad (3.6)$$

The effective moisture diffusivity values were determined by plotting experimental drying data in terms of ln $\left(\frac{M_t - M_e}{M_i - M_e}\right)$ versus drying time t. A plot of ln $\left(\frac{M_t - M_e}{M_i - M_e}\right)$ versus drying time gives a straight line with a slope $\left(\frac{D_{eff}}{4L^2}\right)$. Knowing the tomato slice thickness and the slope from the above plot, the moisture diffusivity (D_{eff}) was calculated for different slice thicknesses.

3.3.7 Rehydration ratio

The rehydration ratio of dried tomato slices was determined as the ratio of rehydrated mass to the initial dehydrated mass, which gives a measure of the ability of dried tomato slices to reabsorb water. A sample of 5 g of the dried tomato slices was placed in a 250 ml beaker containing 150 ml of boiling distilled water. The contents were boiled for 5 min to allow the slices to rehydrate. After rehydration, the free surface water on the tomato slice was removed before assessing the rehydrated mass (Prakash et al., 2004). Triplicate measurements were done and the average values are reported here.

$$\text{Rehydration ratio} = \frac{\text{Wr}}{W_D} \qquad (3.7)$$

Where,

Wr - rehydrated sample mass, g

W_D – initial mass of the sample before rehydration, g

3.3.8 Colour

The colour of fresh and dried tomato slices was determined in terms of the tristimulus colour values L*, a* and b* using Minolta Chromameter, CR-300 (Minolta Co., Japan). Where, L* indicates lightness or darkness of the material; a* is the colour coordinate in red-green axis +ve value redness, -ve for greenness; b* is the colour coordinate in yellow-blue axis, +ve for yellowness and -ve blueness.

The colour of the tomato slices was measured after calibrating the instrument with the white standard plate using D_{65} illumination and 2° standard observer.

3.3.9 Water activity

The water activity of fresh and dried tomato slices was measured at room temperature (23.4 ± 1°C) using a water activity meter (Aqua Lab, Model Series 3TE, USA). A mean of three measurements were reported here.

3.3.10 Ascorbic acid

Ascorbic acid content in fresh and dried tomatoes was measured by titration method (Ranganna, 1995). One gram of sample was soaked in 4% oxalic acid for ten minutes and it was ground using a pestle and mortar. The contents were filtered and the volume was made up to 100 ml with oxalic acid. Out of this, 10 ml aliquot was titrated against a dye solution containing 42 mg of sodium bicarbonate and 52 mg of 2, 6 dichlorophenol indophenol in 50 ml of water. The ascorbic acid contents in the samples were determined and the results were expressed in mg/100g dry matter.

3.3.11 Statistical analysis

All observations were reported as means of three replications. The data pertaining to colour, water activity, rehydration ratio and ascorbic acid content were statistically analyzed to determine the significant difference, if any between dried tomato slices using AGRES software package of Indian Agricultural Statistics Research Institute, New Delhi at 5% significance level. ANOVA under Completely Randomized Design and the mean separation by LSD method was carried out for all the experimental data.

3.4 Results and Discussion

3.4.1 Variation in product temperature

During the experimental period of 20 days in August'05, the average daily variations of solar radiation, wind velocity, ambient relative humidity and air temperature ranged from 312 to 795.6 W/m^2, 0 to 6.5 m/s, 16.0 to 31.9% and 27.7 to 30^{o}C, respectively in Montreal, Canada (Fig.3.2). When drying 4 mm thick tomato slices, the product temperatures recorded were 42.65 - 63^{o}C in solar cabinet dryer (SCD) and 27.3 - 37.5^{o}C in open sun drying (Fig.3.3). The maximum temperature and minimum relative humidity recorded inside the drying chamber were 63°C and 5.5% when the corresponding ambient temperature and relative humidity were 30°C and 16%, respectively. For 6 mm thick tomato slices, the maximum product temperatures in SCD and open sun drying were found to be 58.7 and 34.5°C, respectively. It is observed that the maximum product temperature of 8 mm thick tomato slices in SCD was 56.6°C and in open sun drying, it was 31.5°C.

From the Figure 3.3, it is clear that the product temperature inside the solar cabinet drying chamber was significantly higher when compared to the open sun drying. It might be due to two reasons: i) better absorption of solar energy by the product as most of the solar energy entering the cabinet is trapped inside the SCD facilitating absorption, ii) the collector (black surface) gives away of its energy to the product by conduction heating. iii) the chimney facilitates the removal of moisture by natural circulation of atmospheric air. This explicitly indicates that the drying rate of tomato slices in the solar cabinet dryer will be higher than that of open sun drying experiment.

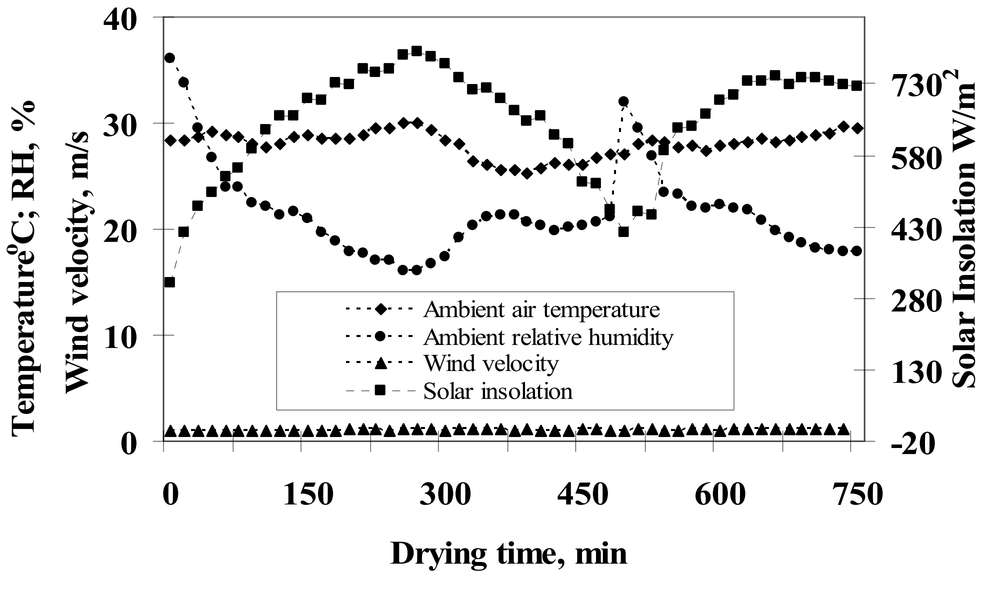


Figure 3.2. Ambient temperature, relative humidity and wind velocity observed during the drying experiments.

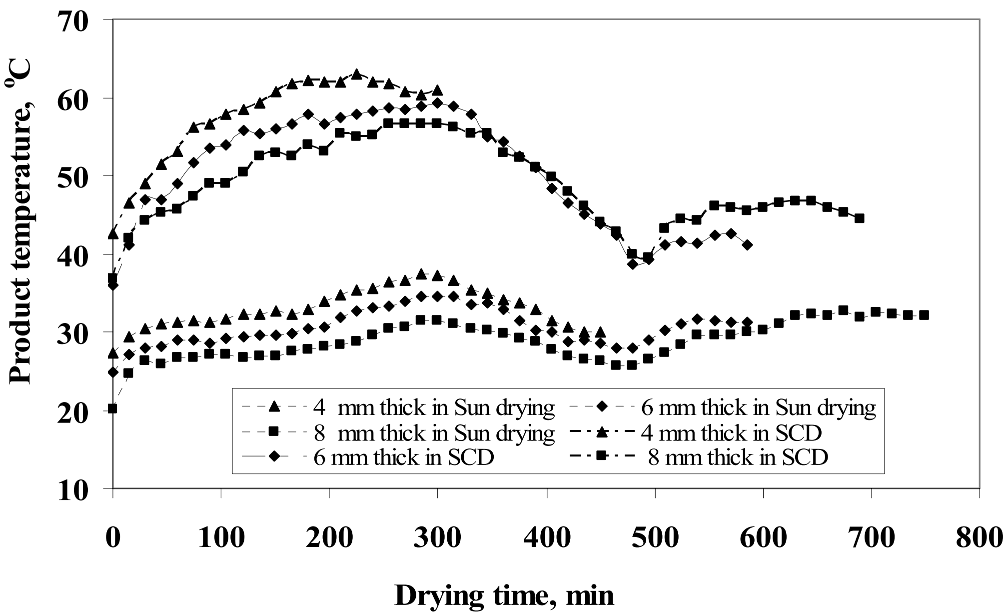
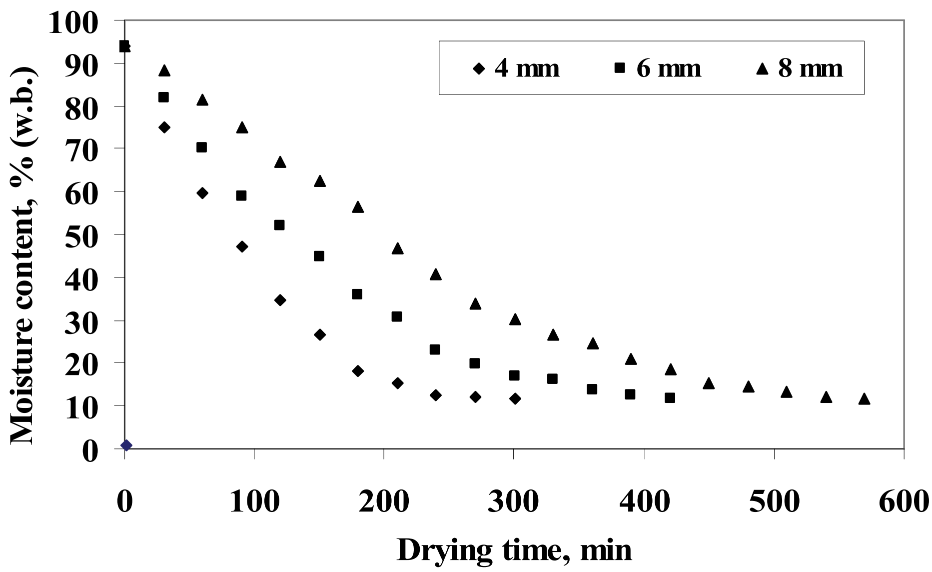


Figure 3.3. Temperature of tomato slices of different thicknesses during drying in solar cabinet dryer (SCD) and in open sun drying.

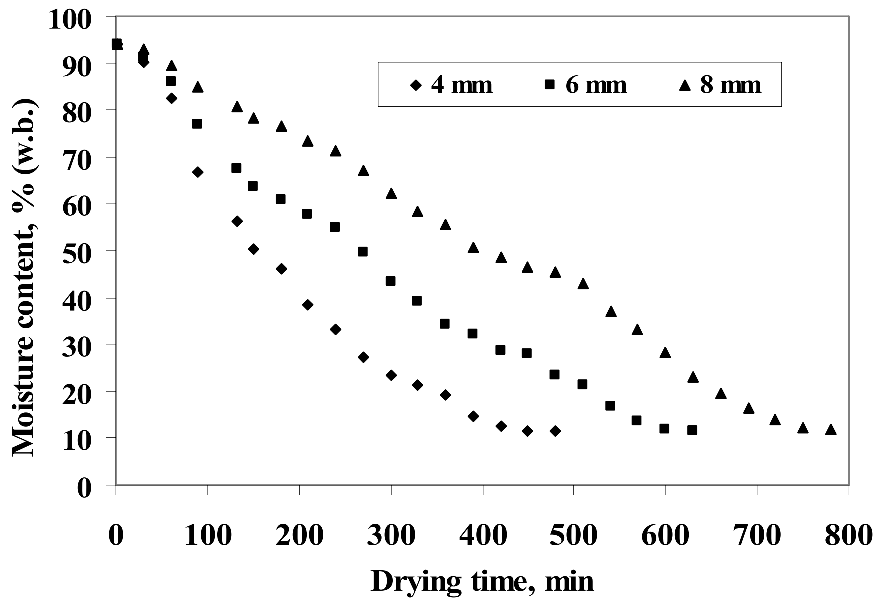
Generally, the drying temperature, relative humidity and wind velocity varied continuously during the drying period of 9:00 to 17:00 h. It was also observed that the product temperatures were mostly higher than that of ambient air temperature due to the absorption of solar radiation by the tomato slices and it was more pronounced in SCD than in open sun drying. However, the product temperatures were highly influenced by the weather parameters.

3.4.2 Drying characteristics of tomato slices

The change in moisture content of tomato slices with drying time in solar cabinet dryer (SCD) and in open sun drying is depicted in Fig.3.4. It is observed that the total drying time for 4, 6 and 8 mm thickness slices was 300, 420, 570 min, respectively in SCD while the corresponding values in open sun drying were 435, 615 and 735 min, respectively. For a given thickness, the solar cabinet dryer required shorter drying time when compared to open sun drying. In other words, drying time was reduced to about 68-77% for 4 - 8 mm thickness tomato slices in solar cabinet dryer when compared to open sun drying.



a) Solar cabinet dryer



b) Open sun drying

Figure 3.4. Drying characteristics of tomato slices of different thicknesses by solar and open sun drying methods.

The drying time reduced significantly as per the thickness of slices decreased in both solar and sun drying, because the resistance to moisture movement is relatively higher in thicker slices than in thinner ones. This resistance is known to decrease the drying rate, which resulted in increased drying time of 8 mm thick slices. Generally, it is observed that the time required to reduce the moisture content of tomato slices to any required moisture level was dependent on the drying conditions that are influenced by weather parameters. Similarly, Sacilik et al. (2006) also observed that the drying characteristics of tomato slices in solar tunnel and open sun drying methods were highly influenced by weather parameters.

The newly developed solar cabinet with open sun drying setup and the dried tomato slices are shown in Figs.3.5 & 3.6.

Figure 3.5. View of solar cabinet and open sun drying setup.

4 mm **6 mm** **8 mm**

Open sun dried tomato slices

4 mm **6 mm** **8 mm**

Solar cabinet dried tomato slices

Figure 3.6. Dried tomato slices

A constant rate drying period was not observed in both the drying methods but only a falling rate drying period, which resulted in shrinkage of the dried samples. The mechanisms of mass transfer in food are complex in nature. However, the main mechanism of moisture movement is assumed to be by diffusion that may have both liquid and vapour diffusion components. Hence, the moisture diffusivity estimated from the experimental results is an effective parameter, which includes the effect of hypothesis with the unknown phenomena (Simal et al., 2005). The effective moisture diffusivity values were found to be 4.25 - 7.67 x 10^{-7} m^2/s in solar cabinet dried slices and 3.09 - 9.28 x 10^{-9} m^2/s in open sun dried tomato slices of 4 to 8 mm thicknesses.

Diffusivity is a function of material characteristics as well as drying temperature. Higher diffusivity values for slices dried in SCD might be due to relatively lesser shrinkage of slices when compared to sun dried slices that were practically observed, better circulation of air due to chimney and perhaps also due to higher temperature and lower RH prevailed in SCD. The experimental moisture diffusivity values were in comparison with the values reported by Sacilik et al., (2006) for open sun dried tomato slices (1.31 x 10^{-9} m^2/s), Ramesh et al. (2001) for paprika and Velic et al. (2004) for apple slices. However, the effective diffusivity values of SCD were higher than the values reported by Giovenelli et al., (2002) as 2.26 -9.14 x 10^{-9} m^2/s and these higher values in the present study might be due to the lesser tomato slice thickness used for the experiment compared to the reported values.

3.4.3 Mathematical modelling of drying characteristics of tomato slices

The summary of model parameters of four thin layer drying models that were used for expressing drying characteristics of tomato slices dried by solar and open sun drying methods and the statistical evaluation of models using three different criteria are presented in the Tables 3.2 & 3.3. As per the procedure of Akpinar et al. (2006), the quality of various models was evaluated using R^2, reduced χ^2 and RMSE values. It is observed that the Page model satisfactorily described the drying kinetics of tomato slices dried both under SCD and by open sun drying methods. For Page model, the R^2 values varied from 0.983 to 0.987, χ^2 varied from 0.000071 to 0.00096 and RMSE varied from 0.02514 to 0.02774 for tomato slices of different thicknesses dried in SCD. Whereas in the case of open sun drying method, the R^2 values varied from 0.946 to 0.983, χ^2 varied from 0.00104 to 0.00440 and RMSE varied from 0.03036 to 0.06384 depending upon thickness of tomato slices.

Page model was also reported to fit the thin layer drying data better than other models in many earlier studies such as Akpinar et al., (2006) for aromatic plants, Doymaz (2004) for carrots and Hossain and Bala (2002) for green chillies. Since the present drying study on tomato slices was also performed in thin layers using solar and open sun drying methods and thus the Page model was found to describe the drying characteristics better when compared to other models.

Table 3.2. Estimated parameters and comparison criteria of moisture ratio for solar cabinet drying

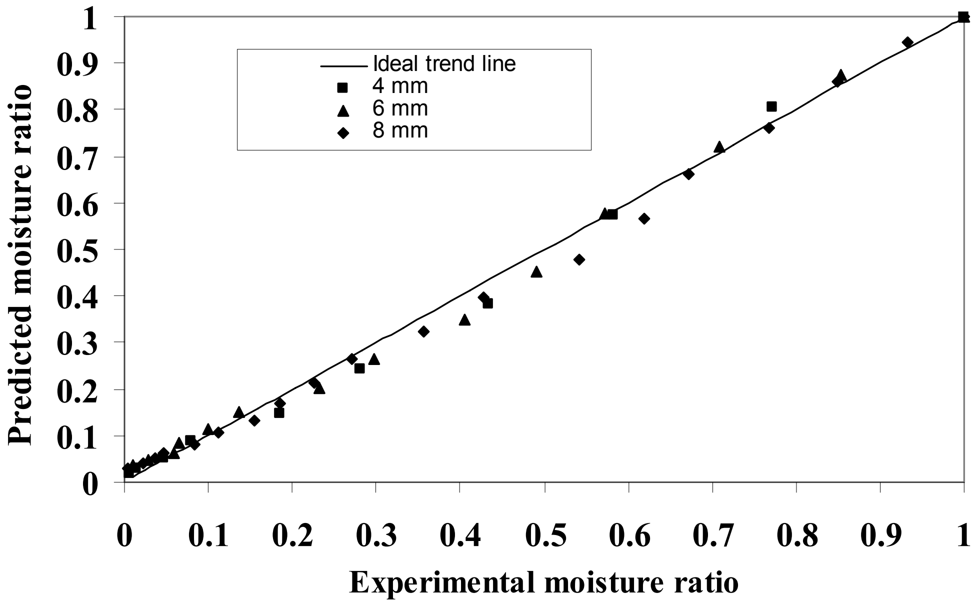
Model	Model constants		Tomato thickness, mm	R^2	χ^2	RMSE
Lewis	k = 0.3986		4	0.877	0.07895	0.26862
	k = 0.2443		6	0.844	0.08017	0.27075
	k = 0.1798		8	0.808	0.11162	0.32518
Page	k = 0.00207	n = 1.367	4	0.985	0.00071	0.02514
	k = 0.00176	n = 1.2792	6	0.987	0.00074	0.02524
	k = 0.00040	n = 1.4493	8	0.983	0.00096	0.02774
Henderson and Pabis	k = 0.5574	A = 3.0389	4	0.967	0.10181	0.30182
	k = 0.3198	A = 2.0825	6	0.940	0.16544	0.37657
	k = 0.2456	A = 2.3518	8	0.909	0.58077	0.68162
Wang and Singh	a = 0.0051	b = 7 x 10^{-6}	4	0.979	0.01219	0.03231
	a = 0.0032	b = 2 x 10^{-6}	6	0.968	0.06445	0.24038
	a = 0.0031	b = 2 x 10^{-6}	8	0.964	0.11984	0.30964

Table 3.3. Estimated parameters and comparison criteria of moisture ratio for open sun drying

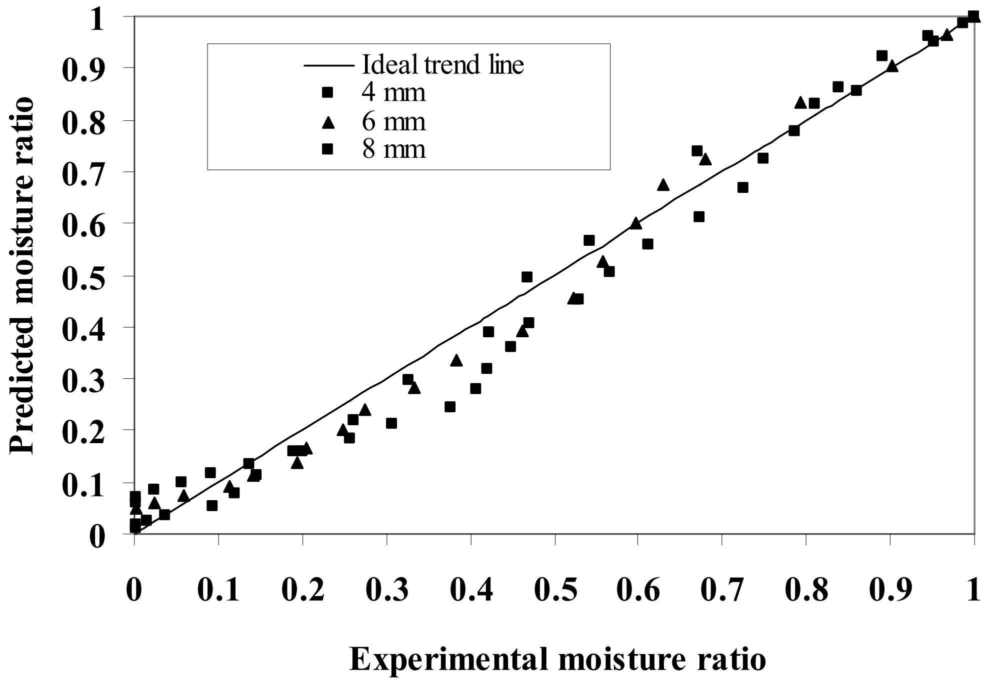
Model	Model constants		Tomato thickness, mm	R^2	χ^2	RMSE
Lewis	k = 0.0072		4	0.866	0.00954	0.01012
	k = 0.0043		6	0.832	0.01089	0.09532
	k = 0.0024		8	0.825	0.01226	0.10867
Page	k = 0.00044	n = 1.649	4	0.983	0.00104	0.03036
	k = 0.00023	n = 1.484	6	0.968	0.00180	0.04038
	k = 0.00018	n = 1.660	8	0.946	0.00440	0.06384
Henderson and Pabis	k = 0.0087	A = 1.572	4	0.906	0.02832	0.01580
	k = 0.0052	A = 1.439	6	0.878	0.02371	0.14646
	k = 0.0029	A = 1.303	8	0.873	0.01928	0.13329
Wang and Singh	a = 0.0041	b = 4 x 10^{-6}	4	0.968	0.00173	0.03015
	a = 0.0024	b = 2 x 10^{-6}	6	0.952	0.00229	0.04555
	a = 0.0012	b = 1 x 10^{-6}	8	0.941	0.00491	0.05113

From the tables, it could be observed that apart from Page model, the other tested models namely Wang and Singh, Henderson-Pabis and Lewis models in that order of priority also described the drying characteristics of tomato slices reasonably well.

Therefore, the Page model was used to predict the moisture ratio of tomato slices dried in both SCD and open sun drying methods. The experimental and the predicted data values using Page model for moisture ratios of tomato slices dried in solar and open sun drying methods are shown in Fig. 3.7 (a & b). The established model provided a very good conformity between the experimental data and the predicted moisture ratios of the tomato slices (4, 6 and 8 mm) dried under solar cabinet dryer and open sun drying methods. It is observed that the predicted data are banded around the ideal trend line indicating the suitability of the model in predicting the drying behaviour of tomato slices both in solar cabinet dryer and by open sun drying.



a) Solar cabinet dryer



a) Open sun drying

Figure 3.7. Comparison of experimental and predicted (Page model) moisture ratios of tomato slices (4, 6 and 8 mm) dried in a) SCD and b) open sun drying methods.

3.4.4 Colour

The colour is an important quality attribute of the dried product from the consumer's point of view. The changes in color of solar cabinet and open sun dried tomato slices for 4, 6 and 8 mm thicknesses are shown in Table 3.4. From the table, it is observed that the dried slices were darker ('L*' decreased) when compared to fresh tomato slice. Between the drying methods, the open sun dried slices were significantly darker ($P< 0.05$) than the solar cabinet dried ones. Also, there was a significant difference in the L* value of the tomato slices studied and among them 8 mm dried slices were found to be more darker than the other thicknesses in both the methods. Kerkhofs (2003) observed that an increase in darkness (L*) of tomatoes were observed after air drying. Olorunda (1990) also observed that an increase in drying time and temperature resulted in tomato tissue darkening.

Table 3.4. Colour values of solar cabinet and open sun dried tomato slices

Methods	Treatments	'L*'	'a*'	'b*'
	Fresh	48.84	12.64	12.06
Open sun drying	4 mm	42.04^{d}	8.98^{d}	18.39^{a}
	6 mm	41.53^{e}	8.44^{e}	18.13^{b}
	8 mm	40.75^{f}	7.84^{f}	18.07^{b}
Cabinet solar dryer	4 mm	44.16^{a}	10.18^{a}	17.51^{c}
	6 mm	43.03^{b}	10.03^{b}	17.22^{d}
	8 mm	42.86^{c}	9.68^{c}	16.94^{e}
F-test		*	*	*
$P < 0.05$		0.16	0.14	0.18
CV%		2.1	4.6	3.6
SEd		0.72	0.65	0.87

Means with same letter are not significantly different

The open sun dried tomato slices had significantly lower 'a*' values of slices (7.84 - 8.98) when compared to solar cabinet (9.68 - 10.18) dried slices. The a* value was declined to about 28-37% after open sun drying. But there was a significant increase in 'b*' values tending towards yellowness of the colour coordinate after drying the slices in both the methods. Overall, it is observed that the colour (L*, a* & b*) change was significantly lower in the solar cabinet dried tomato slices when compared to open sun dried slices. Similarly, Sacilik et al. (2006) reported that the tomato slices dried under solar tunnel drier retained better colour than open sun dried slices due to the exposure of the tomato slices to solar radiations for a longer drying time.

It is also reported that during drying the red color of tomato gradually changed to brick - red and then to brown color in open sun drying (Sacilik et al., 2006). Also, Porretta and Sandei (1991) mentioned that higher color change in open sun drying was mainly due to the direct exposure of the tomato slices to solar radiation for a longer period that induced non-enzymatic browning or Maillard reaction.

3.4.5 Water activity

The water activity (a_w) of the fresh tomato slice was determined to be 0.92. After drying the water activity reduced to 0.502, 0.504 and 0.507 for solar dried slices and 0.526, 0.527 and 0.530 for open sun dried tomato slices of 4, 6 and 8 mm, respectively. It is observed that the water activity (Table 3.5) did not significantly vary with slice thicknesses and drying methods. Similarly, Beaudry et al. (2004) reported that there was no significant difference in water activity of the dried cranberries. As the experimentally determined water activity values of the dried tomato slices were lower than 0.60, they are considered to be safer and shelf-stable with respect to microbial growth as reported by Wang and Brennen (1991).

3.4.6 Rehydration ratio

The rehydration ratio of tomato slices (4, 6 and 8 mm thickness) was higher for SCD samples (3.25, 3.56 and 3.61) when compared to open sun dried (2.95, 3.15 and 3.24) slices (Table 3.5). The samples dried under SCD rehydrated better when compared to open sun dried slices. Similarly, Sacilik et al. (2006) reported that the rehydration ratio of the thin layer solar tunnel dried tomato was little higher (3.15) than the open sun dried tomato (3.10). The lower rehydration ratio for open sun dried slices might be due to long exposure time coupled with higher shrinkage of final product. Rehydration behaviour has been considered as a measure of the induced damage in the material during drying (Lewicki, 1998).

From the table, it is observed that the rehydrated value of 4 mm thick tomato slice in SCD was on par with the rehydrated value of 8 mm thick slice in open sun drying method. Further, it is observed that the thicker slices (8 mm) rehydrated better than the thinner slices (4 mm) in each method. But Giri et al. (2005) reported that the slice thickness had less effect on the rehydration ratio of the product. The overall variation in the rehydration characteristics of the dried product were influenced by the method of processing, sample constitution, preparation of the sample prior to rehydration and extent of the structural and chemical changes induced during drying as reported by Krokida and Maroulis (2001).

Table 3.5. Water activity, rehydration ratio and ascorbic acid content of solar cabinet and open sun dried tomato slices

Methods	Treatments	Water activity (a_w)	Rehydration ratio	Ascorbic acid mg/100g DM
	Fresh	0.920		184.32
Open sun	4 mm	0.526^a	2.95^e	86.95^d
drying	6 mm	0.527^a	3.15^d	80.33^e
	8 mm	0.530^a	3.24^c	75.15^f
Cabinet solar	4 mm	0.502^a	3.25^c	90.39^a
dryer	6 mm	0.504^a	3.56^b	87.73^b
	8 mm	0.507^a	3.91^a	79.09^c
Probability		NS	*	**
$P < 0.05$		0.031	0.06	2.11
CV%		0.23	3.09	7.07
SEd		0.001	0.29	1.05

Means with same letter are not significantly different

3.4.7 Ascorbic acid

The ascorbic acid content was measured on both fresh and dried samples at 4, 6 and 8 mm thicknesses as shown in Table 3.5. There was a significant reduction ($P < 0.05$) in ascorbic acid content in all the dried samples. Between the two drying methods, the reduction was significantly higher in open sun dried (75.15 - 86.95%) tomato slices of 4 - 8 mm thicknesses. From the data, it is observed that the ascorbic acid was very sensitive to oxidative heat damages as the reduction was significant in both the solar and open sun drying methods. This is confirmed with the result reported by Giovanelli et al. (2002) that the reduction in ascorbic acid content was mainly due to the temperature, exposure to direct sun light and the presence of air. Similarly, Gould (1983) mentioned that the ascorbic acid degradation was mainly due to the temperature at which the tomato products were heated in the presence of air. In a similar line, Gregory (1996) mentioned that the loss of ascorbic acid was primarily due to chemical degradation involving oxidation of ascorbic acid.

Also, significant loss of ascorbic acid has been reported in the previous studies using higher temperature and longer drying time. For example, Lavelli et al., (1999) found that about 88% losses in ascorbic acid when tomatoes were dried at 80^{o}C for 7 h to 10% moisture content. Similarly, Zanoni et al. (1998) reported that 40 and 80% loss of ascorbic acid when tomatoes were dried at 80 and 110^{o}C, respectively.

3.5 Conclusions

The study concluded that dehydrated tomato slices could be produced using solar cabinet dryer. The time required to dry the slices were comparatively lower in solar cabinet dryer when compared to open sun drying method. The time required to dry 4 mm thickness tomato slice was lesser as compared to 6 and 8 mm thick slices. The moisture diffusivity was higher in solar cabinet dryer than in open sun drying. The Page model was found to be better in describing the drying kinetics of tomato slices dried in both solar cabinet and open sun drying methods. The colour, rehydration ratio and ascorbic acid retention were comparatively higher in solar cabinet dried tomato slices.

3.7 Acknowledgements

The authors gratefully acknowledge the Canadian International Development Agency (CIDA) and the Natural Science and Engineering Research Council (NSERC) for the financial support.

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CONNECTING TEXT

In the following chapter, vacuum assisted solar drying of tomato slices was evaluated in comparison with open sun drying method at the Department of Bioresource Engineering work shop, Macdonald Campus of McGill University, Canada. The main hypothesis was that due to the creation of vacuum and exclusion oxygen in the vacuum assisted solar drying system, the product quality could be improved in terms of colour, rehydration ratio and ascorbic acid content with a shelf stable final product.

IV. DRYING KINETICS OF TOMATO SLICES IN VACUUM ASSISTED SOLAR AND OPEN SUN DRYING METHODS

4.1 Abstract

A lab model vacuum assisted solar dryer was developed to study the drying kinetics of tomato slices (4, 6 and 8 mm thicknesses) compared with open sun drying under the weather conditions of Montreal, Canada. The drying study showed that the time taken for drying of tomato slices of 4, 6 and 8 mm thicknesses from the initial moisture content of 94.0% to the final moisture content of around 11.5 ± 0.5% (w.b.) was 360, 480 and 600 min in vacuum assisted solar dryer and 450, 600 and 750 min in open sun drying, respectively. During drying, it was observed that the temperature inside the vacuum chamber was increased to 48^{o}C when the maximum ambient temperature was only 30^{o}C. The quality of tomato slices dried under vacuum assisted solar dryer was superior in terms of colour retention, rehydration ratio and ascorbic acid content. The drying kinetics using thin layer drying models and the influence of weather parameters such as ambient air temperature, relative humidity, solar insolation and wind velocity on drying of tomato slices were evaluated.

4.2 Introduction

Tomato (*Lycopersicon esculentum L.var*) is an important fleshy vegetable, widely used throughout the world. It is a rich source of minerals, vitamins, organic acid, and dietary fiber. It is available in fresh and in processed forms. In the processed category, dried tomato slices/powder are becoming popular in the international markets for the development of new food items in the form of ready to eat / use products.

Though sun drying has been used for many years for drying tomato slices, the quality of tomato slices may be seriously affected due to long drying times that may have adverse effect on the product quality as the final product may be contaminated with dirt and microbes leading to enzymatic and microbial activity. Drying at higher temperatures may cause serious damage to the flavour, color and nutrients of the dehydrated product (Prakash et al., 2004; Praveenkumar et al., 2006). Further, undesirable quality changes in the dehydrated products are due to the presence of oxygen in the drying medium. Dehydration of food materials especially fruits and vegetables with antioxidant properties are a difficult food process operation, mainly because of undesirable changes in quality of the dehydrated products. Oxidative heat damage of tomato halves as affected by drying was reported by Zanoni et al. (1998).

To overcome the oxidative problem, vacuum drying is one of the efficient means of drying food materials having oxidative and heat sensitivity properties. The lower pressure (vacuum) in the system allows the use of lower drying temperature in order to reach the similar final moisture content of the product when compared to other drying methods. Fernando and Thangavel (1987) reported that the quality of vacuum dried coconut was superior to the conventionally dried product. As the solar radiation can pass through the vacuum and the moisture can be driven out at lower temperature, vacuum assisted solar dryer could be a better alternative for drying food grade material susceptible for oxidation and heat sensitivity (Pap, 1995).

Several researchers have investigated the drying kinetics of food products and they have evaluated various mathematical models to describe thin layer drying characteristics (Farkas, 2000; Hussain and Bala, 2002; Freire et al., 2005). Drying kinetics is generally affected by air temperature, relative humidity, air velocity and material size. Also the dried products are characterized by low porosity and high apparent density (Kaur et al., 2002). Although considerable literature is available on the drying kinetics using thin layer drying models of various food products, information is not available on vacuum assisted solar drying of tomato slices. The use of solar energy is sustainable and any research work in this line will help to produce quality dried products. Therefore, a study was undertaken to develop a vacuum assisted solar dryer for drying of sliced tomatoes of different thicknesses and compare its performance with open sun drying. The drying kinetics using weather parameters and thin layer drying models were also evaluated.

4.3 Materials and Methods

Fresh Olympian Gold (#4799) green house grown, herbicide and insecticide free Canadian grown tomatoes were procured from local market and stored in a refrigerator maintained at 4^{o}C until the drying experiments. Before starting the experiment, tomatoes of size 65-75 g were maintained at room temperature for one hour. The tomatoes were washed with potable water and sliced into circular discs of 4, 6 and 8 mm thicknesses using a hand operated adjustable mechanical slicer. The sliced tomatoes were dried using Vacuum assisted Solar Dryer (VSD) and the results were compared with open sun drying.

4.3.1 Vacuum assisted solar dryer

A vacuum assisted solar dryer was designed and fabricated in the Department of Bioresource Engineering, McGill University, Canada (Fig.4.1). The drying experiment took place in Montreal (45°30' N and 73° 36'W), Canada. The drying unit consists of a drying chamber (polycarbonate vacuum bell) measuring 254 mm height and 190 mm diameter, a circular disc fitted with a weighing platform, a polyethylene gasket, temperature probe and a vacuum pump. The polyethylene gasket was placed in between the drying chamber and the circular disc to avoid leakage of air. The drying chamber was connected to a vacuum pump, and the vacuum pressure inside the chamber was maintained at 84.7 kPa by adjusting the vacuum valve.

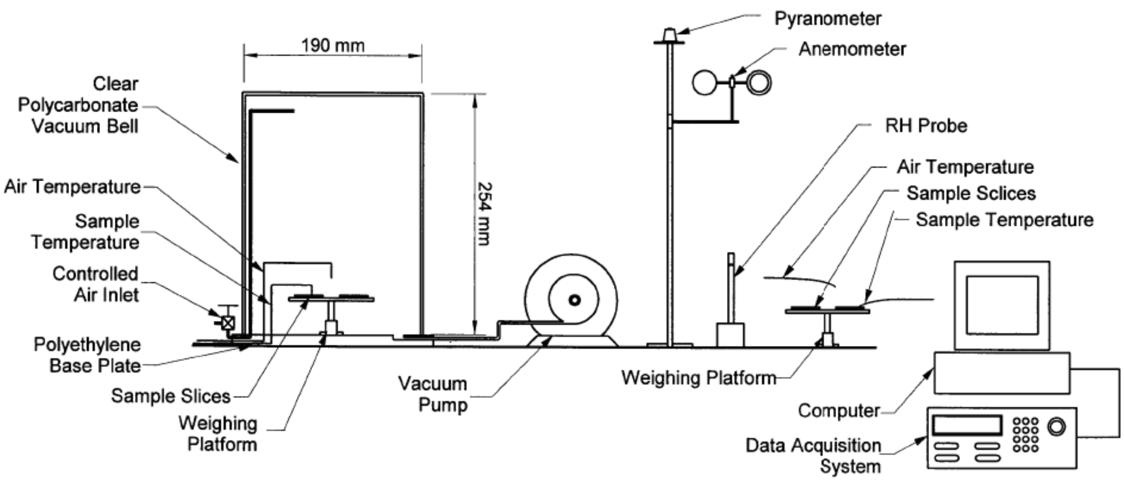


Figure 4.1. Vacuum assisted solar and open sun drying set up for tomato slices

Sliced tomato samples of 100 g were kept in the drying chamber on a digital electronic weighing platform (5 kg capacity) with an accuracy of ± 0.01 g. The chamber was also provided with air inlet at the bottom to avoid condensation of water. During the drying process, provisions were made to record the evolution of product mass and product temperature inside the drying chamber at one minute interval using a data logger

(Agilent 34970A, USA) connected to a personal computer (PC). The experiments were carried out between 9:00 and 17:00 h on sunny days during August 2005. At the end of the day (17:00 h), the partially dried tomato slices were packed in polyethylene bags for continuing the drying study on subsequent days. The drying experiment was continued until no further change in the mass of the tomato slices was observed.

4.3.2 Open sun drying

To compare the performance of the VSD with that of open sun drying, 100 g of sliced tomatoes were placed on a black painted tray, which was positioned on a digital electronic weighing platform (5 kg capacity) with an accuracy of ± 0.01 g. Provisions were also made to record the reduction of mass, product temperature, ambient air temperature, relative humidity, wind velocity and solar insolation using a data logger (Agilent 34970A, USA) connected to the PC. The sun drying experiments were carried out simultaneously with the VSD experiments between 9:00 and 17:00 h.

4.3.3 Moisture content

The moisture content of the tomato samples was determined by using vacuum oven at 70^{o}C for 24 h (AOAC, 1980). Triplicate samples were used for the determination of moisture content and the average values were reported.

4.3.4 Drying kinetics study using thin layer drying models

As drying proceeds, the moisture content of the material decreases and the mechanism of drying changes, which is controlled by the liquid diffusion mechanism described by Fick's second law (Crank, 1975). The semi - theoretical models are directly obtained by simplification of the Fick's law. The most commonly used thin layer drying equation is similar to the Newton's law for cooling process. Lewis (1921) proposed the first general form:

$$\frac{dM}{dt} = -k(M - M_e) \tag{4.1}$$

By assuming the bulk moisture (*M)* to depend on drying time (t), a solution to the above equation is obtained by integration:

$$\text{Moisture Ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} = e^{-kt} \tag{4.2}$$

Where,

M_i and M_e are the initial and equilibrium moisture contents, % (d.b) and

M_t is the moisture content at any time ‘t’, % (d.b).

The drying rate constant ‘*k*’ is a function of drying air temperature, which can be determined by linearising the thin layer drying equation (4.2):

$$\ln(\mathrm{MR}) = \ln\left(\frac{M_t - M_e}{M_i - M_e}\right) = -kt \tag{4.3}$$

Where, *k* is the drying rate constant, min^{-1} and t is the drying time, min

By plotting the drying data for each thickness of tomato slices on semi - log paper, the drying rate constant ‘*k*’ could be obtained from the slope of the straight line. Similarly, Page (1949) proposed a thin layer drying equation:

$$\mathrm{MR} = \frac{M_t - M_e}{M_i - M_e} = e^{-qt^n} \tag{4.4}$$

Where, ‘*q*’ and ‘*n*’ are drying constants that depend on the air temperature and type of material. These parameters are calculated by linearising equation (4.4):

$$\ln\left[-\ln\left(\frac{M_t - M_e}{M_i - M_e}\right)\right] = \ln q + n \ln t \tag{4.5}$$

The plot of moisture ratio versus time on a log-log graph sheet gives a straight line from which *q* and *n* values could be determined as slope and intercept, respectively.

Moisture diffusion was calculated based on the Fick’s second law by considering the tomato slices as a thin slab (Crank, 1975):

$$\frac{M_\theta}{M_\infty} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{\left(\frac{-D(2n+1)^2 \pi^2 t}{4L^2}\right)} \tag{4.6}$$

Equilibrium at the inter phase as a boundary condition is a key factor for using equation (4.6). For long drying periods (t > 5 min), Eqn. (4.6) can be simplified ($M_\theta = M_i - M_t$ and $M_\infty = M_i - M_e$) to the following form by taking n = 0:

$$\frac{M_\theta}{M_\alpha} = \frac{M_t - M_e}{M_i - M_e} \tag{4.7}$$

$$\text{Moisture ratio (MR)} = \frac{M_t - M_e}{M_i - M_e} = \frac{8}{\pi^2}\ e^{\left(\frac{-D\pi^2 t}{4L^2}\right)} = A\ e^{\left(\frac{-D_{eff} t}{4L^2}\right)} \qquad (4.8)$$

Where, the constant A = $(8/\pi^2)$. By linearization, equation (4.8) can be expressed as:

$$\ln(\text{MR}) = \ln\left(\frac{M_t - M_e}{M_i - M_e}\right) = \ln\ A - \left(\frac{D_{eff}\, t}{4L^2}\right) \qquad (4.9)$$

The moisture diffusivity values were thus calculated by plotting experimental drying data in terms of ln (MR) versus drying time. From Eqn. (4.9), a plot of ln (MR) versus drying time should give a straight line with a slope: $S = \frac{D_{eff}}{4L^2}$ (4.10)

Using the slope value (Eqn. 4.10), the moisture diffusivity (D_{eff}) could be determined.

4.3.5 Colour

The colour of fresh and dried tomato slices was determined in terms of the tristimulus colour values L*, a* and b* using Minolta Chromameter, CR-300 (Minolta Co., Japan). Where, luminance (L*) forms the vertical axis, which indicates whiteness to darkness. Chromatic portion of the solids is defined by: a* (+) redness, a* (-) greenness, b* (+) yellowness and b* (-) blueness. The equipment was calibrated against a white Minolta calibration plate of CR-300, with 2° observer values.

4.3.6 Water activity

The water activity of fresh and dried tomato slices at room temperature of 23.4 ± 1°C was measured in triplicates by using a water activity meter (Aqua Lab, Model Series 3TE, USA).

4.3.7 Rehydration ratio

Rehydration ratio gives a measure of the ability of dried tomato slices to reabsorb water. The rehydration ratio of dried tomato slices was determined as the ratio of rehydrated mass to the dehydrated mass. A sample of 5 g of the dried tomato slices was placed in a 250 ml beaker containing 150 ml of boiling distilled water. The contents were boiled for 5 min for rehydration. After rehydration, the excess free water on the tomato slice surface was removed before assessing the rehydrated mass (Prakash et al., 2004). Triplicate measurements were done and average values are reported here.

4.3.8 Ascorbic acid

Ascorbic acid content in fresh and dried tomatoes was measured by titration method (Ranganna, 1995). One gram of sample was soaked in 4% oxalic acid for ten minutes and it was ground using a pestle and mortar. The contents were filtered and the volume was made up to 100 ml with oxalic acid. Out of this, 10 ml aliquot was titrated against a dye solution containing 42 mg of sodium bicarbonate and 52 mg of 2, 6 dichlorophenol - indophenol in 50 ml of water. The ascorbic acid contents in the samples were determined and the results were expressed in mg / 100 g dry matter.

4.3.9 Experimental design

All observations were reported as means of three replications. Analysis of variance and least significance difference (LSD) at $P < 0.05$ were calculated based on the Completely Randomized Design using AGRES software package of Indian Agricultural Statistics Research Institute, New Delhi to determine the significant differences among the dried tomato slices.

4.4 Results and Discussion

4.4.1 Drying Characteristics due to Weather Parameters

During the experimental period of 20 days in August'05, the average daily variations of solar radiation, wind velocity, ambient relative humidity and air temperature were ranged from 312 to 795.6 W/m^2, 0 to 6.5 m/s, 16.0 to 31.9% and 27.7 to 30^{o}C, respectively in Montreal, Canada (Fig.4.2).

The product temperatures of 4 mm thick tomato slices in vacuum assisted solar dryer (VSD) were recorded as 31.5 - 48^{o}C and in open sun drying, they were recorded as 27.3 - 37.5^{o}C (Fig.4.3). The maximum temperature recorded inside the vacuum chamber was 48^{o}C when the corresponding ambient temperature and relative humidity were 30^{o}C and 16%, respectively. It is observed that the maximum product temperature of 6 mm thick tomato slices in VSD was 45.0^{o}C and in open sun drying, it was 34.5^{o}C. For 8 mm thick tomato slices, the maximum product temperatures in VSD and open sun drying were found to be 42.4 and 31.5°C, respectively. From the figure, it is clear that the product temperature inside the vacuum chamber was significantly higher when compared to the open sun drying. The higher product temperature inside the VSD might be due to the direct absorption of solar energy and nearly zero relative humidity maintained in the vacuum chamber. The vacuum was maintained at 84.7 kPa during all the drying experiments.

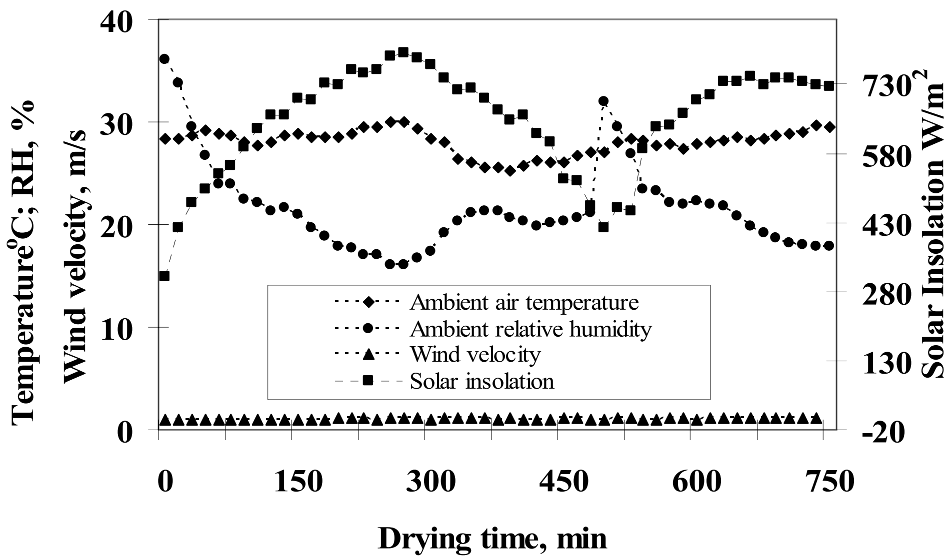


Figure 4.2. Ambient temperature, relative humidity and wind velocity observed during the drying experiments.

The air and product temperatures started increasing significantly during 12:00 - 14:00 h, where as the relative humidity reached the lowest value during this period. Generally, the drying temperature, relative humidity and wind velocity varied continuously during the drying period of 9:00 to 17:00 h due to the variation of solar insolation. There was a significant difference between the product temperatures of VSD and open sun drying. It was also observed that the product temperatures were higher than that of ambient air temperature. This might be due to the absorption of solar radiation by the tomato slices and the dark paneling through conduction and radiation heat transfer during drying.

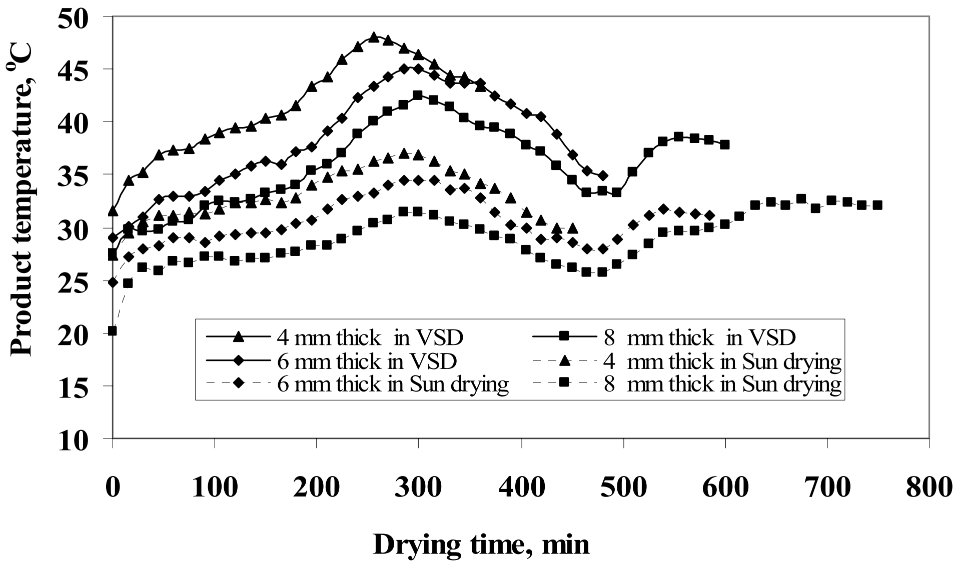


Figure 4.3. Relationship of product temperatures of tomato slices (4, 6 and 8 mm thickness) during drying in vacuum assisted solar drying (VSD) and open sun drying.

From figures (4.2-4.3), it was observed that the product temperatures in both VSD and open sun drying increased slowly during 9:00 -12:00 h, attained their maximum values during 12:00 - 14:00 h and then started decreasing due to a decrease in ambient temperature. Overall, it was observed that the product temperatures were highly influenced by the weather parameters such as change in ambient air temperature, relative humidity and wind velocity due to solar insolation.

4.4.2 Drying Characteristics of tomato slices

The initial moisture content of the tomato slices was found to be 94% (w.b.). The changes in moisture ratio with drying time of tomato slices in vacuum assisted solar dryer (VSD) and open sun drying methods are shown in Fig.4.4 (a & b). It is seen from Fig.4.4a that the time required to dry the tomato slices of 4, 6 and 8 mm thickness was 360, 480 and 600 min, respectively. For the similar thickness in open sun drying, the time required to dry the slice was 450, 600 and 750 min, respectively (Fig. 4.4b). Between the drying methods, the time taken to dry the sample was lower in VSD than in open sun drying. The decrease in drying time was mainly due to the higher vapour pressure gradient created in the vacuum, which helped in faster removal of moisture from the sample. It is observed that a small difference in the slice thickness greatly affects the drying time especially at lower drying temperatures. The results are similar to the previous works on onion slices by Praveenkumar et al. (2006).

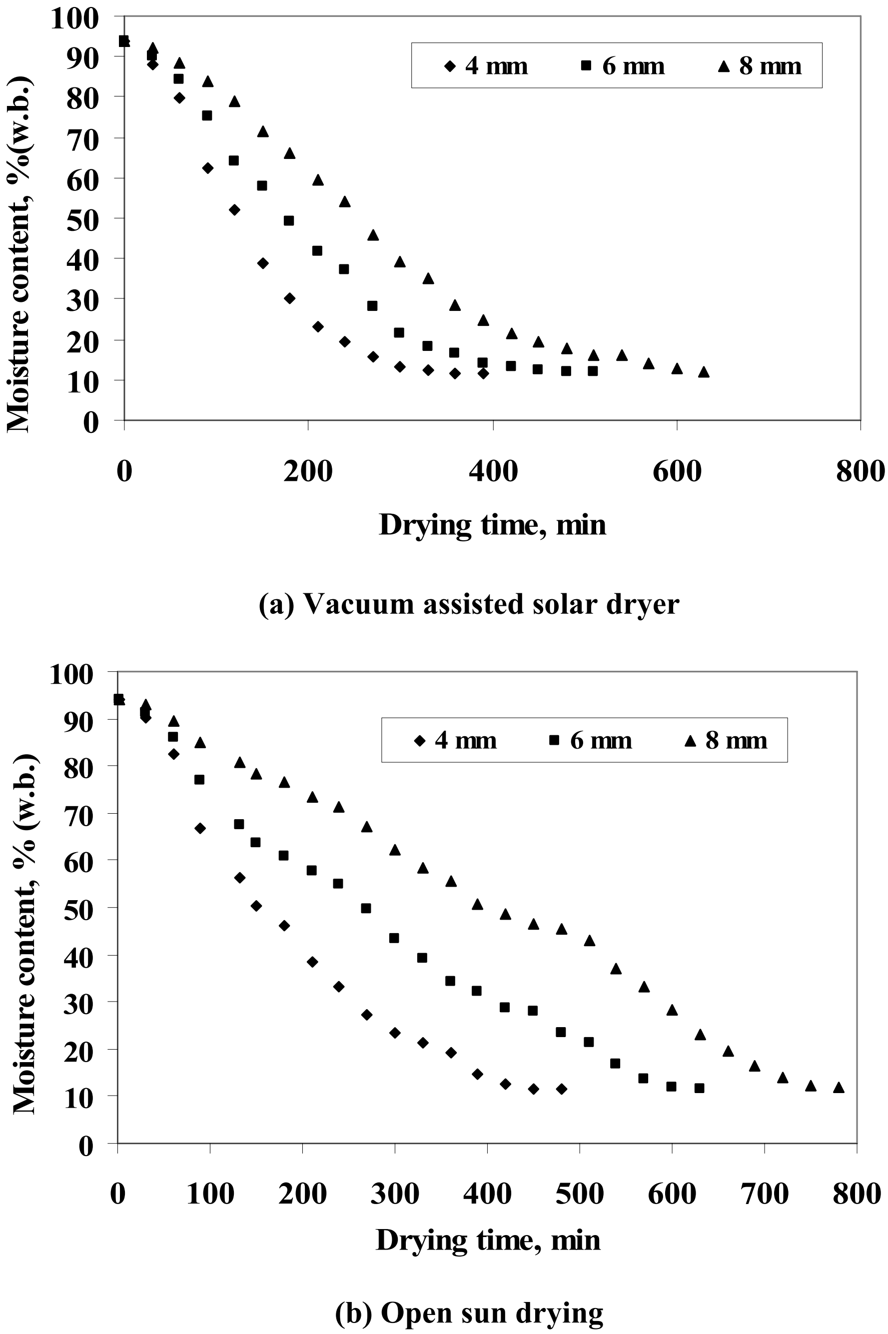


Figure 4. 4. Relationship between moisture ratios and drying time of tomato slices (4, 6 and 8 mm thickness) dried in a) VSD and b) open sun drying.

In order to determine the moisture ratio as a function of drying time, the semi-theoretical Lewis and empirical Page equations were fitted and coefficient of determinations (R^2) were estimated. The values of R^2 obtained from Page equation were higher than for the Lewis model. Therefore, the Page model was used to simulate the moisture ratio of tomato slices dried in both the drying methods. A constant rate drying period was not observed in both the drying methods but only a long falling rate drying period, which resulted in shrinkage of the dried samples. This result is in agreement with the results reported by Hawlader et al. (1991), Prabhanjan et al. (1995) and Markowski et al. (1998).

The developed vacuum assisted solar dryer with open sun drying setup for drying tomato slices and the dried tomato slices are shown in Figures 4.5 & 4.6.

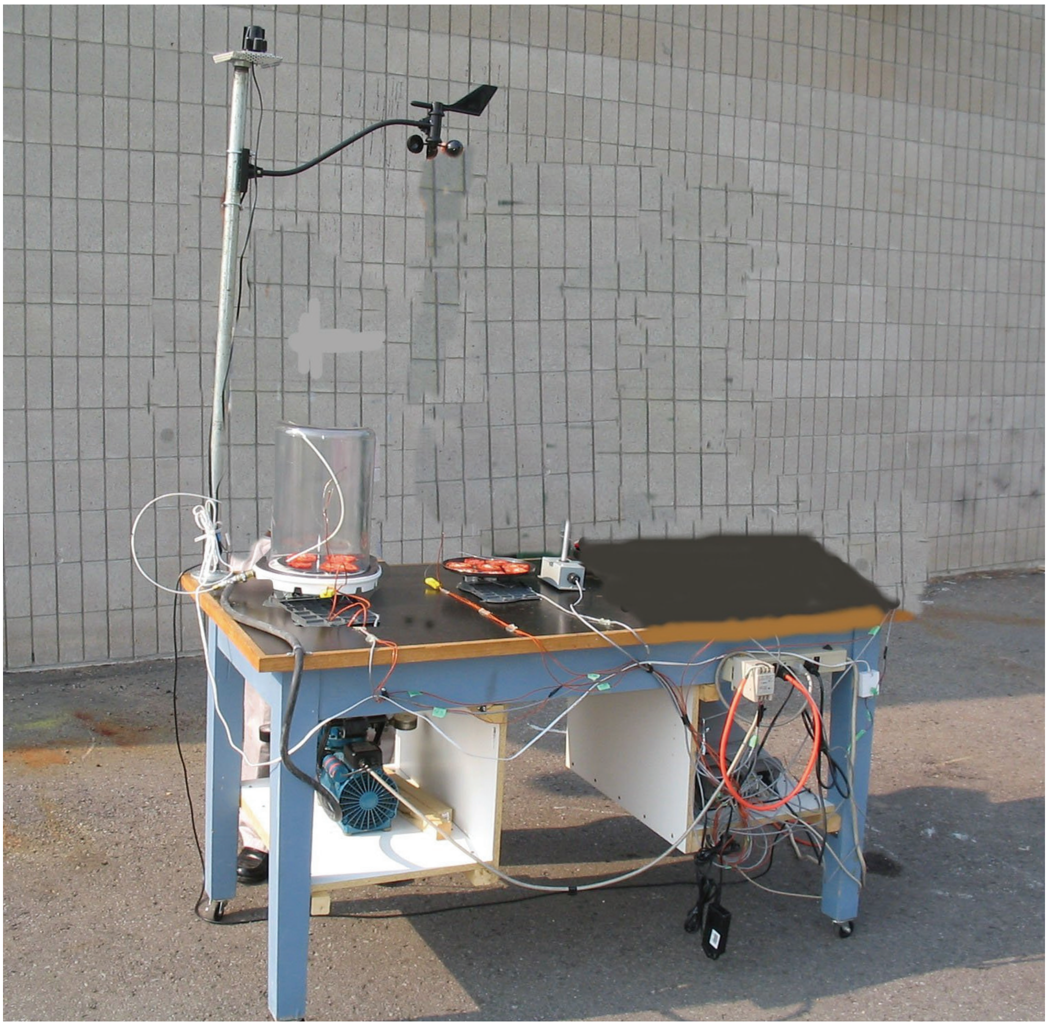


Figure 4.5 View of vacuum assisted solar and open sun drying setup

4 mm **6 mm** **8 mm**

Open sun dried tomato slices

4 mm **6 mm** **8 mm**

Vacuum assisted solar dried tomato slices

Figure 4.6. Dried tomato slices

4.4.3 Drying Rate Constant and Moisture Diffusivity

The vacuum effect on solar drying of tomato slices was studied and the results are compared with open sun drying. The drying rate constant '*k*' was determined for the tomato slices dried in VSD and open sun drying by plotting the drying data ln (MR) *vs* drying time as per equation 4.3. The results are presented in Table 4.1. From the table, it is observed that the drying rate constant '*k*' value decreased with an increase in slice thickness. As expected, the drying rate value was higher (0.013 to 0.003) in VSD when compared to open sun drying (0.008 to 0.002), signifying faster drying due to vacuum. An increase in temperature coupled with lower pressure resulted in substantial increase in drying rate of tomato slices in VSD. Madamba (2003) reported that the drying air temperature and slab thickness significantly affected the average drying rate of mango slices.

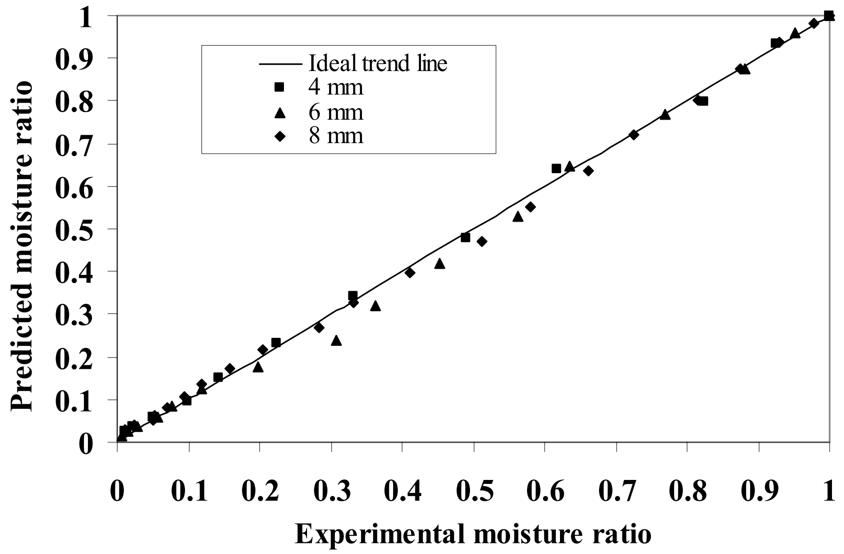
Table 4.1. Equation parameters for the two different drying methods for tomato slices

Drying methods	Tomato slice thickness	Lewis method '*k*'	Fick's D_{eff} x 10^{-9} (m^2/s)	R^2	Page '*q*' x10^{-3}	Page '*n*'	R^2
Vacuum	4 mm	0.013	14.50	0.939	0.195	1.72	0.996
assisted	6 mm	0.011	11.30	0.908	0.118	1.71	0.993
solar dryer	8 mm	0.003	7.57	0.927	0.045	1.76	0.997
Open sun	4 mm	0.008	9.28	0.906	0.181	1.64	0.983
drying	6 mm	0.005	5.54	0.878	0.131	1.48	0.968
	8 mm	0.002	3.09	0.873	0.045	1.66	0.946

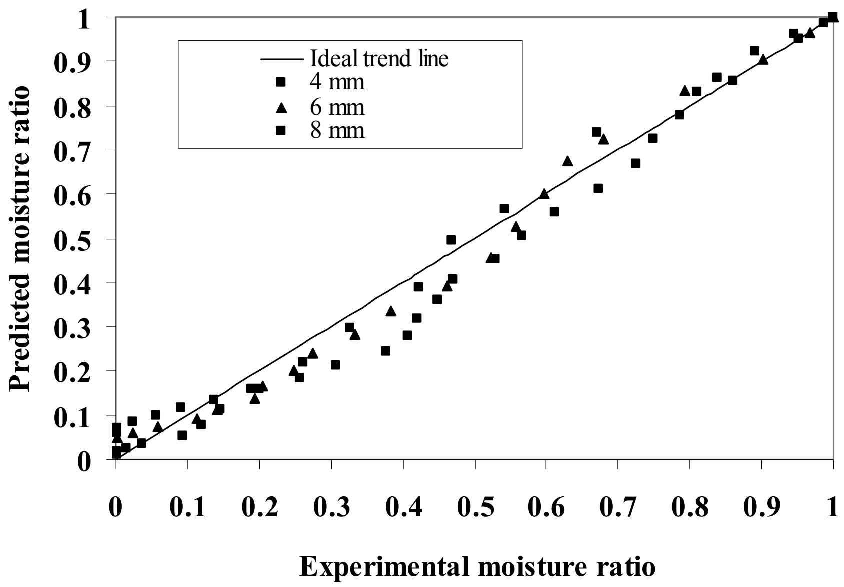
Based on the Fick's moisture diffusion model, the moisture diffusivity in tomato slices was obtained and the values are presented in Table 4.1. The moisture diffusivity in vacuum assisted solar dried tomato slices (7.57 - 14.5 x 10^{-9} m^2/s) was higher than that of open sun dried slices (3.09 - 9.28 x 10^{-9} m^2/s), respectively at all selected thicknesses. It can be seen that the effective moisture diffusivity varies with pressure and material thickness. It is evident that the moisture diffusivity has a tendency to increase with decrease in pressure that facilitated the increase in drying rate in vacuum assisted solar dryer when compared to open sun drying as reported by Drouzas et al. (1999) and Park (1998).

The parameters '*q*' and '*n*' obtained from the linear plot of Page model for VSD and open sun drying of tomato slices are also presented in Table 4.1. The Page model gave higher coefficient of determination R^2 values (0.996 - 0.993) in VSD than in open sun drying. It is observed that the drying rate constant '*q*' value increased with a decrease in slice thickness. However, the '*n*' value did not show any clear trend as it depends on additional processing conditions. This is in agreement with the findings of Arora et al., (2003), Drouzas et al., (1999) and Praveenkumar et al., (1995). The experimental and predicted data using Page model for moisture ratio of tomato slices dried in vacuum assisted solar dryer and open sun drying are shown in Fig. 4.7 (a & b). There is a good agreement between the experimental moisture ratios and the predicted values for vacuum assisted solar dried tomato slices when compared with open sun dried tomato slices.

Wang (2002) also concluded that Page model was found to give the best results in describing single-layer far-infrared radiation drying of onion.



(a) Vacuum assisted solar dryer



(b) Open sun drying

Figure 4.7. Comparison of experimental and predicted (Page model) moisture ratios of tomato slices (4, 6 and 8 mm) dried in a) VSD and b) open sun drying methods.

4.4.4 Colour

The changes in color of open sun dried and vacuum assisted solar dried tomato samples at 4, 6 and 8 mm thicknesses are shown in Table 4.2. After drying, an in crease in the darkness (a decrease in the L* value) was observed in all the dried tomato slices when compared to fresh tomato slice and also there was a significant change in the L* values of the dried slices. This showed that the dried slices were significantly darker than the fresh one. However, ‘a*’ values of dried slices decreased significantly in open sun drying when compared to VSD dried samples due to direct exposure and longer drying time. Olorunda, (1990) also reported that an increase in drying time and temperature resulted in tissue darkening of tomato slices.

Table 4.2. Colour values of vacuum assisted solar dried and sun dried tomato slices

Methods	Treatments	‘L*’	‘a*’	‘a*/b*’
	Fresh	48.84	12.64	1.05
Open sun drying	4 mm	42.04^{d}	8.98^{b}	0.48^{c}
	6 mm	41.53^{e}	8.44^{c}	0.46^{c}
	8 mm	40.75^{f}	7.84^{d}	0.43^{d}
Cabinet solar dryer	4 mm	48.15^{a}	12.51^{a}	0.58^{b}
	6 mm	46.64^{b}	12.55^{a}	0.57^{a}
	8 mm	45.73^{c}	12.46^{a}	0.57^{a}
F-test		**	**	*
P <0.05		0.13	0.23	0.02
CV%		1.6	5.2	9.5
SEd		0.58	0.45	0.87

Means with same letter are not significantly different

An a*/b* value is commonly used as an index to report the colour quality (brightness of red colour of tomato) as reported by Shi et al. (1999). The experimental a*/b* values varied from 0.57 to 0.58 for VSD and from 0.43 to 048 for open sun dried tomato slices. This showed that the brightness was higher in VSD tomato slices than in open sun dried slices. Kerkhofs (2003) also observed that an increase in darkness (L*) and decrease in ratio (a*/b* value) of tomatoes after air drying. Shi et al., (1999) reported a 50% decrease in the a*/b* value when tomatoes dried to a moisture content of 3-4% using conventional air drying at 90^{o}C. Further, they reported that the colour (L* and a*/b* values) of tomatoes was retained best under conditions of osmotic dehydration at 25^{o}C.

The amounts of sugar, acid (pH) and amino acids as well as time of processing have been reported to affect the colour of the dried tomatoes by causing formation of brown pigments (Gould, 1983). However, in the present study, the colour change in terms of 'a*' was not significant in the vacuum assisted solar dried tomato slices due to the exclusion of air i.e., without oxidation. This is in agreement with the results reported by Clary and Ostrom (1995) that the colour retention was better in vacuum dried Thomson grapes when compared to microwave and hot air dried grapes.

4.4.5 Water Activity

The water activity (a_w) of the fresh sample was found to be 0.92. After drying, the water activity values reduced to 0.5 ± 0.017 corresponding to the moisture content of 11.5 ± 0.01% (w.b). It is observed that there was no significant difference in water activity between vacuum and sun dried samples (Table 4.3). Beaudry et al. (2004) also reported that there was no significant difference in water activity of the vacuum dried cranberries. The water activity values of the dried tomato slices were within the range reported by Akanbi et al. (2006) for dehydrated tomato slices. As the water activity values of the dried tomato slices were lower than 0.60, they are considered to be safer and shelf-stable with respect to microbial growth as reported by Wang and Brennen (1991).

4.4.6 Rehydration Ratio

The rehydration ratio of tomato slices (4, 6 and 8 mm thickness) was significantly higher ($P < 0.05$) for VSD samples (4.61, 4.75 and 4.83) when compared to open sun dried (2.95, 3.15 and 3.24) samples (Table 4.3). The analysis of variance indicated that there was a significant difference in the rehydration ratios among the dried tomato slices in both the methods. The higher rehydration ratio for VSD samples indicated that the samples retained good texture and absorbed more water when compared to open sun dried samples. It is also obvious that the dehydration processes that change product composition in lesser extent are expected to offer better rehydration ratio of the finished product such as freeze and vacuum drying methods. Madamba and Liboon (2001) mentioned that the rehydration ratio of vacuum dried celery was influenced by the temperature, vacuum pressure and slice thickness. Also, Giri and Prasad (2005) suggested that the rehydration ratio could be improved by maintaining lower pressure (higher vacuum) and higher microwave power.

The direct sun light and long exposure time might have affected the rehydration capacity of the open sun dried samples. Also, the variation in the rehydration ratio values might be influenced by the drying temperature, soaking time, air displacement, pH and ionic strength (Salunkhe, 1991). Among the slice thicknesses, the rehydration ratio was lower for 4 mm slice when compared to 6 and 8 mm slices. This might be due to higher damage of cell walls at lower thickness, leading to decreased water absorption capacities. Similar results for open sun dried tomatoes were reported by Sacilik et al. (2006).

Table 4.3. Water activity, rehydration ratio and ascorbic acid content of vacuum assisted solar dried and open sun dried tomato slices

Methods	Treatments	Water activity (a_w)	Rehydration ratio	Ascorbic acid mg/100g DM
Open sun drying	Fresh	0.920	-	184.32
	4 mm	0.526^a	2.95^e	86.95^d
	6 mm	0.527^a	3.15^d	80.33^e
	8 mm	0.530^a	3.24^c	75.15^f
Vacuum assisted solar dryer	4 mm	0.519^a	4.61^a	138.25^a
	6 mm	0.539^a	4.75^b	131.66^b
	8 mm	0.533^a	4.83^c	124.35^c
F-test		NS	**	**
$P < 0.05$		0.029	0.04	4.12
CV%		0.23	3.6	6.05
SEd		0.002	0.62	1.02

Means with same letter are not significantly different

4.4.7 Ascorbic acid content

Vacuum dried tomato slices showed a significant, but a smaller loss of ascorbic acid (24-32%) when compared to open sun dried tomato slices (52 - 82%) of 4 - 8 mm thickness due to the exclusion of oxygen and creation of vacuum (Table 4.3). Tomato slices dried at 4 mm thickness has been found to have a higher ascorbic acid than 6 and 8 mm thickness in both the drying methods.

Data confirmed that ascorbic acid content was very sensitive to heat damage since a significant loss of ascorbic acid has been observed after sun drying. Kaur et al. (2002) reported that tomatoes are the rich source of ascorbic acid; however, processing of tomatoes has detrimental effect on their ascorbic acid retention (Takeoka et al., 2001). Davey et al. (2000) suggested that the milder the treatment and lower the temperature, the better the retention of ascorbic acid in tomatoes. There are many reports of peroxidase activity in all common vegetables, and these enzyme catalyses the oxidation of different substrates such as ascorbic acid (Dilley, 1970). The present experimental values of ascorbic acid in dried tomato slices were found to be lower than the values reported by Toor et al., (2006) on semi-dried tomato slices and losses were also higher since, the reported values were based on semi-drying to the moisture level of 50 - 55% only.

4.5 Conclusions

The study concluded that good quality shelf stable dried tomato slices could be produced using vacuum assisted solar drying method. The time required to dry the slices was comparatively lower in vacuum assisted solar drying when compared to open sun drying. The drying rate and moisture diffusivity of tomato slices were higher in vacuum assisted solar dryer. Page model was found to be better in describing the drying kinetics. It is concluded that the drying time and product temperatures were highly influenced by the weather parameters mainly temperature induced by solar insolation. From the study, it is also concluded that the colour retention, rehydration ratio and ascorbic acid retention were higher in vacuum assisted solar dried slices than the open sun dried tomato slices.

4.6 Acknowledgements

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V. GENERAL SUMMARY AND CONCLUSIONS

Drying is one of the important food preservation methods, which has been extensively researched in the past few years. Hence, this field takes considerable importance and there is also a need to improve and develop this process to the highest extent possible. Since, the vegetable commodities are highly heat sensitive commodities and the drying methods have to be designed to suit these commodities. Dried tomato products in the form of slices, halves, quarters and powder are becoming popular for adding as a component in pizza, soup and preparation of other food items. Drying itself is an energy intensive operation and hence, the renewable form of energy has been selected to make the drying operation sustainable. Therefore, experiments were performed to develop and evaluate the solar drying methods to improve the product quality.

Tomato slices were cut into 4, 6 and 8 mm thick slices by using manually adjustable mechanical slicer. The slices were dried by using the developed natural convection solar cabinet and vacuum assisted solar dryers and the results were compared with open sun drying.

During drying the weather parameters such as solar radiation (312 to 795.6 W/m^2), wind velocity (0 to 6.5 m/s), ambient relative humidity (16.0 to 31.9%) and air temperature (27.7 to 30^oC) were recorded. The product temperature inside the solar cabinet drying chamber was significantly higher (63, 58.7 and 56.6^oC) than vacuum assisted solar dryer (48, 45 and 42.4^oC) and open sun drying (37.5, 34.5 and 31.5^oC) for 4, 6 and 8 mm thick tomato slices, respectively. Because of the higher temperature recorded in the solar cabinet dryer, the total drying time was reduced to 300, 420, 570 min, followed by 360, 480 and 600 min in vacuum assisted solar dryer and 435, 615 and 735 min, in open sun drying methods, respectively for 4, 6 and 8 mm thicknesses.

The main mechanism of moisture movement is assumed to be by diffusion during drying of tomato slices and the effective moisture diffusivity values were found to be 4.25 - 7.67 x 10^{-7} m^2/s in solar cabinet dried slices, 7.57 -14.5 x 10^{-9} m^2/s in vacuum assisted solar dried and 3.09 - 9.28 x 10^{-9} m^2/s in open sun dried tomato slices of 4 to 8 mm thickness, respectively. The higher diffusion values in both the solar cabinet and vacuum assisted solar dryers were due to the higher temperature and lower relative humidity prevailed in the drying chamber compared to open sun drying. Among the thin layer drying models, Page model was found to satisfactorily describe the drying kinetics of tomato slices dried under solar cabinet dryer, vacuum assisted solar dryer and open sun drying methods with higher coefficient of determination.

The colour observation using L*, a* and b* values showed that the dried product exhibited darker colour than the fresh tomato slices. But among the drying methods, the vacuum assisted solar dried slices retained better colour than the solar cabinet and open sun dried slices due to the exclusion of air during drying. Since, in both solar and open sun drying methods, the slices were exposed to atmospheric air and in turn the non-enzymatic browning was induced in the slices. The water activity values were ranged from 0.519 to 0.539 for vacuum assisted solar dried, from 0.502 to 0.507 for solar cabinet and from 0.526 to 530 for open sun dried tomato slices of 4-8 mm thickness. There was no significant difference among the thicknesses of the slices studied and the dried slices were found to be safer from microbiological growth.

The rehydration ratio of tomato slices (4, 6 and 8 mm thickness) was higher for vacuum assisted solar dried slices (4.61, 4.75 and 4.83) when compared to solar cabinet dried (3.15, 3.46 and 3.61) and open sun dried (2.95, 3.15 and 3.24) slices, respectively. The lower rehydration ratio for solar and open sun dried samples might be due to higher temperature and longer exposure time during drying. Further, it was observed that the thicker slices (8 mm) rehydrated better than the thinner slices (4 mm) in all the drying methods.

The ascorbic acid content was measured on both fresh and dried samples at 4, 6 and 8 mm thicknesses. There was a significant reduction in ascorbic acid content in all the dried samples. But the reduction was significantly lower in vacuum assisted solar dryer than solar cabinet and open sun dried tomato slices. The data confirmed that the ascorbic acid was very sensitive to oxidative heat damages and the higher reduction in ascorbic acid content might be due to the temperature, exposure to direct sun light and the presence of air.

The study concluded that the time required to dry the slices were comparatively lower in solar cabinet dryer when compared to vacuum assisted solar and open sun drying methods. Consequently the moisture diffusivity was also higher in solar cabinet dryer than vacuum assisted solar dryer and open sun drying methods. But the physicochemical parameters such as colour retention, rehydration capacity and ascorbic acid retention were comparatively higher in vacuum assisted solar dryer than in solar cabinet and open sun drying methods. Therefore, the overall study concluded that good quality dehydrated tomato slices could be produced by using vacuum assisted solar dryer compared to solar cabinet and open sun drying methods. The Page model was found to be better in describing the drying kinetics of tomato slices in all the drying methods studied.

Further research in this study can thoroughly explore the retention of antioxidants in tomato slices after vacuum drying. In addition, the vacuum assisted solar dryer has to be tested on large scales and the vacuum pump has to be operated by solar power (photovoltaic panels), so that the entire vacuum assisted solar drying operation will be based on sustainable renewable energy.

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