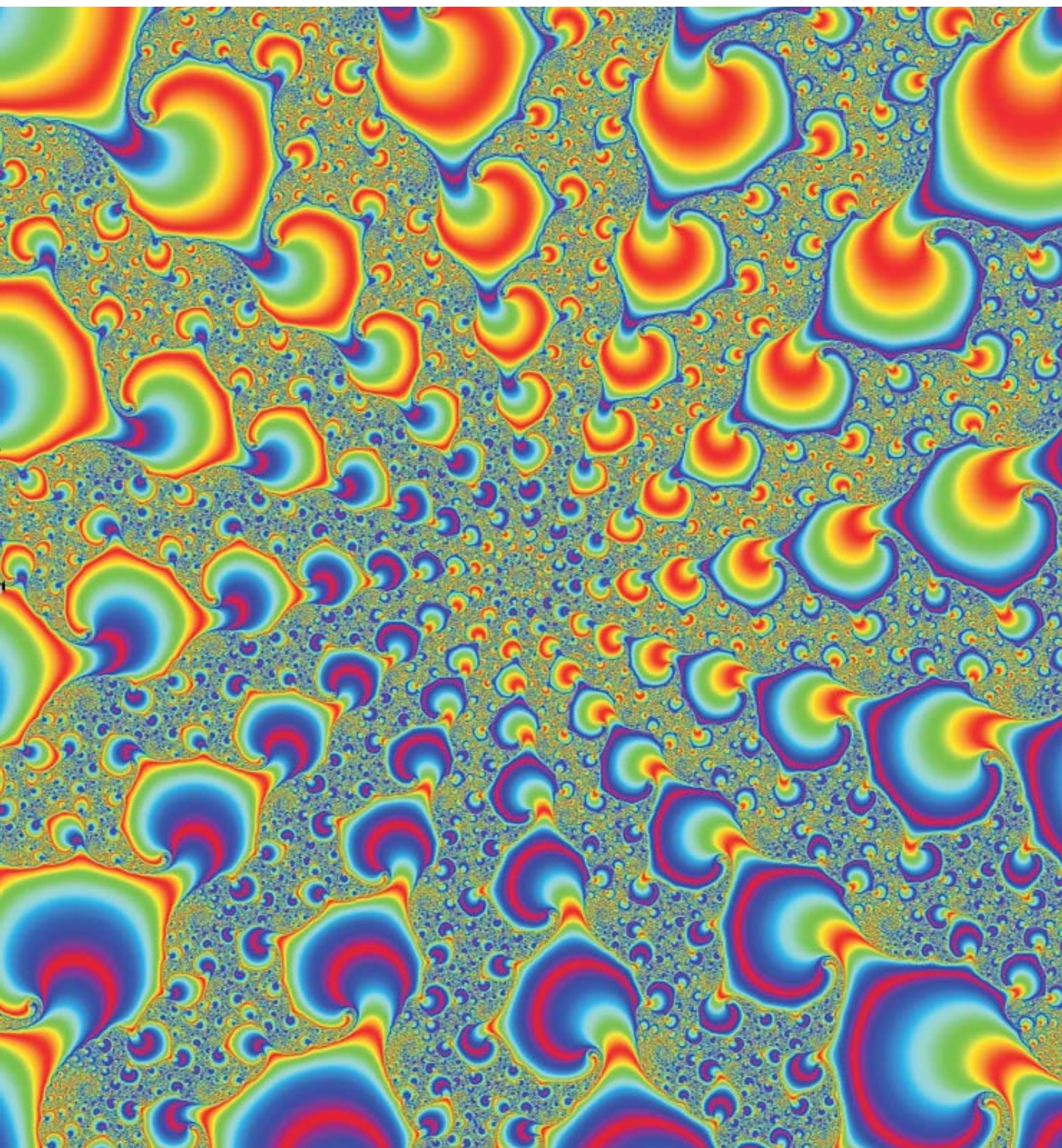


# *Drying of Foods, Vegetables and Fruits*

*Volume 2*



**Editors**  
**Sachin V Jangam, Chung Lim Law, Arun S Mujumdar**





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# Drying of **Foods**, **Vegetables** and **Fruits**

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**Volume 2**



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**Volume 2**

**Editors:** Sachin V. Jangam, Chung Lim Law and  
Arun S. Mujumdar

**2011**

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## PREFACE

Drying is an important unit operation used in numerous industries and well known as a dominant industrial consumer of fossil fuel-derived energy in developed countries. As standard of living rises in the developing world energy usage for drying operations will rise along with the demand for energy-efficient, faster, environmentally friendly (minimal carbon foot print) and cost-effective drying technologies will continue to increase worldwide. Indeed, the growth in energy consumption for drying will increase at a higher pace in the rapidly developing world, in particular the rapidly developing as well as very large economies of China, Brazil and India. As the fuel prices rise, it is necessary to develop sustainable drying technologies using renewable sources using innovative ideas. Drying of food products has been a very important industrial sector for many years. This is also reflected in the continuing success of the International Drying Symposium (IDS) series and numerous sister conferences as well as a premier archival journal devoted exclusively to drying science, technology and engineering. Drying R&D seems to have reached a sustainable level of activity around the globe, still there is tremendous scope to carry out R&D in this complex process.

Although a large volume of highly recognized technical literature is available on drying of foods, it is still a daunting task to access and assimilate the essence of this voluminous literature for researchers in developing and under-developed countries. To alleviate this problem, Professor Arun S. Mujumdar has initiated a series of e-books which can be made available freely or at minimal affordable cost even in the poorer countries with access to the internet. Indeed, the internet has 'flattened' the world in providing access regardless of the state of the economic development. The first e-book of this type is entitled *Mathematical Modeling of Industrial Transport Processes*, which is available for free download at <http://serve.me.nus.edu.sg/arun/>. This e-book is also a part of this activity and provides a simple convenient introduction to the basic principles, terminology, selection and classification of dryers, details on commonly used dryers and new developments in drying of foods, vegetables and fruits. Our main goal is to make useful technical literature available for particularly those who have little access to expensive books and journals. Students and faculty members can use these books for teaching purposes as well as for research and industrial needs. Contributors of this book have tried to put their ideas in simple terms without sacrificing quality. All chapters are reviewed by the editors at the same standards as those used by well known international publishers. Indeed all authors are writing by invitation and have a strong publication record themselves. This is a professional service on their part. We all must be grateful for this thankless service they are providing in the name of humanity and sustainability of global resources.

It is important to note that authors and editors have made special efforts to ensure that this book and its companion books properly credit relevant early work but the chapters do not include any copyrighted material. This e-book is carried out as professional service by members of our international network of researchers and educators in the hope of making the knowledge contained herein available freely without geographical or economic barriers. The internet has made the world "flat"; yet access to knowledge is generally restricted. We hope that this effort will provide rapid and free access to relevant knowledge freely to those who can most benefit from it. We are truly grateful for the outstanding effort of our authors and referees for their truly thankless contribution in the interest of global dissemination of useful information. We believe the e-books we are planning can be used for teaching as well as R&D purposes.

This book is divided in three volumes; the first volume is dedicated to fundamentals of drying FVF, second volume has detailed discussion on drying of various types of food, while the third volume covers special topics of wide interest. The first volume (published in 2010) starts with basic discussion of relevant principles, terminologies and introduction to advances in drying of food products followed by a chapter on hygrothermal data for various FVFs. This is followed by a comprehensive discussion on selection and classification of dryers for food products. This is followed by chapters on osmotic pretreatments, quality and safety in food drying, energy optimization and use of renewable sources of energy for drying of foods. This is the second volume of this book series which covers drying of most of the food variety such as drying of rice, medical plants, roots, marine products, exotic tropical fruits, probiotics and recently popularized functional food and snack food. The third volume will cover special topics such as low temperature drying, spray drying, microwave drying, superheated steam drying, extrusion and drying of food materials, vacuum frying and baking of bread. We are happy to bring out the second volume of this effort, however, the third volumes will be published soon.

We believe this book is suitable for self-study by engineers and scientists trained in any discipline and so as for the readers who have some technical background. It should also be helpful to industrial users of dryers, dryer manufacturers as well as entrepreneurs. The topics chosen are designed to give readers a quick practical overview of the subject without going into deep mathematical or theoretical considerations. It could serve as a text or supplementary text for professional development short courses as well.

We are grateful to a large number of individuals, mainly the contributors of individual chapters which are listed following the preface. We are very grateful for their support in making this e-book available freely. We hope that this book will be useful to researchers working in food dehydration. We hope that the authors of this book have succeeded at least partially in achieving goals behind this e-book. We plan to put up enhanced editions of these books in due time. Response from readers is always welcome along with ideas for new e-books and offers of chapters.

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## **Chapter 1** **Drying of Exotic Fruits**

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## 1.1. INTRODUCTION

Most fruits contain more than 80% water and the water content varies in different types of fruits. Particularly, fruit with such high amount of moisture is highly perishable. Fruits are composed of living and metabolising tissues; therefore, fruits cannot withstand the stresses of time, temperature and physical handling. For instance, it is reported that ciku(sapota) spoils within thirteen days after harvest due to intense metabolic activity ([Mohamed et al. 1996](#)). Substantial portions of fruits are wasted during peak production period due to disease, excess production, inadequate cultivar, improper harvesting and post-harvest practices, improper transportation conditions and poor storage conditions ([Paull, 2001](#)). In addition, this can be also due to some inherent attributes of the fruit itself for instance soft in texture which is vulnerable to mechanical injury. Mechanical injury of fresh fruit can be caused by ([Barkai-Golan, 2001](#); [Atungulu et al., 2004](#)):

- Poor postharvest practices
- Unsuitable field or marketing containers
- Over-packing and careless handling

Splitting of fruits or roots, tubers, internal bruising and scratches occurs during transportation and storage. Damage such as scraping or bruising of the outer skin of fruit provides entry points for moulds and bacteria causing decay, increase of respiration rate and thus heat production, which make the fruit highly perishable.

### 1.1.1. Applications of freezing or chilling technology

Fruit commodities vary considerably in their temperature tolerance. They can be stored at lower temperature to maintain freshness. However, this method is not applicable to exotic tropical and sub-tropical fruits as they are sensitive to freezing or chilling injury ([Malik, 2006](#)). The level of tolerance is dependent on the type of the fruit.

Freezing and chilling may cause injury to fruit. Freezing temperature at 0°C may cause the fruit to have a water-soaked and glassy appearance. This storage temperature is not suitable as the frozen product is highly susceptible to decay except when the fruit is further processed by freeze drying when water removal occurs only by sublimation without going through the liquid phase. Chilling injury is another problem which is related to low temperature storage at certain temperatures, fruit is susceptible to injury at low temperatures but not at the freezing temperature. The approximate lowest safe temperature for various fruits is given in [Table 1.1](#) ([Lutz and Hardenburg, 1966](#)).

**Table 1.1.** The lowest safe temperature for various fruits

Fruit	The lowest safe temperature / °C
Banana	12-14
Grapefruit	10
Lemon	13-15
lime	7-10
Watermelon	5
Okra	7
Orange	7
papaya	7
Pineapple	7-10
pumpkin	10

### 1.1.2. Applications of drying technology

Drying is one of the widely used postharvest technologies which overcome problems related to overproduction/ oversupplied, postharvest handling, fruit fly host and short shelf life. Drying is applied to lower the moisture content of fruit to a level that can prevent the growth of mould and fungi and thus minimize microbial degradation.

Different drying techniques can be applied to reduce water activity and thus achieving the objective of fruit preservation. It can also help in the development of new product variants such as dehydrated fruit, dry fruit powder and etc. Sun drying, hot air drying, spray-drying, microwave drying, osmotic dehydration and freeze drying are widely used for drying of fruit. Various modes of heat input and drying conditions can be used, which are dependent on the target moisture namely surface moisture and internal moisture. Surface moisture can be easily removed by convective drying especially when it is conducted at high temperature and in rapid mode. Internal moisture is normally removed at the later of drying and the removal rate is generally slow. However, if volumetric heating is applied, the internal moisture can be removed at the initial of drying at a faster rate. Volumetric heating can be achieved in microwave drying ([Law et al. 2008](#)).

Cost-effectiveness and dried product quality vary widely amongst the diverse drying techniques. Slower drying techniques operated at lower temperatures often yield better quality dried product but at higher cost due to longer drying times requiring larger equipment. For different consumer products different quality parameters may be applied. Starting from the same fruits (or blended fruits) one can obtain dried product that may be in the form of slices, granules, powders or leathers. In some cases some additives may need to be added to accomplish drying in the desired form. Presence of sugar makes drying more difficult as is well known. The dried product is more hygroscopic at higher sugar levels which make it more readily perishable if not packaged and stored properly.

The reduction of losses and maintenance of quality of harvested products prior to consumption are extremely important. Biochemical properties and physical properties of dehydrated fruit vary with different drying techniques. For instance, microwave-vacuum drying is good in preserving food materials that contain heat- and oxygen-sensitive phenolic components and ascorbic acid ([Wojdyło et al. 2009](#)). This technique can produce dehydrated fruit with improve texture, color and flavor. [Hu et al. \(2006\)](#)

and [Cui et al. \(2008\)](#) also reported that combination of microwave and vacuum drying can improve the product quality of dehydrated fruit such as color if compared to conventional drying techniques. If pressure superheated steam dehydrated product was used as benchmark, definitely this drying technique can produce dehydrated product with better color and rehydration capacity than microwave vacuum drying ([Devahastin et al. 2004](#)). Other than this, modified atmospheric heat pump dehydrated guava and papaya were found to be one of the techniques that can produce samples with less browning appearance and retain higher amount of vitamin C compared to conventional heat pump drying ([Hawlder et al. 2006](#)).

## 1.2. Exotic fruits

Fleshy fruits can be classified into four categories based on their physical characteristics viz., stone, pome, tender and berry. **Table 1.2** shows the classification scheme for fruits. Stone fruit has hard inner layer (endocarp) surrounding the seed; pome fruit has fleshy receptacle tissue with core surrounded by edible flesh; tender fruit has a leathery rind and parchment-like partitions between sections while the berry fruit has fleshy pericarp with one or many seeds and the skin is often tough. Obviously, different processing and drying techniques are needed to handle different fruit types. The commercial value of dehydrated fruit also affects the choice of dryer as some dryers are feasible for high-margin products.

**Table 1.2.** Classifications of fruit

Fruit	Characteristics
Stone	Fruit with hard inner layer surrounding the seed
Pome	Fruit with fleshy receptacle tissue surrounding a central core of seeds
Tender	Fruit with leathery rind and parchment-like partitions
Berry	Fruit with fleshy pericarp with seeds

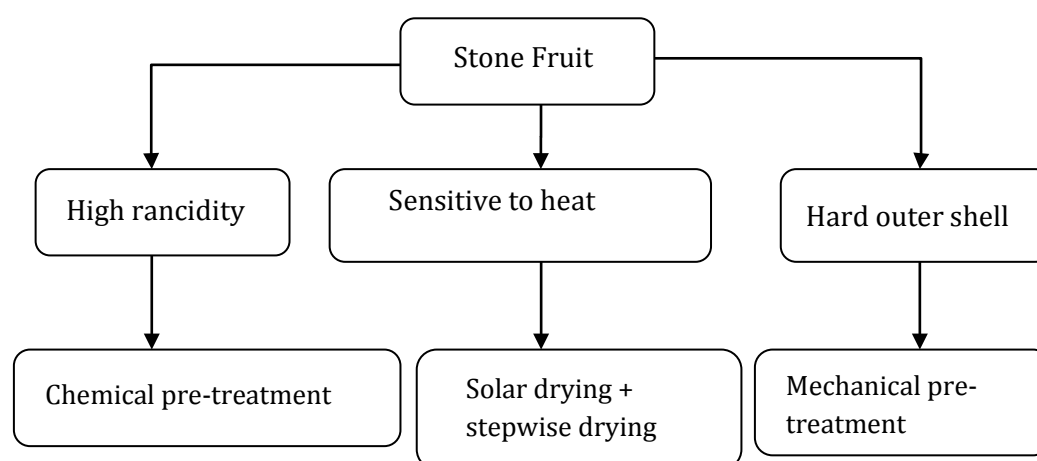
### 1.2.1. Drying of stone fruits

Stone fruit has a seed in the centre of fruit pulp. Stone fruits with different characteristics have been identified and it is further classified into three different categories namely stone that has high rancidity, stone fruit that is sensitive to heat, stone fruit that has hard outer shell (**Figure 1.1**).

For stone fruit that has high rancidity, it has been reported that applying chemical pre-treatment can minimize the rancidity of the fruit. Different types of pre-treatment can be applied prior to stone fruits drying. For instance, avocado (a type of stone fruit) develops rancidity throughout the maturity stages. It has been reported that TBHQ (tertiary butylated hydroxyquinone) cum citric acid mixture can be used as an emulsified paste for spray drying of avocado to reduce the rancidity of fruit ([Grajales-Lagunes et al. 2009](#)). Osmotic dehydration is widely used as a pre-treatment method as well to improve product quality and modify the functional properties of dried fruit ([Nanjundaswamy and Madhkrishniak, 1989](#)). This method is applicable to stone fruit but it should be noted that this process significantly decreases the vitamin C content of the fruit product due to leaching process ([Azoubel and Murr, 2003](#)). Leaching also affects the mineral content, color, flavor as well as the taste of the final product.

For stone fruit that is sensitive to heat, it recommended to consider to apply low temperature or mild drying condition for the drying of stone fruit. [Boubekri et al. \(2009\)](#) reported solar drying with the application of step-wise changing temperature can produce dehydrated date palm fruit with better quality in terms of texture and color ([Boubekri et al. 2009](#)). However, other low temperature drying method has not been reported on the drying of stone fruit such as date palm. Stone fruits contain high nutritional value and flavor compounds. To reduce to decomposition of these valuable compounds, drying at low temperature and pulsed vacuum osmotic dehydration have been recommended.

Most stone fruits have a relatively hard shell, which may lead to a longer drying duration as it acts as an impediment to water removal as well as heat transfer. Removing shell is one of the mechanical treatment methods that can be used to overcome this problem ([Attabhanyo et al., 1998](#)).



**Figure 1.1.** Classification of stone according to its characteristics

The following subtopics discuss the characteristics of some exotic stone fruits and the research findings that have been reported in the literature. In addition, some suitable drying methods which the author thinks could be applied albeit not reported in the literature are also recommended.

#### **1.2.1.1. Avocado (*Persea americana* Mill.)**

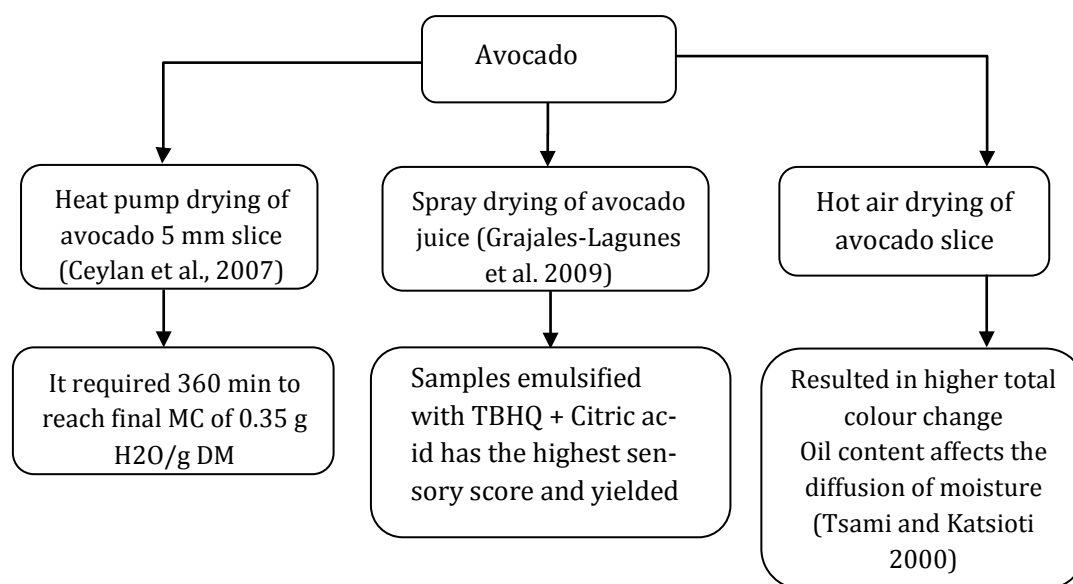
Avocado is native to Mexico, Central and South America and also known as palta, aguacate, abacate, butter pear or alligator pear. This fruit belongs to the family of Lauraceae. It is high in fiber and rich in vitamins A, B, E, as well as in potassium ([Dowling and Morton, 1987](#); [Human, 1987](#)). In addition, chlorogenic and p-coumarylquinic acid isomers, catechins, leucoanthocyanidins, isoflavone and caffeic and p-coumaric acids were the major polyphenol compounds of avocado ([Ramírez-Martínez and Luh, 1973](#)). After harvesting, this fruit becomes highly perishable due to the enzyme-mediated oxidation process and lipid auto oxidation ([Wong, 1989](#)).

Oil content in avocado complicates the drying kinetics of avocado. It is the major factor that affects the drying kinetics ([Alzamora and Chirife, 1980](#)). It has been reported that the effective diffusivity is inversely correlated with oil content of the avocado pulp ([Tsami and Katsioti 2000](#)). Pre-treatment processes like blanching and freezing only



showed relatively little influence on the drying rate ([Alzamora and Chirife, 1980](#)). To control the oxidation activity of fresh avocado, drying techniques including hot air drying, heat pump-assisted drying and spray drying have been tested and reported in the literature. **Figure 1.2** summarizes the finding of avocado dehydrated using these drying techniques.

[Ceylan et al. \(2007\)](#) reported the drying kinetics of avocado subjected to heat pump assisted drying with thickness of 5 mm, that 360 min was required to dehydrated avocado slice to a moisture content of 0.35 g H<sub>2</sub>O/ g DM. Hot air drying of avocado resulted in significant color change in the dehydrated product ([Tsami and Katsioti 2000](#)). [Grajales-Lagunes et al. \(2009\)](#) reported findings on spray drying of avocado juice with the inlet temperature and outlet temperatures of 190°C and 80°C, respectively, with air velocity of 27 m/s. In this study, a mixture that contained TBHQ (Tertiary butylated hydroxyquinone) and citric acid were added to feedstock at flow rate of 0.642 l/min and it was found that lipid in the paste emulsified using TBHQ + Citric acid (0.05 +0.1%) can produce samples with highest acceptance score. In addition, the mixture that contained TBHQ and citric acid yield the lowest rancidity development ([Grajales-Lagunes et al. 2009](#)).



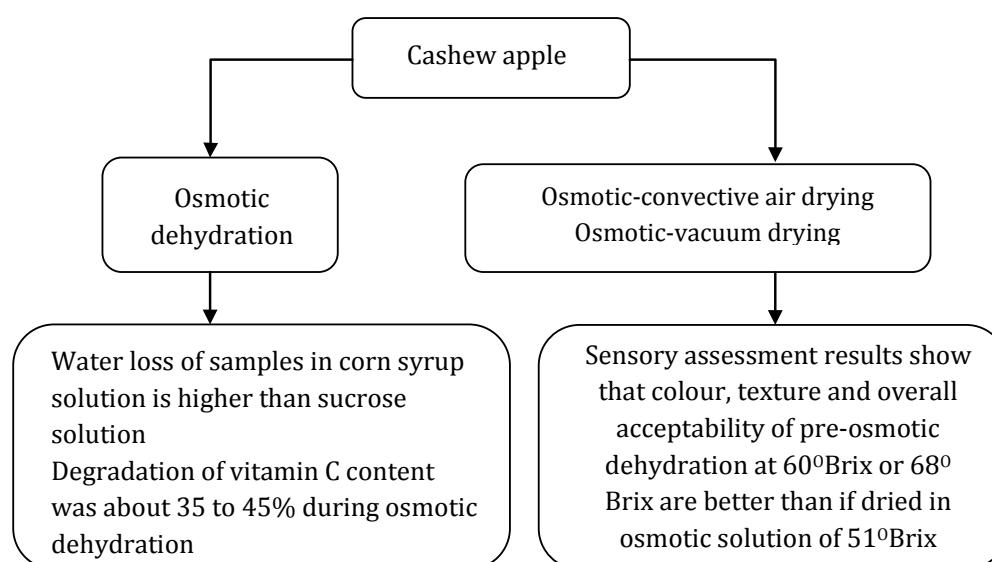
**Figure 1.2.** Drying kinetics and product quality of avocado

Avocado is a fruit that is rich in vitamins and polyphenols. Research on product quality such as texture, color, rheological properties, antioxidant and polyphenol contents as well as sensory assessment flavor and taste of avocado dehydrated are rather scarce. New drying techniques including hybrid heat pump vacuum-microwave drying, hybrid hot air-cold air drying, cyclic temperature drying and combined microwave-vacuum drying techniques have been tested on the drying of avocado. However, the knowledge on the effect of oil content and drying kinetics is rather limited. It has been reported that in order to reduce the rancidity of avocado, it can be pre-treated by dipping the fruit into TBHQ (Tertiary butylated hydroxyquinone) and citric acid mixture before subject to drying. However, the effect of dipping the fruit into the pretreatment mixture on the product quality is unknown this calls future research.

### 2.2.1.2. Cashew apple (*Anacardium occidentale*)

Cashew apple is a high nutritional value fruit which contains high level of ascorbic acid and carotenoid. The reported values are 13.7 to 121.7 mg/ 100 g and 8.2 to 197.8µg/ 100g, respectively ([Assunção and Mercadante, 2003](#)). Tanins like (-)-epigallocatechin and (-)-epigallocatechin-O-gallate are major phenolics of cashew apple followed by minor quantities of (-)-epicatechin and (-)-epicatechin-3-O-gallate (Michod-jehoun-Mestres et al., (2009). This fruit is very astringent, therefore treatments such as steaming ([Akinwale and Aladesuam 1999](#)) and gelatine ([Agustin, 1982](#)) are applied to remove its astringency.

**Figure 1.3** shows the drying techniques that have been tested on the drying of cashew apple as well as the findings reported by researchers. [Azoubel and Murr, \(2003\)](#) found that water losses of cashew apple dried using osmotic solution with concentration of 50% is higher than osmotic solution with concentration of 40% at temperature of 40°C. Under ambient temperature cashew apples may lose up to 35% of its initial water. In addition, the change of medium of solution also significantly affects the water losses. It was reported that the use of corn syrup instead of sucrose reduced the water loss, especially at higher solution concentrations. The sugar gain was about 66% ([Azoubel and Murr, 2003](#)).



**Figure 1.3.** Research findings on the drying kinetics and product quality of cashew apple reported in the literature

Good retention of vitamin C after osmotic dehydration has been reported. The degradation of vitamin C after subjecting to osmotic dehydration was about 35 to 45% depending on the condition applied. Optimization research done by [Martins et al. \(2008\)](#) using response surface methodology showed that osmotic drying of cashew apple for four hours in sucrose concentration of 40°Brix at 50°C can retain highest amount of vitamin C. Further to this, sensory attributes of the pre-osmo in solution with different concentration, osmotic-convective air and osmotic -vacuum dehydrated cashew apple were reported. According to [Falade et al. \(2003\)](#) the color, texture and overall accepta-

bility of cashew apple dried using pre-osmosed in solution with 60°Brix and 68°Brix were better than pre-osmosed solution with 51°Brix.

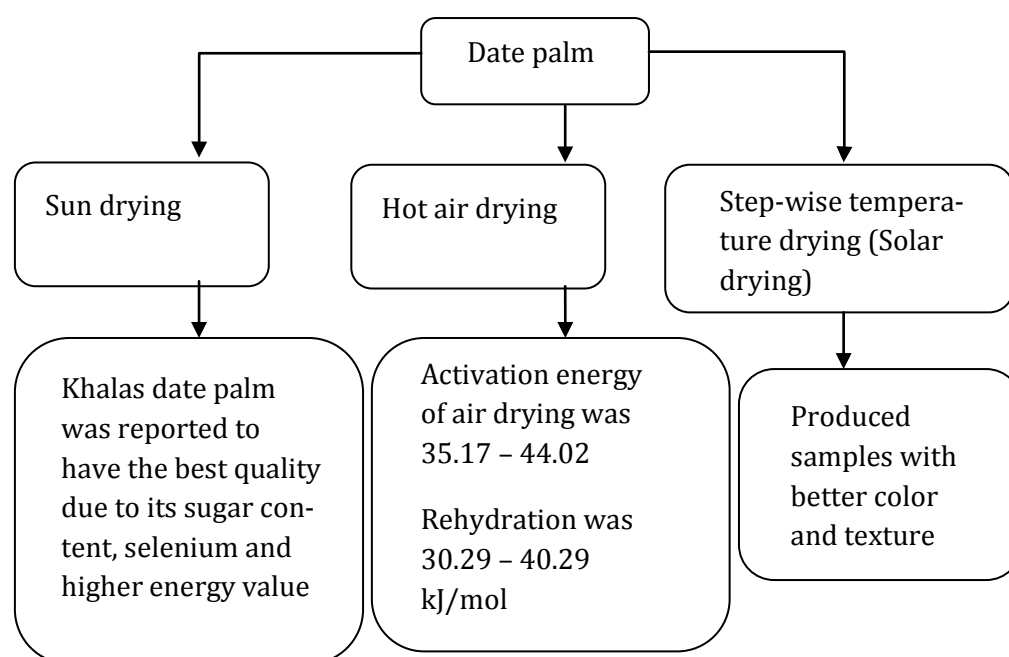
Due to the inherent characteristics of cashew apple, direct drying techniques such as hot air drying, sun drying, heat pump drying and microwave drying are not suitable. Pre-treatment is required for this type of stone fruit, which is astringent. Astringent fruits contain tannins, anthocyanins and flavonoids compounds which have been reported to have antitumor effect ([Kozubek et al., 2001](#)). However, report on the retention of these compounds in dehydrated astringent is rather scarce. Apart from the drying techniques given in Fig 1.3, osmo-microwave vacuum and osmo-hybrid heat pump vacuum-microwave are possible drying technique that one might look into for future research work as these drying techniques can retain valuable phenolic compounds.

### **2.2.1.3. Date palm fruit (*Phoenix dactylifera L.*)**

Date palm belongs to the family of Palmae and is grown extensively in the region of Northern Nigeria. This fruit has a single seed surrounded by a fibrous parchment and is well known in this region due to its marketing and nutritional value. Date palm can be used in the production of cookies, cakes, candy bars, ice cream, alcoholic beverages, sugar (date sugar) and syrup. It is also used as one of the ingredients in adulterate coffees. According to [Vayalil \(2001\)](#), date palm fruit contains antioxidant and antimutagen properties in vitro. The major phenolic compounds of the date fruit are cinnamic acids, ferulic, sinapic and coumaric acids ([Mansouri et al. 2005](#)). The flesh of date contains 0.2-0.5% of oil, 0.9% of potassium, 23 types of amino acids and small amount of vitamins ([Al-shahib and Marshall, 2003](#)).

The moisture content of fresh date palm fruit is about 60% (wet basis). Generally, the safe moisture content for storage of dates is between 24 to 25%. To reduce the moisture content to a safety storage level, drying is commonly used. **Figure 1.4** shows the findings on drying kinetics and product quality of drying of date palm fruit. [Falade and Abbo, \(2007\)](#) reported the effect of hot air drying on the kinetics, heat transfer and rehydration. [Boubekri et al., \(2009\)](#) found that solar drying with the application of step-wise temperature drying can minimize the degradation of date palm fruit in terms of color and texture. On the other hand, [Al-Farsi et al., \(2005\)](#) did a comparison study on the compositional and sensory characteristics of three native sun-dried date palm fruit grown in Oman, viz. Fard, Khasab and Khalas. It was found that Khalas date palm fruit gave better quality attribute due to its sugar content, selenium and high energy value compared to other varieties.

Date palm fruit is a nutritional fruit with high amount of polyphenol compounds and amino acids. Therefore, low temperature drying such as heat pump drying or hybrid drying that employ drying medium at low temperature can be considered as these technique can prevent Maillard reactions that are responsible for the degradation of polyphenol compounds. By applying mild drying temperature, enzymatic activity can be minimized as well.



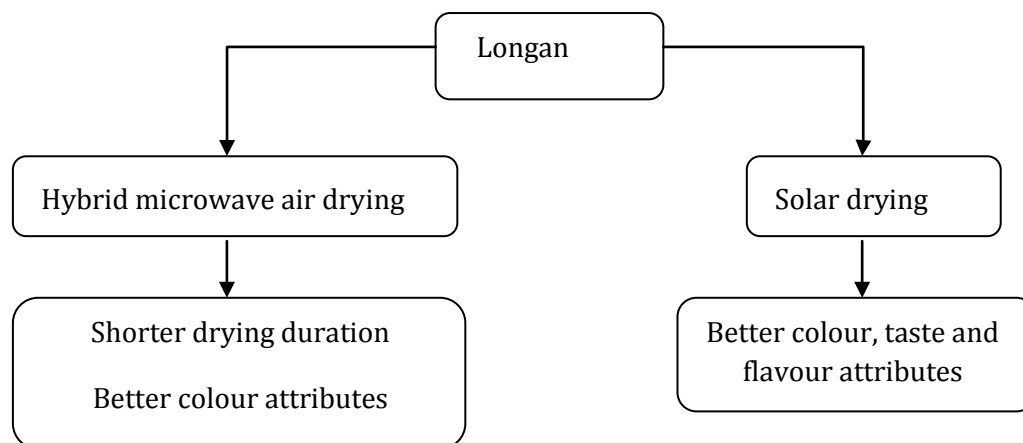
**Figure 1.4.** Drying kinetics and product quality of dehydrated date palm fruit reported in the literature

#### 1.2.1.4. Longan (*Dimocarpus longan*)

Longan is a subtropical fruit which belongs to the family of Sapindaceae. A ripe longan has a spherical shape covered by a thin layer of yellow brown shell. The flesh of longan fruit is translucent and sweet. Longan contains 60.1 mg/ 100g of vitamin C, 324.9 mg/ 100g of K and 0.26 mg/ 100g of Cu (Wall, 2006). The major polyphenol compounds that have been identified in Longan are gallic acid, corilagin (an ellagitannin) and ellagic acid (Rangkadilok et al. 2005). In addition, aldehyde, acid, ester and alcohol are the main volatile compounds in longan (Lapsongphol et al. 2007).

Various drying technologies have applied to dry longan. It was reported that the volatile compound of longan is the highest in longan flesh dried at 70°C for samples dehydrated from temperature of 60 to 90°C at 10°C interval (Lapsongphol et al., 2007). The effects of different drying techniques on drying kinetics and product quality of longan are shown in Figure 1.5. Attabhanyo et al. (1998) reported that unpeeled longan fruit requires longer drying time than peeled longan fruit. To further reduce the drying duration, Varith et al. (2007) found that the drying duration of peeled longan using hybrid microwave-hot air is shorter compared to conventional hot air drying. In addition, combined microwave hot air drying could produce dried longan with better color compared to hot air dried longan at temperature of 65°C (Varith et al. 2007).

On the other hand, Janjai et al. (2009) design a solar drying technique to reduce the drying duration of longan as compared to sun drying. Within the duration of 16 hr, the solar dryer could reduce the moisture content from 84% (wet basis) 12% as compared to sun drying which is 40%. In addition, Janjai et al. (2009) found that solar tunnel dried longan has better color, taste and flavor compared to natural sun dried longan.



**Figure 1.5.** Drying kinetics and product quality of longan

Longan is a highly heat sensitive fruit. Major polyphenol compounds found in longan (mentioned earlier) are polyphenol oxidase (PPO) substrates and thus they are susceptible to enzymatic reactions. In addition, it contains high amount of vitamin C and volatile compounds that are sensitive to heat. Enzymatic reaction and Maillard reaction occurred during drying process are the major concerns. To dry longan, mild temperature drying and hybrid drying techniques can be considered. They can reduce the degradation of volatile flavor compounds, polyphenol compounds and vitamins.

#### **1.2.1.5. Lychee (*Litchi chinensis*)**

Lychee is native to southern China. The lychee or litchi fruit is small with white flesh, which is covered by a thin leathery red rind. It contains nutrients such as 0.0276 g/(100 g of fresh weight) of ascorbic acids, 0.1561 g/(100 g of fresh weight) potassium and 0.195 mg/(100 g of fresh weight) of copper (Wall, 2006). In addition, this fruit contains polyphenol compounds such as gallic acid, galocatechin, procyanidin B2, epicatechin and epicatechin-3-gallate (Prasad et al., 2008). Lychee has a special flavor and excellent texture with red color fruit skin but browning of the skin occurred in a short period of time after harvesting. This results in great commercial losses to the fruit handler. Drying is one of the postharvest processes that is commonly used to overcome preserve the fruit.

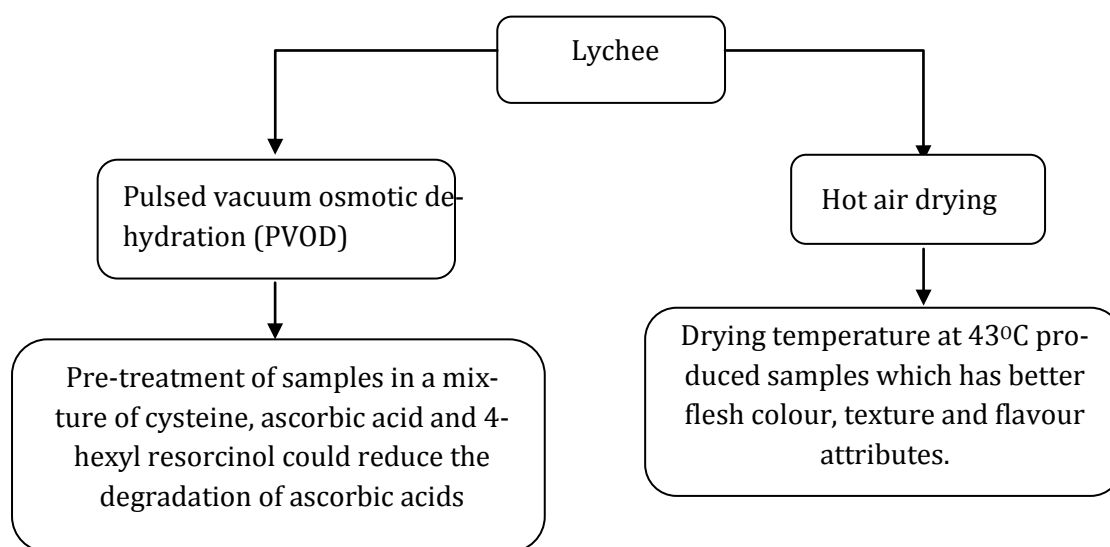
Kuhn (1961) studied the drying kinetics and product quality of hot air drying of lychee. It was reported that lychee fruits dried at 70°C were extremely bitter. This could be because of lychee contains high amount of reducing sugars. According to Higgins (1917), total sugar content of lychee is 15.3% and the reducing sugar to sucrose ratio is 4.5:1. Hui et al. (2006) claimed that more 70% of sugars are reducing sugars. According to Chong (2010), fruit with high amount of reducing sugars and polyphenol oxidase (PPO) substrates should apply low temperature drying technique. In order to retain the polyphenol compounds, it is recommended to apply two-stage drying where the first stage is conducted at low temperature followed by second stage drying that promotes rapid dehydration such as vacuum-microwave drying.

Acharyaviriya and Puttakam (2003) reported that total color change of lychee increased with elevated temperature; therefore, lychee dried at 43°C have better quality in terms of flesh color, texture and flavor compared to those dried at 61.5°C (Kuhn, 1961). On the other hand, Shah and Nath, (2008) found that by using a mixture of cysteine



(0.49% wt/wt), ascorbic acid (0.2% wt/wt) and 4-hexyl resorcinol (0.013% wt/wt) as osmotic agent in pulsed vacuum osmotic dehydration (PVOD), the technique could reduce the degradation of ascorbic acids content significantly. Figure 1.6 summarizes the findings stated above.

Drying kinetics of lychee in form of peel, flesh and seed have been reported by [Kuhn \(1961\)](#). It was found that the moisture level of the peel reduced rapidly, followed by a typical falling-rate ([Kuhn, 1961](#)). As for flesh, the moisture reduction began after 2 hours of drying and the rate was rapid and became constant thereafter. Water loss from seed did not occur until after 8 hours of drying, whereupon it was slow and constant. **Figure 1.6** summarizes the research findings of drying of lychee.



**Figure 1.6.** Drying kinetics and product quality of Lychee

Lychee is similar to longan, which has a soft texture and is very sensitive to heat. Likewise, it is recommended to use mild temperature drying and hybrid drying techniques in drying of lychee.

#### 1.2.1.6. Some remarks on the drying of exotic stone fruits

Exotic stone fruits generally have the following characteristics:

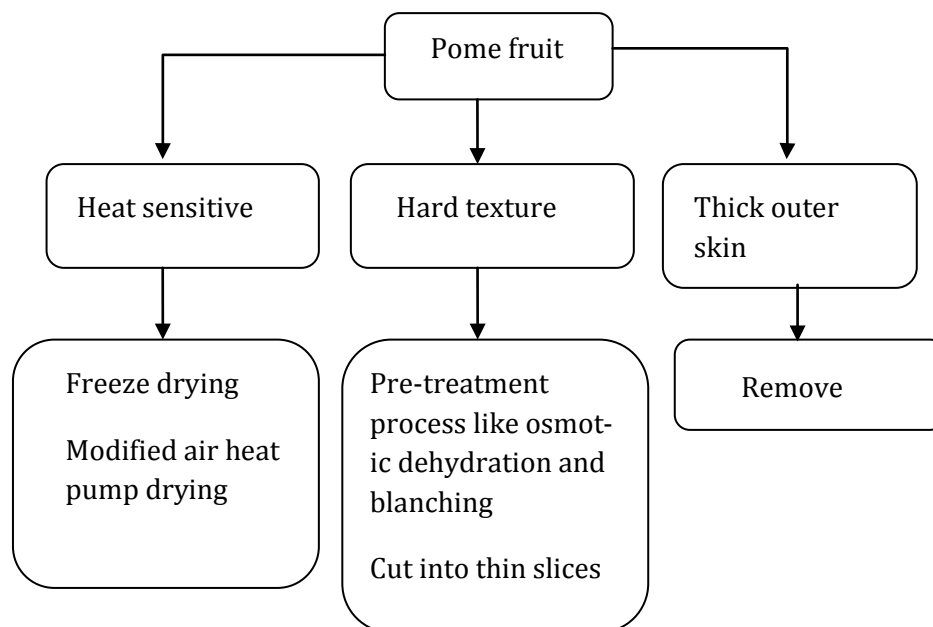
- High astringency
- Rancidity
- Hard outer shell
- High in Vitamin C
- Major polyphenol compounds are PPO substrates

Drying techniques that have been reported in the literature that produced better quality or gave better kinetics pulsed vacuum osmotic dehydration, hot air drying, solar drying, natural sun drying, spray drying, heat pump drying, osmotic dehydration, osmotic convective air drying, osmotic vacuum drying, hybrid microwave air drying and solar stepwise temperature drying. It varies among reports and dependant on the types of fruits as well as the operating conditions. It has been reported that pre-treatment by dipping samples in osmotic solution or pre-dried using osmotic dehydration can minim-

ize the losses of vitamin. Amongst the drying techniques reported in the literature, hybrid microwave vacuum drying and solar drying with stepwise temperature seem promising in producing dried exotic stone fruit with better texture and flesh color.

### 1.2.2. Drying of pome fruit

Pome fruits are fleshy fruits surrounding a central core seed or with lots of seeds such as acerola, ber, guava and snake fruit. Its flesh has a hard texture. **Figure 1.7** shows the classification of pome fruit based on its characteristics and the recommendation on the drying technique or treatment for the drying of pome fruit.



**Figure 1.7.** Classification of pome fruit according to its characteristics and pre-treatment/drying technique recommended for the respective class of pome fruit

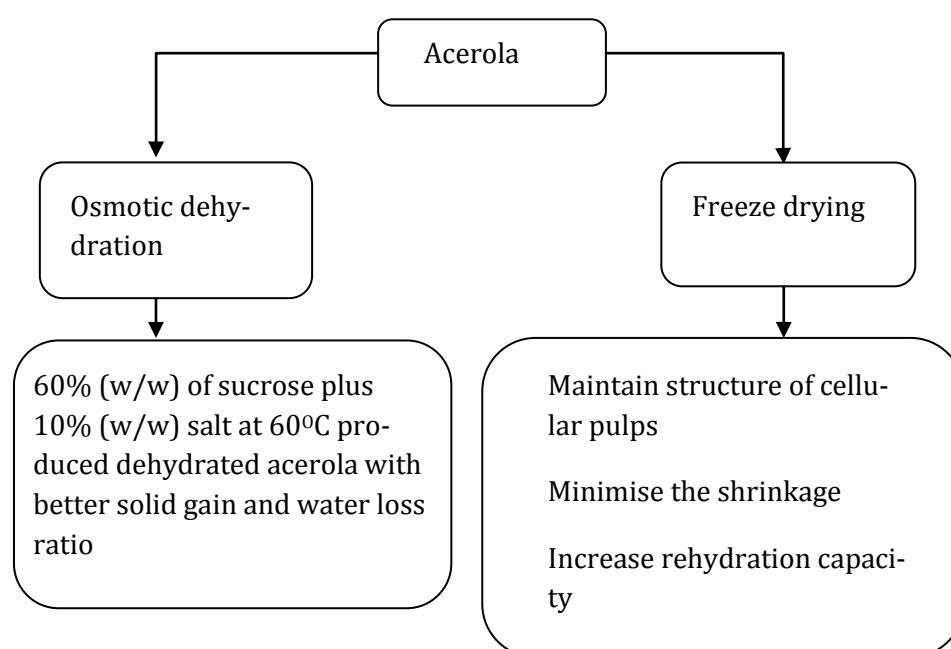
#### 1.2.2.1. Acerola (*Malpighia punicifolia* L.)

Acerola or West Indian cherry is native to Caribbean and Central America. It is round in shape with its diameter ranging from 3 to 6 cm. In the initial stage of ripening, the fruit is in full green color, it changes to yellow-reddish during the ripening process and finally to red or purple when it is completely ripened. It contains nutrients such as carotenes, thiamin, riboflavin, niacin, proteins, and mineral salts, mainly iron, calcium and phosphorus ([Assis et al., 2001](#)). The main polyphenol compounds of acerola are pelargonidin, malvidin, 3-5-diglycoside and cyaniding 3-glycoside ([Vendramini and Trugo, 2004](#)). Quercetin, kaempferol, p-coumaric acid, ferulic, caffeic and chlorogenic acid are also found in acerola fruit ([Vendramini and Trugo, 2004](#)). Its main appealing feature is its high Vitamin C content, which is ranging from 1247.10 to 1845.79 mg/100 g DM ([Lima, 2005](#)). However, these nutrient contents especially vitamin C may degrade after cropping due to rapid deterioration. This fruit is highly perishable because of its initial high moisture content, which is 91% in wet basis. To overcome the problems, drying is applied to extend the shelf life and to retain the nutritional content of acerola. Thus far, only two drying methods have been tested on the drying of acerola, which is osmotic dehydration and freeze drying and the findings are summarized in **Figure 1.8**. Of course

it is in principle possible to use a number of different drying techniques although they have not been reported in the literature.

[Alves et al. \(2005\)](#) found that for osmotic dehydration of acerola, binary solution of 60% (w/w) of sucrose or ternary solution of 50% (w/w) of sucrose plus 10% (w/w) salt, carried out at temperature of 60°C could give good product quality in terms of solid gain and water loss ratio.

Freeze drying of acerola was carried out by [Marques et al. \(2007\)](#) and it was recommended that the crushed pulps and sliced samples are to be pre-frozen using liquid nitrogen. Liquid nitrogen is better than vapor nitrogen as it can maintain the cellular structure of the frozen pulps (formation of small size ice crystals). The author also found that this drying technique can minimize the shrinkage rate and increase the rehydration capacity of acerola. In addition, the retained vitamin C was found to be as high as 153.4 mg/g DM.



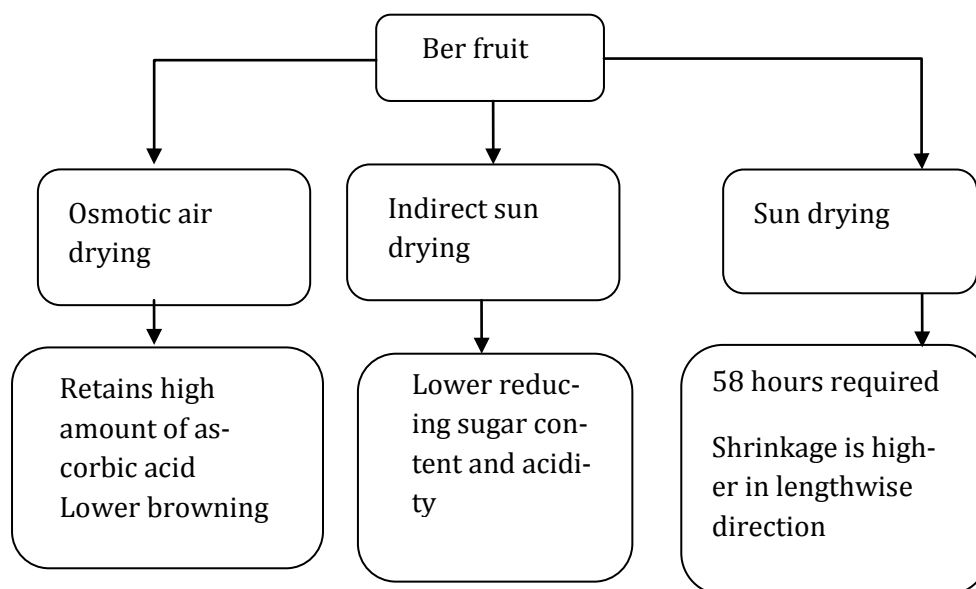
**Figure 1.8.** Drying kinetics and product quality of acerola

Other drying techniques such as heat pump drying, microwave drying, microwave vacuum drying, modified air heat pump drying, hybrid drying and etc can also be applied to the drying of acerola. Apart from this, acerola dry powder can also be produced from spray drying. The research on the drying of acerola is limited and the knowledge on the product quality of acerola including flesh color, flavor, taste, rheological properties, retention of polyphenol compounds, etc. are yet to be investigated.

#### 1.2.2.2. *Ber (Zizyphus mauritian L.)*

Ber is cultivated in India, Pakistan, Bangladesh, Sri Lanka, Central to Southern Africa and Northern Australia. According to [Bakshi and Singh \(1974\)](#), ber fruit has high amount of protein, phosphorous, calcium, carotene and vitamin C. **Figure 1.9** summarizes the research findings of drying of ber fruit reported in the literature. [Kingsly et al. \(2007\)](#) studied the shrinkage of ber fruits subjected to sun drying. The overall drying time required to reduce the initial moisture content of 470.13% to the final moisture content of

38% (dry basis) was 58 hour. The drying duration is relatively long is because due to the fact that it has thicker outer skin compared to other fruit which has thinner skin. According to [Yong et al., \(2006\)](#), mechanical pre-treatments such as drill holes or pin holes can overcome this problem. In terms of shrinkage, the percentage of shrinkage was higher in lengthwise direction. The shrinkage of ber fruits was not significantly different after the moisture content reached 47% (dry basis). This could be because at this moisture content the turgor cell of fruit can withstand the pressure exerting from the surrounding. In terms of product quality, [Singh \(1992\)](#) found that the ascorbic acids of ber fruit dried using osmo-air drying are higher than oven or sun-dried ber fruit. In addition, osmotic dehydrated ber gave less browning. Further, [Khurdiya and Roy \(1986\)](#) found that direct solar dried ber has higher reducing sugar content and acidity as compared to indirect solar dried ber.



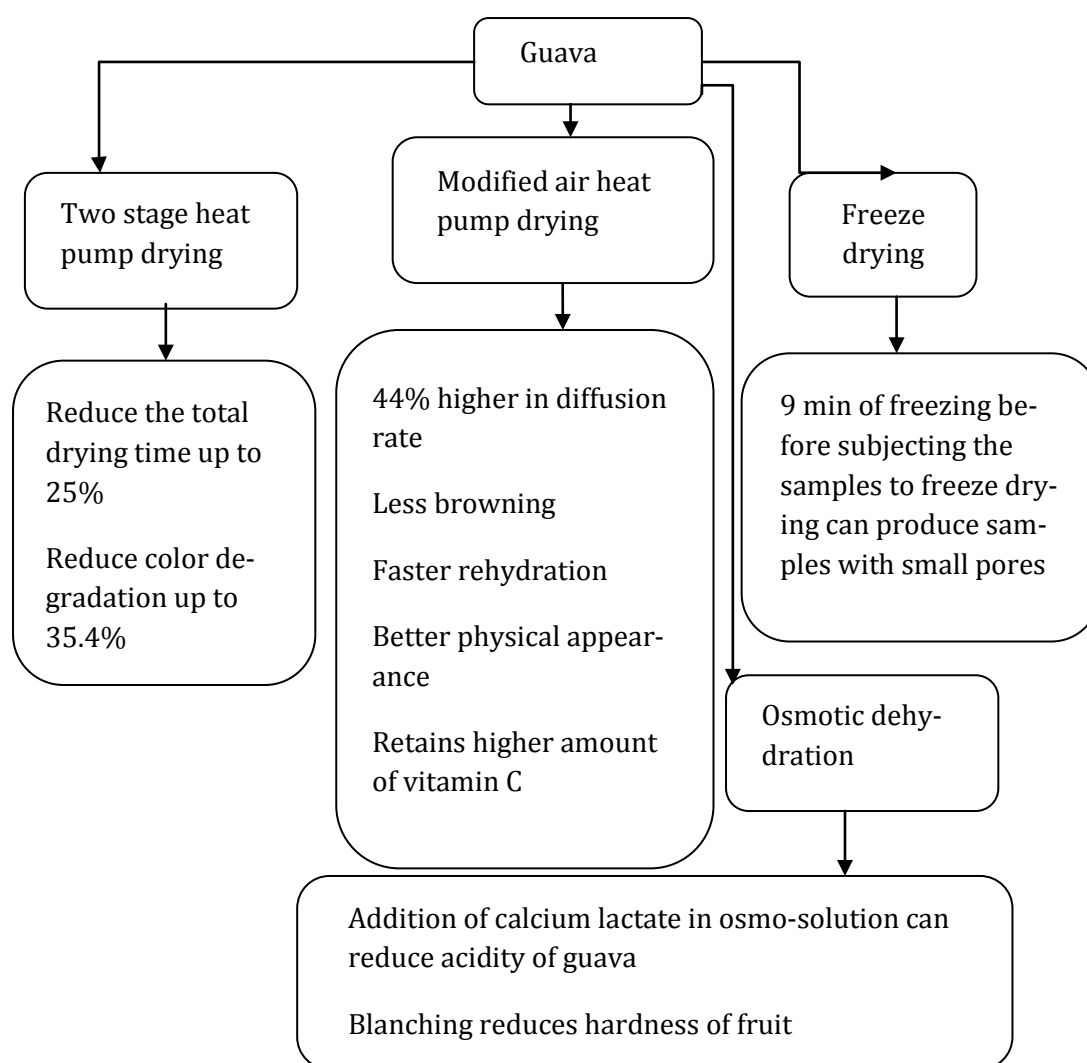
**Figure 1.9.** Summary of research findings on drying of ber fruit

### 1.2.2.3. Guava (*Psidium guajava L.*, *Psidium littorale*, *Psidium cattleianum*)

Guava is native to Central America, Northern South America and parts of the Caribbean. This fruit contains 48.55 to 49.42% of dietary fiber and 2.62 to 7.79% of extractable polyphenols (Jiménez-Escrig et al. 2001). In addition, it contains 40.1 mg/100 g to 180.5 mg/100g of vitamin C ([Yusof, 1990](#)). **Figure 1.10** shows the findings on the effects of different drying techniques on drying kinetics and product quality of guava.

[Chua et al. \(2002\)](#) studied the effects of cyclic temperature profile drying of guava using two-stage heat pump dryer. It was found that step change in drying air temperature with the appropriate starting temperature and cycle time can reduce the total drying duration and improve product color. The drying duration was reduced up to 25%. In terms of product quality, it was reported that the total color change was reduced by 35.4%.

[Marques and Freira \(2005\)](#) analyzed the effects of freeze drying of guava and found that 9.0 min of freezing is require prior to 19 hr freeze drying in order to ensure the formation of small-size ice crystals which can keep the integrity of isodiametric cells of parenchymatous tissue and to keep the membranes intact.



**Figure 1.10.** Findings on the effect of various drying methods on the drying kinetics and product quality of dried guava

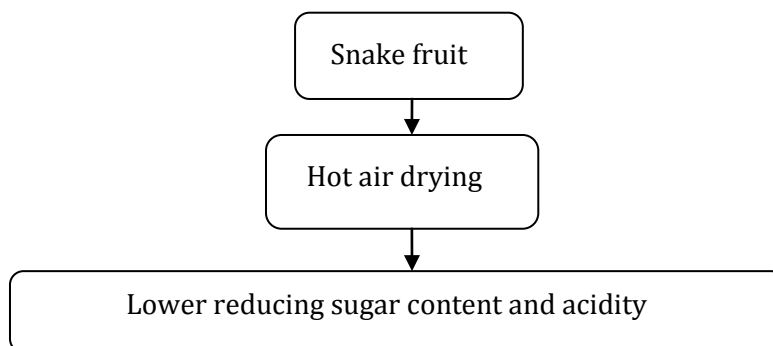
Product qualities such as physical appearance, browning, rehydration rate and retention of nutrient of guava dried using modified air heat pump ( $N_2$  and  $CO_2$ ) drying method were reported by [Hawlder et al. \(2006\)](#). It was found that the effective diffusivity was 44% higher when  $CO_2$  was used to replace atmospheric air as the drying medium. In addition, the technique produced dehydrated product with less browning, better rehydration property, better physical appearance and more vitamin C retention if compared to those obtained from heat pump drying, freeze drying and vacuum drying. This is because of inert gas could reduce oxidation which is unavoidable when the atmosphere of drying chamber contains oxygen.

[Reis et al. \(2007\)](#) reported that blanching and addition of calcium lactate or ascorbic acid did not influence the uptake of sucrose by guavas subjected to an osmotic solution at 65°Brix. In terms of texture, the authors found that blanching process can decrease the osmotic dehydrated samples penetration force by 15%, while the addition of ascorbic acid and calcium lactate in the osmotic solution increased the penetration force by 14.6 and 87.9%, respectively. Sensory assessment showed that the guava pre-treated with osmotic dehydration was preferred ([Queiroz et al. 2007](#)).

#### 1.2.2.4. Snake fruit (*Salacca edulis*)

Snake fruit is native to Indonesia and Malaysia. It belongs to the family of Arecaceae. This fruits named snake fruit because of its brown and scaly skin resembling that of a serpent. It grows in clusters at the bottom of a palm tree and it has the size and appearance of a fig. The skin can be peeled after pinching the tip of the fruit. This fruit have three garlic-looking lobes and each contained a large seed. Salak tastes sweet and acidic at the same time and its consistency can be varied from dry and crumbly to moist and crunchy. It has a good source of fibers and carbohydrate (Lestari et al. 2003). According to Setiawan et al. (2001), [Leong & Shui, \(2002\)](#), [Shui & Leong, \(2005\)](#) and Leontowiez et al. (2007), this fruit contain valuable polyphenol compounds and vitamins, which are good for health.

**Figure 1.11** shows the research finding on the drying of salak. To date, the research on salak drying is rather limited. [Ong and Law, \(2009\)](#) studied the effect of hot air drying on the kinetics of salak fruit with and without a membrane layer covering the flesh. It was reported that the effective diffusivity obtained was in the range of  $4.19 \times 10^{-11}$  to  $2.58 \times 10^{-10}$  m<sup>2</sup>/ s and activation energy 45.27 to 39.78 kJ/ mol. The samples with membrane layer have higher activation energy because membrane layer is a barrier to moisture movement.



**Figure 1.11.** Drying of snake fruit

Salak is an astringent fruit with high content of phenolic compounds and nutritional values. To preserve this type of pome fruit, low temperature drying follow by microwave vacuum drying can be considered for instance hybrid heat pump vacuum-microwave drying. Salak fruit has a special taste which may not be acceptable to everyone; therefore, sensory assessment of flavor and taste has to be carried out.

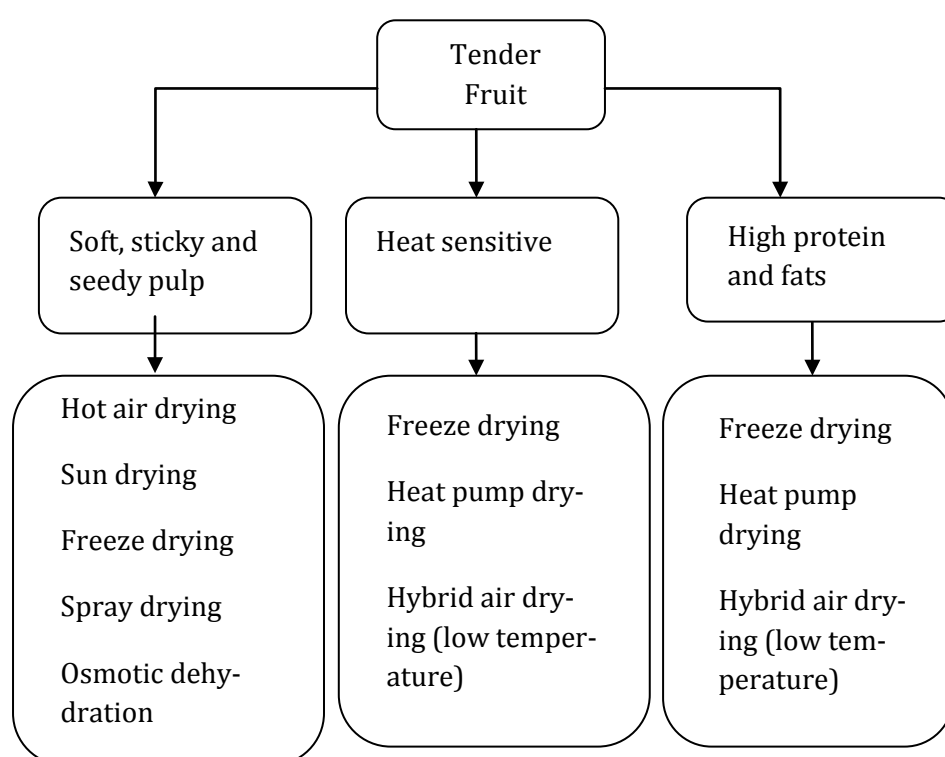
#### 1.2.2.5. Some remarks on the drying of exotic pome fruit

Exotic pome fruits typically have hard texture. It is recommended to pre-dry the fruits with osmotic dehydration or blanching process to soften the texture of pome fruit. Leaching of vitamin C may occur when samples are dipped into the osmotic and blanching solution. However, if osmotic dehydration or blanching is not desirable, direct drying can be applied and the fruit has to be cut into small slices or thin layers before it is subjected to drying.

#### 1.2.3. Drying of exotic tender fruit

Tender fruit typically has soft, sticky, strong flavor and seedy flesh. It generally contains high amount of protein, fats, and compounds that are sensitive to heat. **Figure 1.12**

shows the classification of tender fruit based on its characteristics as well as the recommended drying techniques that can be applied to tackle the characteristics of the respective class when drying is concerned. Generally, tender fruit that has soft, sticky and seedy pulp pose a problem in handling. Conventional drying such as hot air drying and sun drying can be applied. However for tender fruits that contain heat sensitive compounds and high amount of protein and fats, it is recommended to apply low temperature drying such as freeze drying, heat pump drying and hybrid drying where at least one of the modes/stages is conducted at low temperature. Freeze drying is generally suitable for all types of fruit but its capital and operating costs are high. It has been reported that freeze drying is suitable for fruit with concentrated aroma compound as aroma loss is significant as the volatile compounds that contribute to the aroma are lost due to exposure to heat ([Chin et al. 2008](#)).



**Figure 1.12.** Classification of tender fruit based on its characteristics and various drying technique recommended for the respective tender fruit class

### 1.2.3.1. Breadfruit (*Artocarpus altilis*, *A. incisus*)

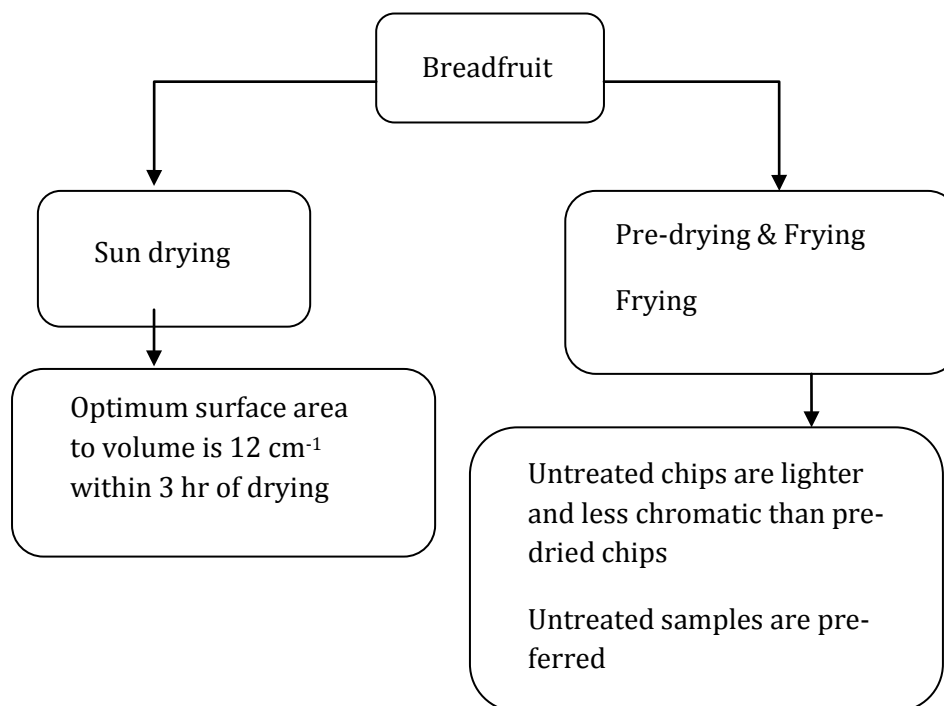
Breadfruit is native to Southeast Asia. Ripe breadfruit contains 84.16 (w/w) of total carbohydrates, 69.21 (w/w) of starch, 6.27 (w/w) of carbohydrates soluble in alcohol, 4.07 (w/w) of total sugars and 2.65 (w/w) of reducing sugars (Graham and De Bravo, 1981). In addition, it contains high amount of minerals (Ca, K and Fe) and vitamins (niacin and riboflavin). **Figure 1.13** shows the research findings reported in the literature regarding the drying of breadfruit.

According to [Ewing \(1996\)](#), breadfruit can tolerate direct sunlight with good preservation of protein, carbohydrate and nutrients. Drying of breadfruit was conducted by [George et al. \(2007\)](#) through sun drying method and the results indicated that the op-



timal surface area to volume ratio of dried sample was  $12 \text{ cm}^{-1}$  within 3 hr with solar radiation heat flux of  $825 \text{ W/m}^2$ , ambient temperature of  $27\text{-}30^\circ\text{C}$  and ambient relative humidity of 60-65%.

[Roberts et al. \(2007\)](#) pre-dried breadfruit with convective drying at temperature of  $60^\circ\text{C}$  for 20 minutes before it is deep fried at temperature of  $205^\circ\text{C}$  for 1 to 4 min. It was reported that untreated chips (without pre-drying) were lighter and less chromatic than pre-dried chips and the sensory assessment showed that untreated chips were preferred.

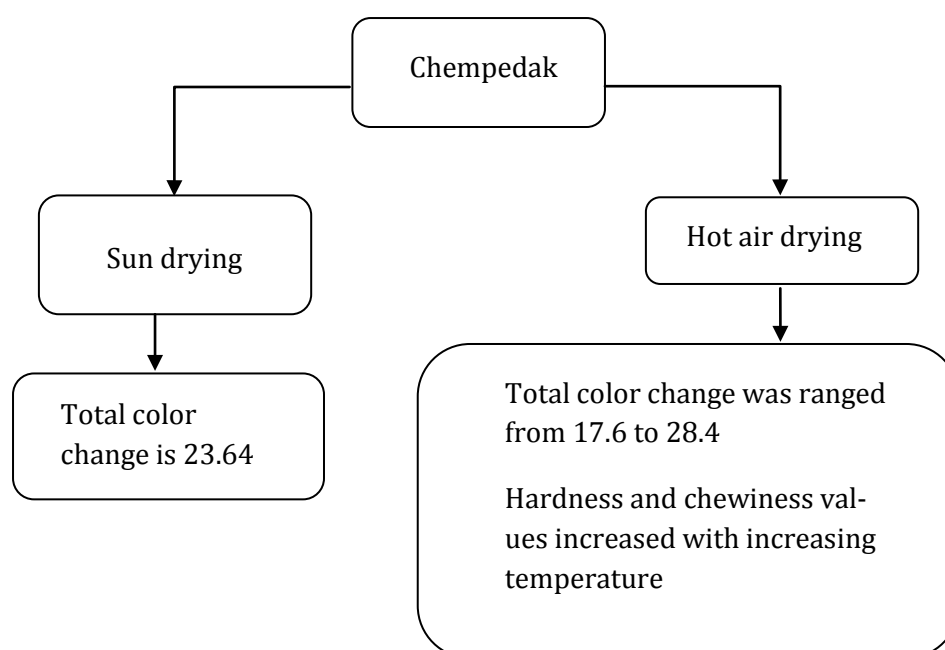


**Figure 1.13.** Research finding summary on the drying kinetics and product quality of breadfruit

### 1.2.3.2. Chempedak (*Artocarpus integer*)

Chempedak (*Artocarpus integer*) is a seasonal fruit native to Southeast Asia. The length is 20 -35 cm and diameter is 10 -15 cm. The outer skin of the fruit is slightly sticky. It has to be cut open in order to expose the edible part inside the fruit. The edible part encompasses pulp coated seed which is orange-yellow in color. The pulp contains 3.5-7.0 g of protein, 84.0-87.0 g of carbohydrates, 5.0-6.0 g of fiber and 2.0-4.0 g of ash in 100 g of serving in dry basis ([Suranant, 2001](#)). **Figure 1.14** shows the summary of literature on the drying of chempedak. Thus far, drying of chempedak has been tested only with sun drying and hot air drying ([Chong et al., 2008a; 2008b](#)). It was reported that chempedak dehydrated by sun drying and hot air drying has significant total color change and textural change compared to fresh fruit ( $p < 0.05$ ). Total color change for sun-dried chempedak slabs was 23.64 whereas hot air drying at  $50\text{-}70^\circ\text{C}$  was 17.6-28.4. In term of textural attributes, it was reported that hardness, cohesiveness, and chewiness except springiness were significantly changed ( $p < 0.05$ ) for chempedak that underwent sun drying. Whereas, hardness and chewiness in hot air drying increased with increasing temperature whilst cohesiveness and springiness remained unchanged with reference to the fresh chempedak.



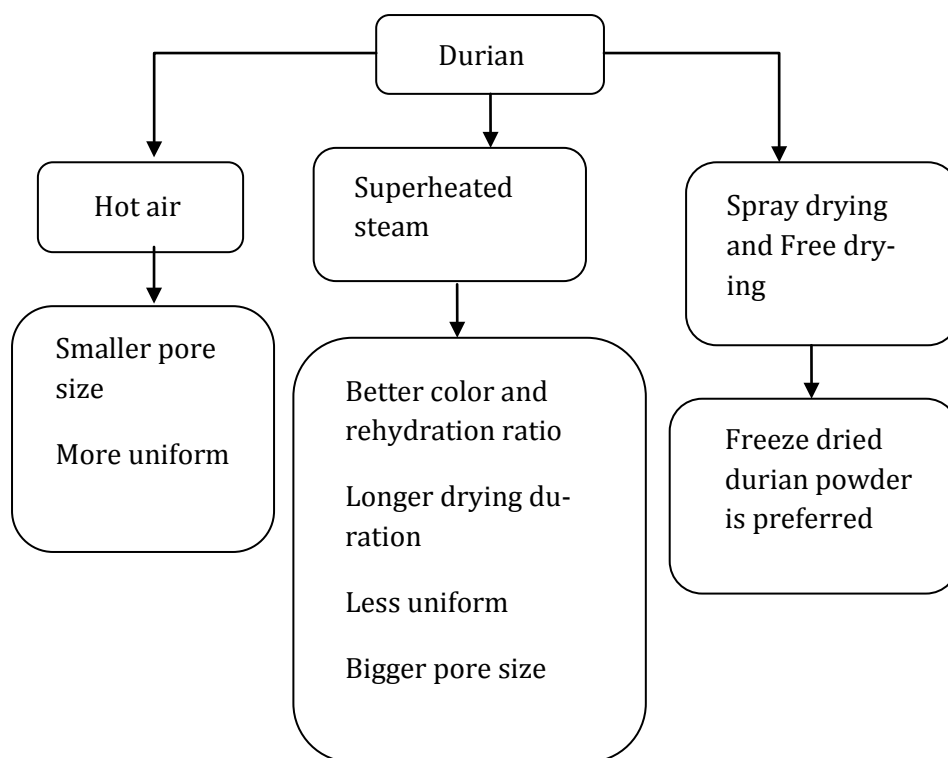


**Figure 1.14.** Summary of literature on the drying of chempedak

### 1.2.3.3. Durian (*Durio sp L.*)

Durian is native to Thailand, Brunei, Indonesia and Malaysia and belongs to family of Malvaceae. It is distinctive for its large size, unique smell, taste and formidable thorn-covered husk. Durian contains high amount of sugars, vitamin C, potassium, serotonergic amino acid tryptophan, carbohydrates, proteins and fats. In addition, caffeic acid and quercetin are the main polyphenol compounds of ripe durian ([Arancibia-Avila et al. 2008](#)). Ripe durian cannot be kept for more than two or three days. Further postharvest processing is needed during the seasoning period to overcome the overproduction problem. Findings on the effects of different drying techniques on product quality and drying kinetics of durian are summarized in **Figure 1.15**.

Drying may decompose or change the volatile constituents of durian. This especially concerns durian as fresh durian pulp contains 30 volatiles constituents ([Chin et al. 2008](#)). It was reported that four esters disappeared after freeze drying and 14 volatile constituents diminished after spray drying ([Chin et al. 2008](#)). However, new volatiles were formed in spray-dried powder, comprising of aldehydes, ketone, furan and pyrrole compounds. During freeze drying, 70%-100% major durian aroma such as propanethiol, ethyl propanoate, propyl propanoate, ethyl 2-methylbutanoate and diethyl disulfide were vanished ([Chin et al. 2008](#)).



**Figure 1.15.** Findings on the effects of different drying techniques on the drying kinetics and product quality of durian

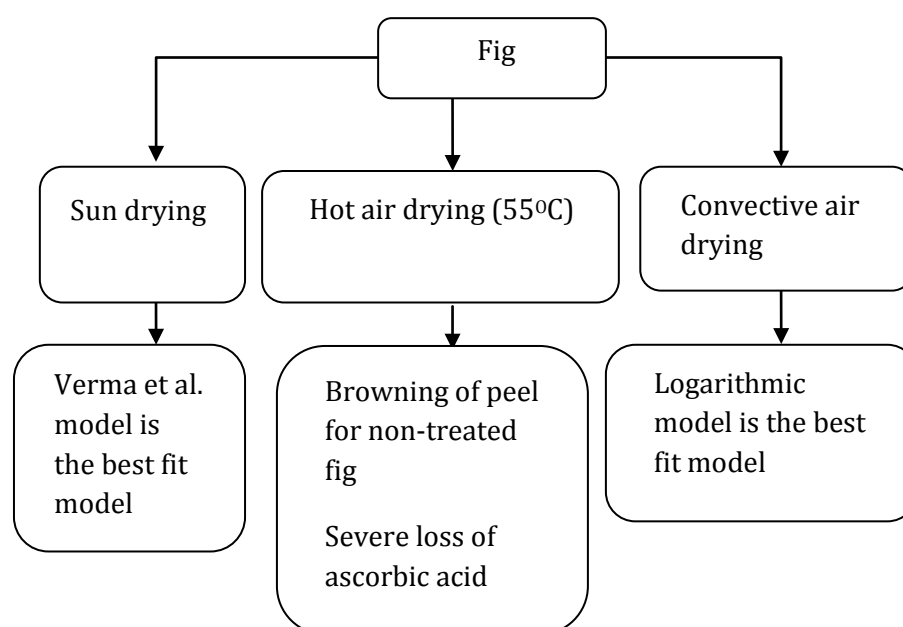
[Jamradloedluk et al. \(2007\)](#) attempted to produce low-fat durian chips from hot air drying and superheated steam drying conducted at drying temperatures of 130–150°C and velocity of drying medium at 2.0 m/s. The results revealed that superheated steam drying produced dried durian chip that has better quality in term color and rehydration ratio but gave lower drying rate. In addition, the superheated steam dried product has less uniform, fewer but larger pores and a dense layer formed on the surface of the durian chip if compared with hot air drying.

[Che Man et al. \(1999\)](#) studied the effects of spray drying and freeze drying of durian where the flesh was blended with water before subjected to freeze and spray drying. It was found that durian powder dried using freeze drying was better in term of physicochemical and sensory assessment as compared to spray dried samples.

Durian is an exotic tropical fruit with antioxidant capacity higher than that of other tropical fruits such as snake fruit, mangoesteen, lychee, guava and mango ([Arancibia-Avila et al. 2008](#)). The major polyphenol compounds of durian are polyphenol oxidase (PPO) substrates and therefore they are susceptible to enzymatic reactions. Thus drying at low temperature (except freeze drying) although can be suitable for heat sensitive materials but it is not suitable for materials that contain high amount of PPO substrates as it may lead to decomposition of the compounds due to the enzymatic activity. High temperature drying is also not recommended because durian contains high amount of vitamin C, proteins and fats. These nutrients may decompose, convert and oxidize at high temperature. As such, the best drying strategy is to apply mild temperature drying where relatively low temperature drying is carried out at a faster pace. For examples, hybrid air drying, freeze drying are recommended to be used in drying of durian or tender fruit with similar characteristics.

#### 1.2.3.4. Fig (*Ficus carica L. var. tsapela*)

Fig is a tough plant that is easy to grow which sometimes causes over-production. It is probably originated in Western Asia and later spread to the Mediterranean. The nutrition contents of fig include carbohydrate, essential amino acids, vitamins and minerals (Vinson et al. 2005). According to the literature, cyaniding-3-O-rhamnoglucoside is the main anthocyanin in Fig (Solomon et al., 2006). The total anthocyanin content in the pulp is 1.5 to 15 µg/g (Duenas et al. 2008). This fruit is very sensitive to microbial spoilage, even when it is stored in cold condition (Hardenburg et al. 1986). Sun drying is the most common postharvest method in the current processing practise. However, the risk of the development of aflatoxins is a major concern (Piga et al., 2004). **Figure 1.16** gives the summary of the research findings on the effects of different drying techniques on the drying kinetics and product quality of dried fig.



**Figure 1.16.** Drying kinetics and product quality of fig

Doymaz (2006) studied the drying kinetics of fig dried using sun drying technique. The drying kinetics was fitted to eight thin-layer drying models and it was found that Verma model gave a better fit to the experimental data. The effective moisture diffusivity reported as  $2.47 \times 10^{-10} \text{ m}^2/\text{s}$ . However, the quality parameters of dehydrated fig is not reported. On the other hand, Xanthopoulos et al. (2007, 2009) fitted seven thin-layer models to simulate convective drying of figs at 46.1–60°C using non-linear regression analysis. The statistical analysis revealed that the best model is the Logarithmic model.

Piga et al. (2004) studied the effects of dehydrating fig using mild temperature hot air drying technique with and without pretreatment (by blanching or blanching plus sulphuring). It was reported that pretreatment gave good results in terms of flavor and chewiness. In addition, the drying duration of fig was shorter compared to the untreated fig.

Fig is a highly heat sensitive tender fruit. Therefore high temperature drying is not advisable. However, mild temperature drying may cause a severe loss of vitamin C. Thus,

it is recommended to dehydrate fig using low temperature heat pump drying or hybrid heat pump vacuum-microwave drying.

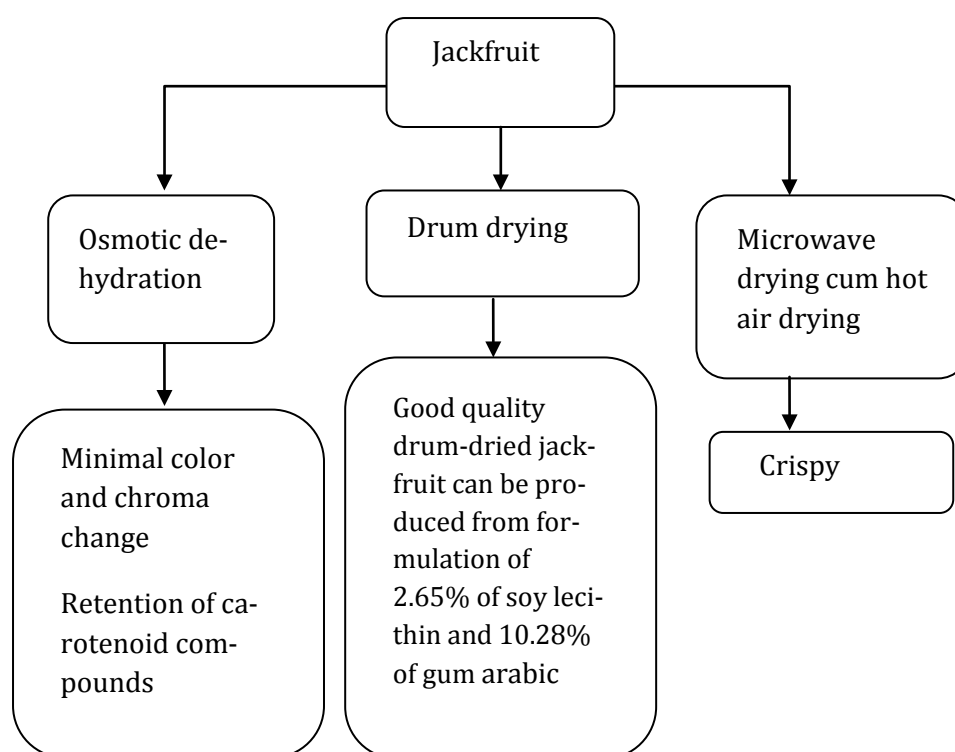
#### **1.2.3.5. Jackfruit (*Artocarpus heterophylla*)**

For jackfruit, microwave drying was found to be the method that can produce crispier product ([Yang et al. 2005](#)).

Jackfruit is native to India. Nowadays, this fruit grows in many parts of Southeast Asian countries. About 23 compounds are found in jackfruit and the major flavor compound is esters. The major esters compound are Isovaleric acid, 3-phenylpropyl ester, Isopropyl myristate, 3-phenylpropanol, octadecane and methyl dodecanoate ([Ong et al. 2006](#)). For organic acids, it was reported that the dominant organic acids in jackfruit are malic acid and citric acid ([Ong et al. 2006](#)). This fruit is also popular and it has yellow and orange bulb that contains 18.9 g carbohydrates, 0.8 g minerals and 30 IU vitamin A and 0.25 mg thiamine per 100 g of sample ([Samaddar, 1985](#)). In addition, it was reported that the carotenoids for 24 different type of jackfruit are ranged from 0.363 to 0.879 mg/ 100 of sample. Fresh jackfruit can only be stored for 4 to 5 days at temperature of 25 to 35°C ([ICUC, 2004](#)). Therefore, jackfruit is commonly processed into dried, leather, pickles and beverage after harvest. Several drying methods have been tested in the drying of jackfruit viz. osmotic dehydration, drum drying, microwave drying and the findings are summarized in **Figure 1.17**.

[Sexena et al. \(2008\)](#) reported that osmotic dehydration of jackfruit using solution concentration of 5.90Brix and temperature of 68.5°C could minimize the color and chroma changes of dried jackfruit significantly. In addition, the retention of carotenoid compounds and tissues integrity was higher. Mathematical modelling of jackfruit dried by osmotic dehydration is reported by [Giraldo-Zuñiaga et al. \(2004\)](#). The effective diffusivity is within  $0.446 \times 10^9$  to  $1.84 \times 10^9$  m<sup>2</sup>/s. On the hand, Yang et al. (2005) studied the effect of microwave drying of jackfruit texture. It was reported that 4 hr of microwave dehydration cum hot air drying can produce crispy jackfruit chips.

[Pua et al. \(2007\)](#) carried out the drying of jackfruit puree in a double drum dryer with steam pressure of 2.3 bar and found that 2.65% of soy lecithin and 10.28% of gum arabic with jackfruit puree which concentration was 40% v/w water gave the best results.



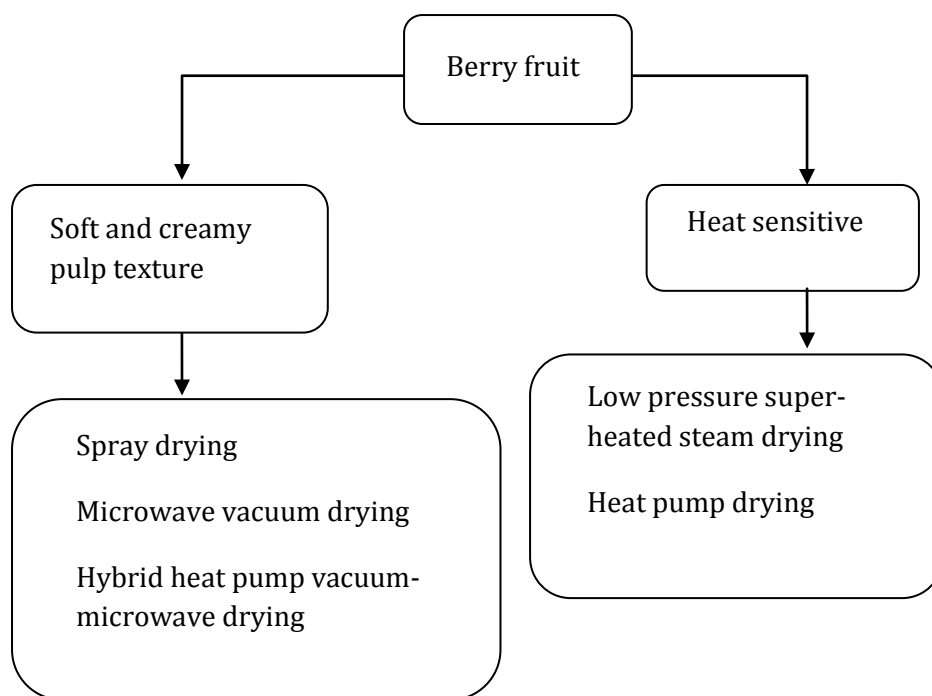
**Figure 1.17.** Summary of the research findings of drying kinetics and product quality of jackfruit

#### 1.2.3.6. Some remarks on the drying of exotic pome fruit

Most exotic tender fruits contain high amount of proteins, fats, volatile constituents and polyphenol compounds. Conventional drying techniques are not suitable to dehydrate fruits with these chemical compositions. To prevent oxidation, decomposition and change of flesh color, low or mild temperature drying techniques can be considered for instances, freeze drying, heat pump drying, hybrid air drying and low temperature combined drying technique. In addition, it is interesting to investigate the change of volatile constituents of tender fruit in the future.

#### 1.2.4. Drying of berry fruit

**Figure 1.18** shows the classification of berry fruit based on its characteristics. recommended drying techniques for exotic berry fruit with different characteristics. It was reported that low pressure superheated steam (LPSSD) required long drying time to complete the drying process but this drying method can retain higher amount of ascorbic acid ([Menthakhup et al. 2005](#)). Therefore a combined drying technique like LPSSD cum microwave vacuum drying is recommended. Microwave drying is considered as rapid drying technique, as it can reduce the moisture content of the dehydrated product in a short period of time. This drying method may also overcome the problem of microwave drying, which is related to the change of textural attributes during drying.

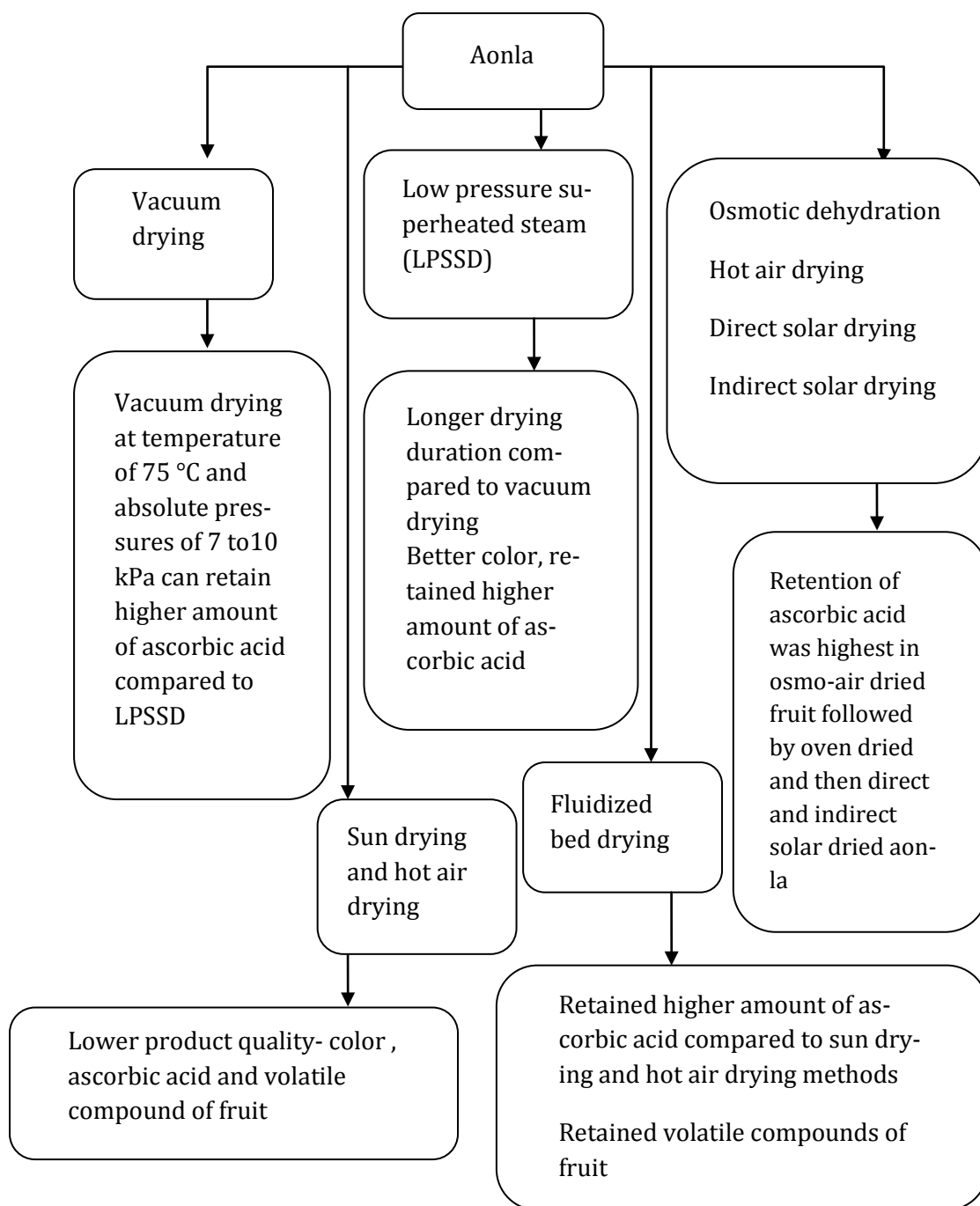


**Figure 1.18.** Classification of berry fruit based on its characteristics

#### 1.2.4.1. Aonla (*Phyllanthus emblica L.*)

Aonla or Indian gooseberry is indigenous to tropical Southeast Asia. It has a very short harvesting period, which is from October to January. The pulp of fresh aonla contains 500 to 1500 mg of ascorbic acid per 100 g of samples (Chauhan et al. 2005), which is 20 times higher than vitamin C of orange juice (Goyal et al. 2008). Gallic acid, elegendic acid and glucose are the main polyphenol compounds of aonla (Goyal et al. 2008). It also contains 3.11% total sugar content, 2.37% reducing sugar and 0.74% non-reducing sugars (Goyal et al. 2008). According to Montri (1998), it is commonly consumed as a health food in various preserved forms such as pickles, dried fruits and beverage products. This fruit is not consumed in fresh due to its astringent taste. Indian gooseberry tea is one of the well-known aonla that is further processed into instant beverage powder and pasteurized juice. Generally, thermal treatment such as drying may affect the quality of dried product such as ascorbic acid and color, which greatly influence the consumer satisfaction. Therefore, suitable drying process is needed to minimize the quality degradation. Figure 1.19 shows the research findings of the drying kinetics and product quality of aonla.

Menthakhup et al. (2005) studied the drying kinetics and product quality of Indian gooseberry flakes. Drying techniques applied were vacuum drying and low-pressure superheated steam drying (LPSSD) drying. The blended pulps were dried by using vacuum and low-pressure superheated steam at drying temperature ranging from 65 to 75°C with absolute pressure of 7, 10 and 13 kPa. The authors found that LPSSD required relative long drying time to complete the drying of aonla because of the existence of the condensation period and the lower evaporation rate in LPSSD than that of vacuum drying. However, the LPSSD could retain ascorbic acid better than the vacuum drying (except for vacuum drying at 75 °C and absolute pressures of 7 and 10 kPa) and preserve the color of aonla.



**Figure 1.19.** Research findings on the drying kinetics and product quality of aonla

The retention of ascorbic acid in dehydrated aonla was reported to be the highest in osmo-air dried aonla (243.74 mg/100 g), followed by oven dried (189.10 mg/100 g), direct solar dried (170.17 mg/100 g) and lastly indirect solar dried aonla (159.08 mg/100 g) (Pragati and Dhawan, 2003). Ascorbic acid content of dehydrated aonla decreased further when it was stored for 3 months. The reduction was the highest in osmo-air dried fruit followed by oven dried and then direct and indirect solar dried aonla. The reduction in ascorbic acid content might be due to oxidation during storage at high ambient temperature (Pragati et al. 2003). The authors also reported that the level of anti-nutrient such as tannins were lower in osmo-air dried aonla due to leaching and browning process. The retention of ascorbic acid in the samples dried in fluidized bed



drying was greater compared to those dried under sun and hot air tray drying ([Murthy & Joshi, 2007](#)). In the dryers mentioned above, volatile chemical compounds along with moisture were lost to some extent. But fluidized bed drying was proved to be better than the other methods tested for aonla drying.

#### **1.2.4.2. Ciku / Sapota (*Manilkara zapota*)**

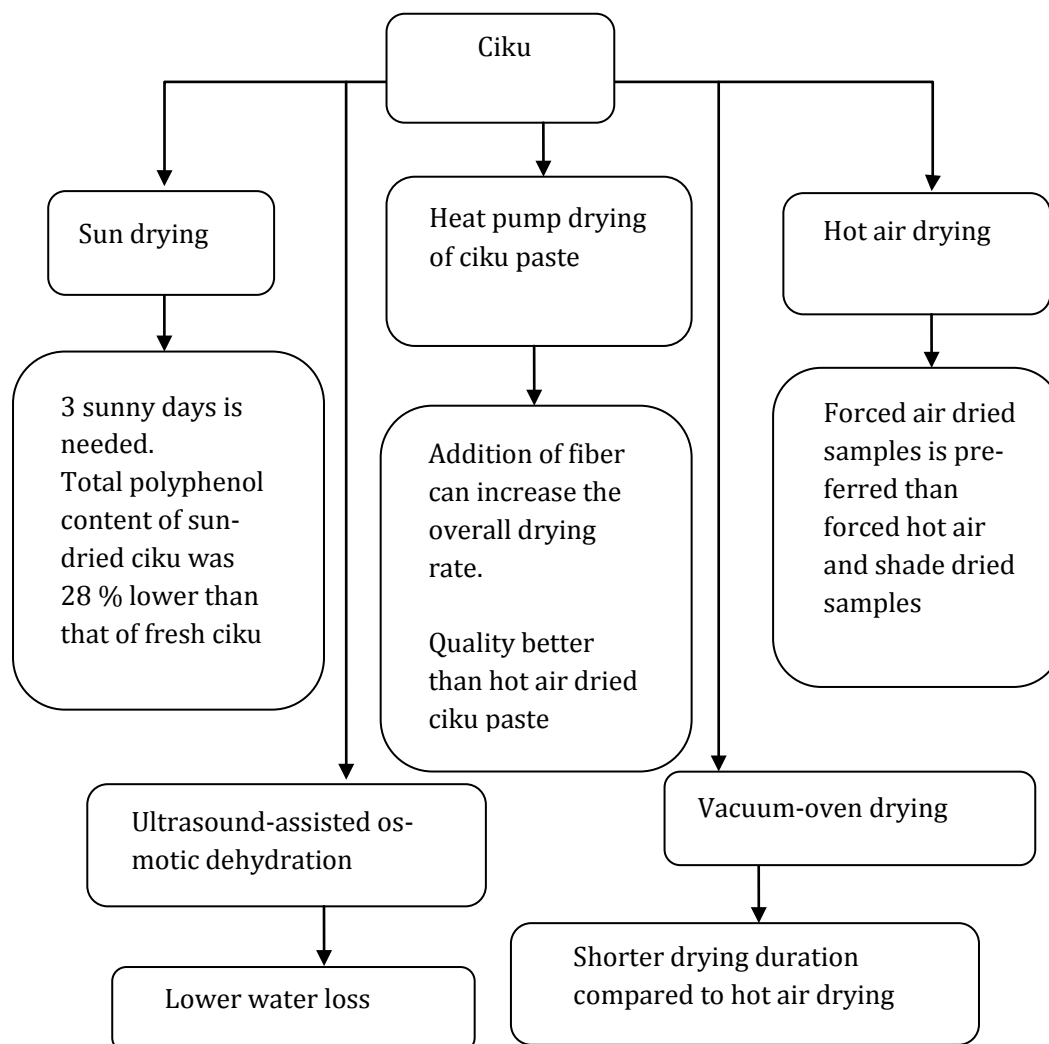
[Leong and Shui \(2001\)](#) studied the antioxidant capacity of 27 tropical fruits. It was reported that ciku (*Manilkara zapota*) has the highest antioxidant capacity among all tropical fruits. Unripe ciku contains 3396 mg/100 g L-ascorbic acid equivalent antioxidant capacity (AEAC) and 2000 mg GAE/ 100g total polyphenol content (TPC) ([Leong and Shui, 2001](#); [Shui et al. 2004](#)). However, the total polyphenol content (TPC) of ciku declines significantly from 1300 to 300 mg GAE/100g of sample and changes gradually during day four and day five from ripe to the overripe stage ([Shui et al. 2004](#)). Drying can be applied to convert this perishable fruit into stabilised dehydrated products that can be stored for an extended period of time ([Chong et al. 2010](#)). **Figure 1.20** summarizes the research findings on the drying techniques that were tested in the drying of ciku as well as its product quality.

[Ganjyal et al. \(2003\)](#) found that vacuum-oven drying (14 to 31 hours) of *Achras zapota* was better than convection air-oven drying (15 to 35 hours) at the temperatures tested (55°C to 70°C) in terms of drying duration. [Chong and Law \(2007\)](#) found that three sunny days were needed if sun drying is to be applied in tropical country. [Jain and Jain \(1998\)](#) found that dehydrated sapota (*Achras zapota* L.) slices at forced air (T<34°C) were preferred over the shade (T<30°C) and forced hot air (T<55°C) dehydrated slices. Sun drying of ciku, which temperature fluctuated at 28-32°C, reduced significantly the retention of antioxidant content. This is due to long exposure to heat during sun drying. It was found that total polyphenol content of sun-dried ciku was 28 % lower than that of fresh ciku ([Chong et al. 2009](#)).

In addition, textural attributes sun-dried ciku slabs is significantly different ( $p<0.05$ ) from fresh ciku. This is because of the formation of shrunken structure after drying. It was found that hardness of sun-dried ciku increased significantly ( $p<0.05$ ) as compared to fresh ciku. On the other hand, total color change of sun-dried ciku is also significant where [Chong et al. \(2009\)](#) reported that the total color change was 30. High total color change is owing to pigment degradation and long drying duration. Apart from drying of *Achras zapota* slabs, [Jangam et al. \(2008\)](#) carried out the drying of *Achras zapota* paste. The authors found that addition of fiber can increase the overall drying rate. Under ultrasound-assisted osmotic dehydration sapota presented low water loss, which is related to the starch content of the fruit ( $16\% \pm 5\%$ , dry basis), because high amount of starch favour water uptake ([Witrowa-Rajchert and Lewicki, 2006](#)). Expressive water loss (13.2% after 30 minutes) was observed only when an osmotic solution of 70°Brix was employed ([Fernandes and Rodrigues, 2008](#)).

Ciku showed a different behavior regarding sugar gain. In the first 10 minutes under ultrasound-assisted osmotic dehydration, ciku lost 12.1% and 11.2% of its soluble solid to the osmotic solution, respectively for osmotic solutions of 35 and 70°Brix. After 30 minutes, the pre-treatment carried out with an osmotic solution of 35°Brix still showed a slight reduction in sugar loss, whereas when the pre-treatment was carried out with an osmotic solution of 70°Brix the fruit showed a sugar gain of 10.0%. The behavior ob-

served for ciku might be explained by the physical-chemical composition of the fruit, which contain high amounts of sugar and starch (85% dry basis) ([Morton, 1987](#); [Brito and Narain, 2002](#)).



**Figure 1.20.** Summary of the research findings on the drying kinetics and product quality of ciku

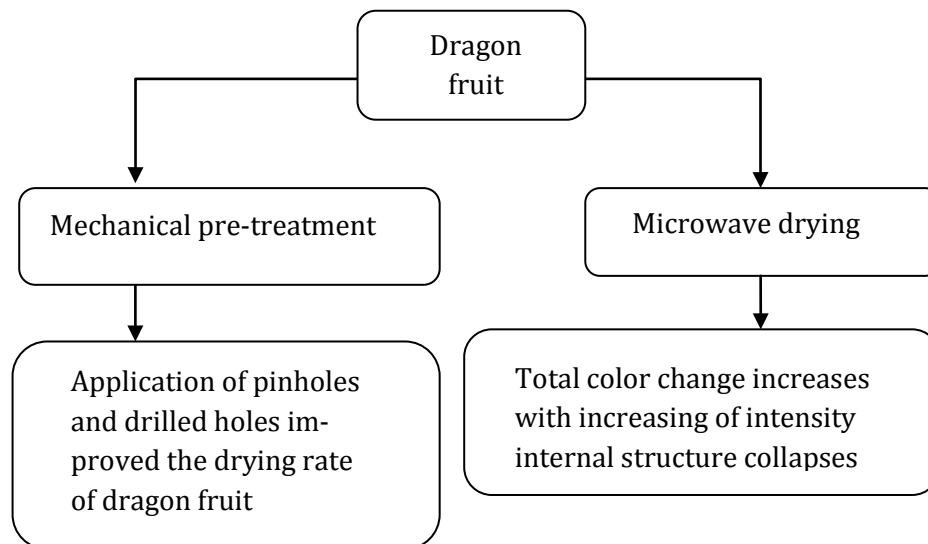
### 1.2.4.3. Dragon Fruit (*Hylocereus undatus*)

Dragon fruit is native to Mexico, Central and South America. It is a seeded fruit covered by a red or white creamy pulp. The flesh and seed is consumed at the same time. **Figure 1.21** shows literature report on the effects of different drying techniques on drying kinetics and product quality of dragon fruit.

[Yong et al. \(2006\)](#) studied the effects of different non-chemical and mechanical pre-treatment on the drying kinetics and product quality of dragon fruit. It was found that mechanical pre-treatment such as application of pinholes and drilled holes improved the drying rate of dragon fruit. The drying rates increased with increase of the diameter of the hole. In terms of product quality (color and shrinkage), the pre-treated and non-pre-treated samples were not significantly different.

The microwave drying technique was applied in drying of dragon fruit by [Nordin et al. \(2008\)](#). It was reported that color change of microwave dehydrated fruit was rela-

tively high at higher intensity and temperature because of fast browning rate. In addition, textural analysis results showed that the internal structure collapses during microwave drying if the field strength is high.



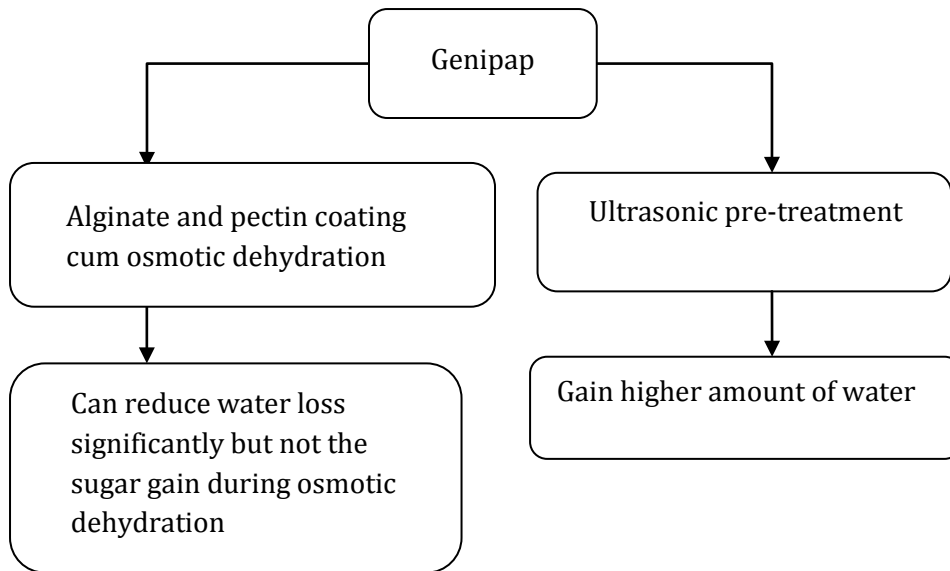
**Figure 1.21.** Literature report on the drying kinetics and product quality of dragon fruit

Dragon fruit has seedy creamy pulp that contains high antioxidant value. Conventional drying techniques are not suitable for the drying of dragon fruit. This is because the cell structure of the fruit may collapse after the critical moisture content is reached. It becomes sticky and very soft. Therefore, drying technique with puffing effect can be used in the drying of this fruits. Other options include foam mat drying and spray drying.

#### 1.2.4.4. *Genipap (Genipa americana L.)*

Genipap is native to northern Caribbean, South America and Southern Mexico. It is commonly known as jagua, chipara, guayatil, maluco and caruto. This fruit belongs to the family of Rubiaceae. It is mainly used in beverage production (liquor) due to its strong flavor and its flesh can be used as a substitute for commercial pectin to aid the jelling of low-pectin fruit juices. Hexanoic, 2- and 3-methylbutanoic acids, methyl hexanoate, methyl, ethyl octanoate, acetic and 2-methylpropanoic acids are the high potent volatile compounds of genipap (Pinto et al. 2006). Figure 1.22 shows literature reports on the effects of drying and pre-treatment techniques on product quality of genipap. The findings on the drying of genipaps is rather scarce.

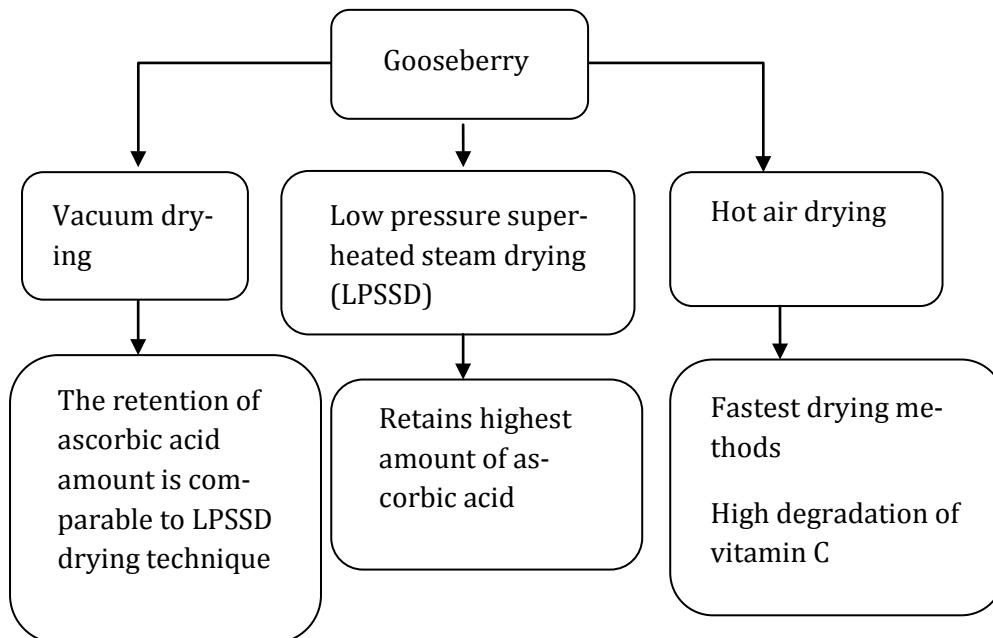
Andrade et al. (2007) reported that genipaps lost more water to the osmotic solution and incorporated less sucrose when a coating agent was applied. According to Fernandes and Rodrigues, (2008), genipaps gained 14.9% of water after 30 minutes when ultrasound pre-treatment was applied, which is relative high than other fruits. However, the sugar gain was relatively low, which was about 8.2% compared to other fruits (up to 52.0% for pinha (*Annona squamosa* L.) and melon (*Cucumis melo* L.). The use of coatings (alginate and pectin) was proposed by Andrade et al. (2007) and the authors found that coatings can reduce the water loss significantly but not the sugar gain during osmotic dehydration.



**Figure 1.22.** Literature reports on the drying kinetics and product quality of genipap

**1.2.4.5. Gooseberry (*Phyllanthus acidus*, *Phyllanthus distichus*)**

Gooseberry is a rare fruit of yellow color, which is grown on tree trunks and branches and is native to Southeast Asia. This fruit can be eaten fresh with salt to minimize the acidic taste or made into jelly. **Figure 1.23** shows the research findings on the drying of gooseberry.



**Figure 1.23.** Drying kinetics and product quality of gooseberry

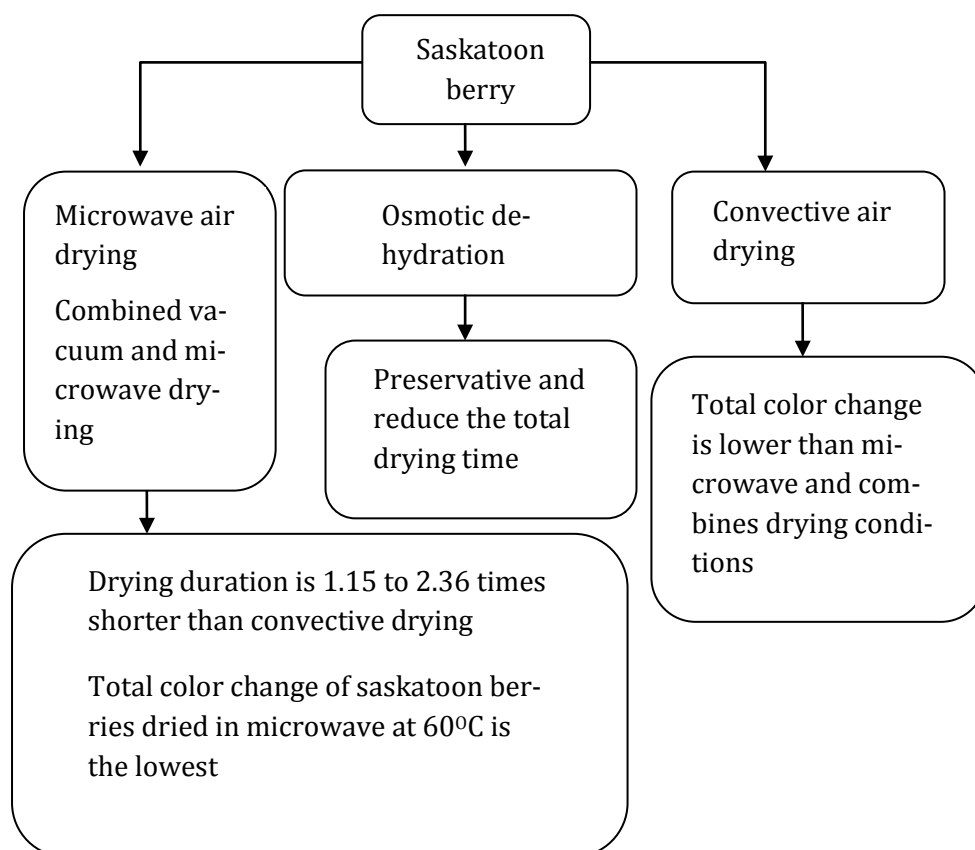
[Methakhup et al. \(2005\)](#) studied the drying of gooseberry using vacuum drying and low pressure superheated steam drying (LPSSD) methods. It was reported that the total acidity can be reduced through the drying methods. However, the ascorbic acid content was also decreased after drying. The retention of ascorbic acid was in the range of 64 to 94% for vacuum drying and 93 to 96% for LPSSD. Retentions increased with increasing

drying temperature and may be due to the shorter drying time. Pressure gave little influence to the retention of ascorbic acid.

Gooseberry is also ground into small pieces for the production of tea ([Kongsoontornkijkul et al., 2006](#)). Grinded samples were dehydrated using hot air drying, vacuum drying and low pressure superheated steam drying. It was reported that hot air drying was the fastest drying process but it gave the lowest retention of total ascorbic acid (cumulative ascorbic acid release 79.9 to 83.6%) whilst low pressure superheated steam could retain higher amount of total ascorbic acid (cumulative ascorbic acid release 66.6 to 74.1%). According to [Kongsoontornkijkul et al. \(2006\)](#), this is because of "oxygenless" environment that prohibited the aerobic degradation of ascorbic acid.

#### 1.2.4.6. Saskatoon berries (*Amelanchier alnifolia*)

Saskatoon berry is native to Canada. It contains high amounts of vitamin C, thiamin, riboflavin, pantothenic acid, vitamin B-6, vitamin A, vitamin E, minerals and antioxidants ([Mazza and Cottrell, 2008](#), [Hu et al. 2005](#), [Mazza, 1986](#)). In addition, it contains 68 to 114 mg/100g of anthocyanins ([Mazza and Davidson, 1993](#)). Immediate preservation of the saskatoon berries after harvesting is required because of its highly perishable characteristics. Traditional drying techniques such as hot air drying is not suitable as anthocyanins of saskatoon berries are heat sensitive ([Green and Mazza, 1986](#)). **Figure 1.24** gives the summary of the research findings on the drying of Saskatoon berry.



**Figure 1.24.** Drying kinetics and product quality of saskatoon berry

Microwave, convection and microwave combination drying process were used by [Reddy \(2006\)](#) to dry saskatoon berries with the application of pre-osmosed drying tech-

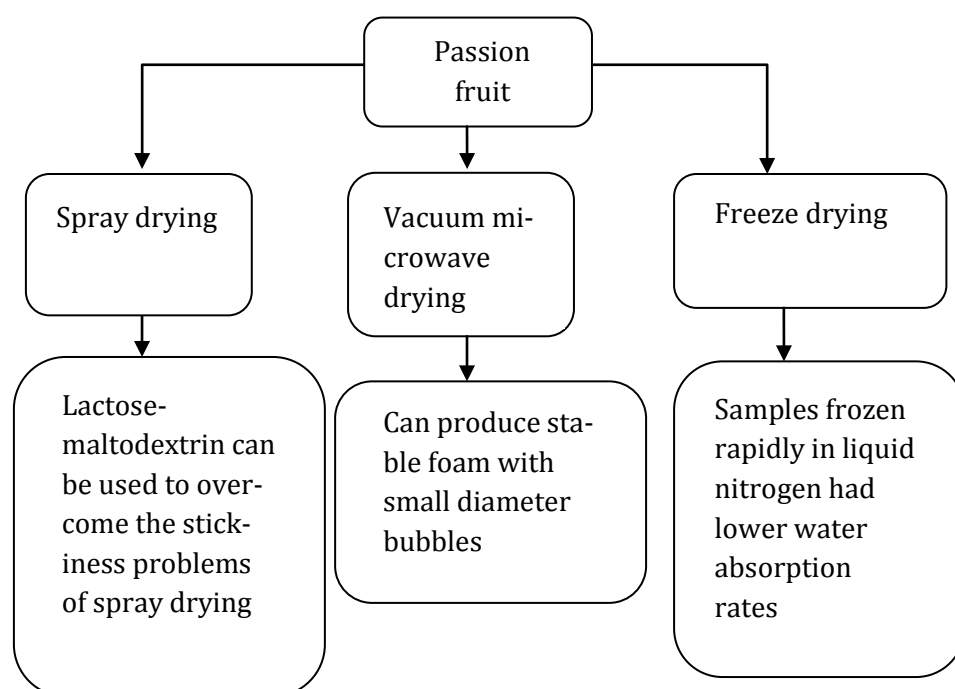
nique. It was reported that osmotic dehydration can act as a preservative and this drying method can effectively reduce the total drying time. It was concluded that microwave convective combined drying at 70°C gave the best results in terms of drying rates and end-product quality.

[Mitra and Meda \(2009\)](#) used combined vacuum and microwave drying technique to dry saskatoon berries. Based on the response surface methodology results, it was concluded that microwave power of 5.7 –6 kW, drying time of 51.5 –55 min and fruit load of 10 –9.75 kg is the optimum setting that can be used to reduce the berry moisture content to 20% (water activity –0.5).

It was reported that freeze drying of Saskatoon berry could retain higher amount of anthocyanin and antioxidant activity as compared to conventional technique ([Kwok et al. 2006](#)). However, this drying technique is energy intensive.

#### 1.2.4.7. Passion fruit (*Passiflora edulis v. flavicarpa*)

Passion fruit is native to South America. It is one of the seeded exotic berry fruits with soft and juicy flesh. It is commonly processed into juice for consumption. According to [Chan et al. \(1972\)](#), this fruit is highly acidic and it contains good source of niacin, riboflavin, vitamin C and vitamin A. It contains 14.41 to 21.9% of refractometric solids, 21.9 to 69.9 mg/ (100 g samples) of ascorbic acid and 1073-1547 as i.u. of vitamin A/ (100g of samples) of carotene ([Pruthi and Lal, 1959](#)). 3,7-dimethylocta-1,5-diene-3, 7-diol, 3,7-dimethylocta-1,7-diene-3.6-diol, 3,7-dimethloct-1-ene-3,7-diol and 3,7-dimethyloctene-3,6,7-triol were identified as aroma components from non-volatile precursors in passion fruit ([Engel and Tressl, 1983](#)). In addition, the authors reported that linalool, nerol, geraniol and - terpineol are present in bound glycosidic form. **Figure 1.25** shows the summary of the literature report on the product quality and drying kinetics of passion fruit.



**Figure 1.25.** Drying kinetics and product quality of passion fruit

[Angel et al. \(2009\)](#) studied the effects of lactose-maltodextrin (8:5, 10:5, and 12:5 % w/v) on spray-drying of the passion fruit juice. The result revealed that low amounts of the lactose-maltodextrin can be used to overcome the stickiness problems of spray drying. However, due to the utilization of lactose, the powder obtained was highly hygroscopic. The response surface results showed that the lowest values of the moisture content and hygroscopicity were reached in the temperature within the range of 188–190°C and 12:5 % (w/v) of the lactose-maltodextrin concentration. Spray drying at temperature and pressure at 180°C and 0.2 MPa, respectively with 10:5% (w/v) of the carrier agent could retain 48% of vitamin C.

[Cal-Vidal and Falcone \(1985\)](#) studied the effects of freezing rate, freeze drying temperature, sucrose and anti-caking agents on freeze dried passion fruit juice. The author found that the samples frozen rapidly in liquid nitrogen had lower water absorption rates due to re-crystallisation of sugars (exposed to relative humidity of 78%). Besides, the addition of anti-caking agents to the juice before freezing had a much less significant effect because of the poor crystal coverage and formation.

Research on vacuum microwave oven drying of passion fruit juice was conducted by [Hui \(2006\)](#). The author found that to produce stable foam with small diameter bubbles for drying at 45°C and 6-8 torr, sucrose and maltodextrin with 59°Brix must be added to the raw material.

#### **1.2.3.6. Some remarks on the drying of exotic berry fruit**

Exotic berry fruit has extremely soft texture. Drying techniques that can produce a “puff texture” is recommended. Further, this fruit has high amount of polyphenol compounds and vitamins, appropriate drying technique should be carefully selected. Drying techniques like hybrid heat pump vacuum-microwave drying, hybrid air drying, vacuum-microwave drying is recommended for the drying of exotic berry fruit. Apart from this, the fruit can be blended and spray dried into powder form.

### **Concluding Remarks**

Drying is widely used to extend the shelf life of fruit. Since different exotic fruits have different biochemical and physical properties, therefore selection of drying methods must be considered carefully. **Table 1.3** shows the recommended drying techniques for the drying of fruit based on the four classes fruits discussed in this chapter. It can be concluded that fruit with hard texture should be pre-treated using osmotic dehydration process or blanching process. In addition, mechanical treatment such as cutting into thin layer can overcome the problem as well. On the other hand, fruit with soft texture can be dried with microwave drying as it can produce dried fruit with puffing structure. To retain the heat sensitive compounds of fruit such as vitamins, polyphenol compounds and volatile constituent, low temperature heat pump drying followed by short microwave vacuum drying and mild temperature drying are recommended. Selection of dryer should also be considered from the point of view of techno-economics and quality of dried product as demanded by the market. Drying of exotic fruits has not been researched as extensively as other traditional fruits. However, it is expected that as a result of globalization, exotic fruits native to certain developing regions of the world will become known to the other part of the world.



**Table 1.3.** Recommended drying techniques for exotic stone, pome, tender and berry fruit

Types of fruit	Characteristics	Possible drying techniques
Stone	High rancidity, high in oil content, heat sensitive and hard outer shell	Pre-treatments such as osmotic dehydration and blanching followed by final drying processes such as pulsed vacuum osmotic dehydration, hot air drying, solar drying, natural sun drying, spray drying, heat pump drying, osmotic dehydration, osmotic convective air drying, osmotic vacuum drying, hybrid microwave air drying and solar stepwise temperature drying.
Pome	Hard texture, heat sensitive and hard outer shell	Pre-treatments are osmotic dehydration and blanching. This processes including mechanically cut the fruit into thin layer before drying. Freeze drying, modified air heat pump drying and heat pump drying are recommended as final stage drying.
Tender	Soft, sticky, seedy, high protein and fat	Hot air drying, sun drying, freeze drying, spray drying, osmotic dehydration, freeze drying, heat pump drying and hybrid air drying (low temperature).
Berry	Soft texture with creamy pulp, heat sensitive, seeded	Microwave drying, freeze drying, spray drying, low pressure superheated steam drying and hybrid heat pump vacuum-microwave drying

## REFERENCES

Achariyaviriya, S & Puttakarn, B. (2003). A mathematical model of effective moisture diffusivity for Lychee drying. In Proceedings of the International Conference on Crop Harvesting and Processing, Louisville, Kentucky, USA, 9-11 Feb.

Al-shahib, W. & Marshall, R.J. (2003). The fruit of the date palm: its possible use as the best food for the future? *International Journal of Food Sciences and Nutrition*, 54, 247-259.

Arancibia-Avila, P., Toledo, F., Park, Y., Jung, S., Kang, S., Heo, B.G., Lee, S., Sajewicz, M., Kowalska, T., Gorinstein, S. (2008). Antioxidant properties of durian fruit as influenced by ripening. *LWT- Food Science and Technology*, 41, 2118-2125.

Akinwale, T.O. & Aladesua, O.O. (1999). Comparative study of the physico-chemical properties and the effect of different techniques on the quality of cashew juice from Brazilian and local varieties. *Nigerian Journal of Tree Crop Research*, 3, 60-66.

Al-Farsi, M., Alasalvar, C., Morris, A., Shahidi, F. (2005). Compositional and sensory characteristics of three native sun-dried date (*Phoenix dactylifera* L.) varieties grown in Oman. *Journal of Agricultural and Food Chemistry*, 53, 7586-7591.

Alves, D.G., Barbosa Jr., J.L., Antonio, G.C. & Murr, F.E.X. (2005). Osmotic dehydration of acerola fruit (*Malpighia puniceifolia* L.). *Journal of Food Engineering*, 68, 99-103.

Alzamora, S.M. & Chirife, J. (1980). Some factors controlling the kinetics of moisture movement during avocado dehydration. *Journal of Food Science*, 45, 1649-1651.

Andrade, S.A.C., Barros Neto, B., Salgado, S.M. & Guerra, N.B. (2007). Influência de revestimentos comestíveis na redução de ganho de sólidos em jenipapos desidratados osmoticamente. *Ciência e Tecnologia de Alimentos*, 27, 39-43.

Angel, R.C.M.A., Espinosa-Muñoz, L.C., Aviles-Aviles, C., González-García, Moscosa-Santillán, M., Grajales-Lagunes, A., Abud-Archila, M. (2009). *Brazilian Archives of Biology and Technology*, 52(4), 1011-1018.

Assis, S.A., Lima, D.C. & Oliveira, O.M.M.F. (2001). Activity of pectinmethylesterase, pectin content and vitamin C in acerola fruit at various stages of fruit development, *Food Chemistry*, 74, 133-137.

Assunção, R.B. & Mercadante, A.Z. (2003). Carotenoids and ascorbic acid composition from commercial products of cashew apple (*Anacardium occidentale* L.). *Journal of Food Composition and Analysis*, 16, 647-657.

Attabhanyo, R., Ngramsomsut, K., Attabhanyo, A., Arrayarungsarit, S., Chaowanapoonpon, Y. & Kitchaijaron, J. (1998). *Longan Process Industry*. Faculty of Agriculture. Chiang Mai University, pp. 210

Atungulu, G., Nishiyama, Y. & Koide, S. (2004). Electrode configuration and polarity effects on physicochemical properties of electric field treated apples post harvest. *Biosystems Engineering*, 87, 313-323.

Augustin, A. (1982). Studies on the clarification of cashew apple for the preparation of cashew syrup. *The Indian Journal of Nutrition and Dietetics*, 19, 169-172.

Azoubel, P.M. & Murr, F.E.X. (2003). Optimisation of osmotic dehydration of cashew apple (*Anacardium occidentale* L.) in sugar solutions. *Food Science and Technology International*, 9, 427-433.

Bakshi, J. C. & Singh, P. (1974). The ber – a good choice for semi-arid and marginal soils. *Indian Horticulture*, 19, 27-30.

Barkai-Golan, R. (2001). *Postharvest disease of fruit and vegetables*. Development and control. Elsevier, Amsterdam, pp. 1.

Boubekri, A., Benmoussa, H. & Mennouche, D. (2009). Solar drying kinetics of date palm fruits assuming a step-wise air temperature change. *Journal of Engineering Science and Technology*, 4, 292-304.

Brito, E.S. & Narain, N. (2002). Physical and chemical characteristics of sapota fruit at different stages of maturation. *Pesquisa Agropecuária Brasileira*, 37, 567-572.

Cal-vidal, J. & Falcone, M. (1985). Processing Conditions Affecting the Hygroscopic of Freeze-Dried Passion Fruit Juice *Journal of Food Science*, 50, 1238-1241.

Ceylan, İ., Aktaş, M. & Doğan, H. (2007). Mathematical modeling of drying characteristics of tropical fruits. *Applied Thermal Engineering* 27, 1931-1936.

Chauhan, O.P., Srivastava, S., Pandey, P. & Rao, G.K. (2005). A study on the development of aonla blended sauce. *Beverage and Food World*, 32, 31-33.

Chan, H.T., Chang, T.S.K. & Chenchin, E. (1972), Nonvolatile acids of passion fruits juice. *Journal Agriculture Food Chemistry*, 20 (1), 110-112.

Che Man, Y.B., Irwandi, J. & Abdullah, W.J.W. (1999). Effect of different types of maltodextrin and drying methods on physico-chemical and sensory properties of encapsulated durian flavor. *Journal of the Science of Food and Agriculture*, 79, 1075-1080.

Chin, S.T., Nazimah, S.A.H., Quek, S.Y., Che Man, Y., Rahman, R.A. & Mat Hashim, D. (2008). Changes of volatiles' attribute in durian pulp during freeze- and spray-drying process. *LWT - Food Science and Technology*, 41, 1899-1905.

Chong, C.H. & Law, C.L. (2007). Sun drying of ciku (Manilkara zapota). In *Proceeding of the 14th Regional Symposium on Chemical Engineering (RSCE)*, Yogyakarta, Indonesia, 4-5 Dec.

Chong, C.H., Law, C.L., Cloke, M., Luqman Chuah. A. & Daud, W.R.W. (2008a) Drying kinetics, texture, color, and determination of effective diffusivities during sun drying of chempedak. *Drying Technology*, 26, 1286-1293.

Chong, C.H., Law, C.L., Cloke, M., Hii, C.L., Luqman Chuah. A. & Daud, W.R.W. (2008b). Drying kinetics and product quality of dried Chempedak. *Journal of Food Engineering*, 88, 522-527.

Chong, C.H., Law, C.L., Cloke. M., Luqman Chuah, A. & Daud, W.R.W. (2009). Drying models and quality analysis of sun-dried ciku. *Drying Technology*, 27(9), 985-992.

Chong, C.H. (2010). Improving product quality of dehydrated fruits using hybrid drying technique. Ph.D thesis, The University of Nottingham.

Chua, K.J., Hawlader, M.N.A, Chou, S.K. & Ho, J.C. (2002). On the study of time-varying temperature drying-effect on drying kinetics and product quality. *Drying Technology*, 20, 1559-1577.

Cui, Z., Li, C., Song, C. & Song, Y. (2008). Combined microwave-vacuum and freeze drying of carrot and apple chips. *Drying Technology*, 26, 1517-1523.

Devahastin, S., Suvarnakuta, P., Soponronnarit, S. & Mujumdar, A.S. (2004). A comparative study of low-pressure superheated steam and vacuum drying of a heat-sensitive material. *Drying Technology*, 22, 1845-1867.

Dowling, C.F. & Morton, J.F. (1987). Avocado. In *Fruits of warm climates*; Morton, J.F., Ed.; Morton Publ.: Miami.

Doymaz, I. (2006). Sun drying of figs: an experimental study. *Journal of Food Engineering*, 71, 403-407.

Duenas, M., Pérez-Alonso, J.J., Santos-Buelga, C. & Escribano-Bailón, T. Anthocyanin composition in fig (*Ficus carica* L.). *Journal of Food Composition and Analysis*, 21, 107-115.

Engel, K.H. and Tressl, R. (1983). Studies on the volatile components of two mango varieties. *Journal of Agricultural and Food Chemistry*, 31, 796-801.

Ewing, G. (1996). Breadfruit flour analysis. Personal communication with Compatible Technologies International. Feb 4.

Falade, K.O. & Abbo, E.S. (2007). Air-drying and rehydration characteristics of date palm (*Phoenix dactylifera* L.) fruits. *Journal of Food Engineering*, 79, 724-730.

Fernandes, F.A.N. & Rodrigues, S. (2008a). Dehydration of sapota (*Acharas sapota* L.) using ultrasound as pretreatment. *Drying Technology*, 26, 1232-1237.

Fernandes, F.A.N. & Rodrigues, S. (2008b). Application of ultrasound and ultrasound-assisted osmotic dehydration in drying of fruits. *Drying Technology*, 26, 1509-1516.

Ganjyal, G.M., Hanna, M.A. & Devadattam, D.S.K. (2003). Processing of sapota (sapodilla): Drying. *Journal of Food Science*, 68, 517-520.

George, C., McGruder, R. & Torgerson, K. (2007). Determination of optimal surface area to volume ratio for thin-layer drying of breadfruit (*Artocarpus altilis*). *International Journal for Service Learning in Engineering*, 2, 76-88.

Graham, H. & De Bravo, E.N. (1981). Composition of the breadfruit. *Journal of Food Science*, 46, 535-539.

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

Giraldo-Zuñiga, A.D., Arévalo-Pinedo, A., Rodrigues, R.M., Lima, C.S.S. & Feitosa, A.C. (2004). The air drying behavior of osmotically dehydrated for jackfruit (*Artocarpus Integrifolia*) slices. In *Proceedings of the 14th International Drying Symposium (IDS 2004)*. São Paulo, Brazil, 22-25 Aug, Vol. C., 2120-2126.

Grajales-Lagunes, A., Garcia-Galindo, H.S., Angulo-Guerrero, O. & Monroy-Rivera, J.A.S. (2009). Stability and sensory quality of spray dried avocado paste. *Drying Technology*, 17, 318-326.

Goyal, R.K., Patil, R.T., Kingsly, A.R.P., Walia, H. & Kumar, P. (2008). Status of post harvest technology of Aonla in India- A review. *American Journal of Food Technology*, 3, 13-23.

Hawllader, M.N.A., Perara, C.O., Tian, M. & Yeo, K.L. (2006). Drying of guava and papaya: Impact of different drying methods. *Drying Technology*, 24, 77-78.

Hardenburg, R.E., Watada, A.E. & Wang, C.Y. (1986). Fig. In: *The Commercial Storage of Fruits, Vegetables and Nursery Stocks*. Agriculture Handbook Nr. 66, pp. 40, Washington: US Government Printing Office.

- Higgins, J.E. (1917) Litchi in Hawaii, Bull. Hawaii Agric. Exp. Stn., 44, 1-21.
- Hui, Y.H. (2006). Handbook of food science, technology, and engineering, Volume 3, CRC Press, pp. 1049-9-1049-10.
- Hui, Y.H., Barta, J., Cano, M.P., Gusek, T., Sidhu, J.S. & Sinha, N.K. (2006). Handbook of fruits and fruit processing. Blackwell Publishing Ltd, Oxford, UK, pp. 607.
- Hu, C., Kwok, B.H.L. & Kitts, D.D. (2005). Saskatoon berries (*Amelanchier alnifolia* Nutt.) scavenge free radicals and inhibit intracellular oxidation. Food Research International, 38, 1079-1085.
- Hu, Q., Zhang, M., Mujumdar, A.S., Du, W. & Sun, J. (2006). Effects of different drying methods on the quality of granular edamame. Drying Technology, 24, 1025-1032.
- Human, T.P. (1987). Oil as a byproduct of the avocado. In Proceedings of the First World Avocado Congress. South African Avocado Growers' Association Yearbook, 10, 159-162.
- ICUC (2004). Jackfruit (*Artocarpus heterophyllus*): Processing and product information. Newsletter.
- Jain, R.K. & Jain, S.K. (1998). Sensory evaluation of an intermediate moisture product from "Sapota" *Achras zapota* L. Journal of Food Engineering, 37, 323-330.
- Jagadeesh, S.L., Reddy, B.S., Swamy, G.S.K., Gorbali, K., Hegde, L. & Raghavan, G.S.V. (2007). Chemical composition of jackfruit (*Artocarpus heterophyllus* Lam.) selections of Western Ghats of India. Food Chemistry, 102, 361-365.
- Jamradloedluk, J., Nathakaranakule, A., Soponronnarit, S. & Prachayawarakorn, S. (2007). Influences of drying medium and temperature on drying kinetics and quality attributes of durian chip. Journal of Food Engineering, 78, 198-205.
- Jangam, S.V., Joshi, V.S., Mujumdar, A.S. & Thorat, B.N. (2008). Studies on dehydration of sapota (*Achras zapota*). Drying Technology, 26, 369-377.
- Janjai, S., Lamlert, N., Intawee, P., Mahayothee, B., Boonrod, Y., Haewsungcharern, M., Bala, B.K., Nagle, M. & Müller, J. (2009). Solar drying of peeled longan using a side loading type solar tunnel dryer: experimental and simulated performance. Drying Technology, 27, 595 - 605.
- Jiménez-Escrig, A., Rincón, M., Pulido, R. & Saura-Calixto, F. (2001). Guava fruit (*Psidium guajava* L.) as a new source of antioxidant dietary fiber. Journal of Agricultural and Food Chemistry, 49, 5489-5493.
- Kingsly, A.R.P., Meena, H.R., Jain, R.K. & Singh, D.B. (2007). Shrinkage of ber (*Zizyphus mauritian* L.) fruits during sun drying. Journal of Food Engineering, 79, 6-10.
- Kongsoontornkijkul, P., Ekwongsupasarn, P., Chiewchan, N. & Devahastin, S. (2006). Effects of drying methods and tea preparation temperature on the amount of vitamin C in indian gooseberry tea. Drying Technology, 24, 1509-1513.
- Kozubek, A., Zarnowski, R., Stasiuk, M. & Gubernator, J. (2001). Natural amphiphilic phenols as bioactive compounds. Cellular and Molecular Biology Letters, 6, 351-355.

Kuhn, G.D. (1962). Dehydration studies of lychee fruit. Florida state horticultural society, 273-277.

Khurdiya, D.S. & Roy, S.K. (1986). Solar drying of fruits and vegetables. Indian Food Packer, 40(4), 28-39.

Kwok, B.H.L., Hu, C., Durance, T. & Kitts, D.D. (2006). Dehydration techniques affect phytochemical contents and free radical scavenging activities of Saskatoon berries (*Amelanchier alnifolia* Nutt.) Journal of Food Science, 69, 122-126.

Lapsongphol, S., Mahayothee, B., Phupaichitkun, S., Leis, H., Haewsungcharoen, M., Janjai, S. & Mueller, J. (2007). Effect of drying temperature on changes in volatile compounds of longan (*Dimocarpus longan* Lour.) fruit. In Proceedings of Conference on International Agricultural Research for Development, University of Kassel-Witzenhausen and University of Göttingen, 9-11, Oct.

Law, C.L., Waje, S.S., Thorat, B.N. & Mujumdar, A.S. (2008). Advances and recent developments in thermal drying for bio-origin and agricultural products. Stewart Post-harvest Review, 1, 1-23.

Leong, L.P. & Shui, G. (2001). An investigation of antioxidant capacity of fruits in Singapore markets. Food Chemistry, 76, 69-75.

Lima, D.E.S. (2005). Total phenolic and carotenoid contents in acerola genotypes harvested at three ripening stages. Food Chemistry, 90, 565-568.

Lutz, J.M. & Hardenburg, R.E. (1966). The commercial storage of fruits, vegetables and florist and nursery stocks. USDA Agricultural Handbook, No. 66, Washington, D.C.

Malik, N.J. (2006). Post-harvest management of fruit and vegetables. Training manual. (Vol, V-English), 10.

Mansouri, A., Embarek, G., Kokkalou, E. & Kefalas, P. (2005). Phenolic profile and antioxidant activity of the Algerian ripe date palm fruit (*Phoenix dactylifera*). Food Chemistry, 89, 411-420.

Marques, L.G. & Freire, J.T. (2005). Analysis of freeze-drying of tropical fruits. Drying Technology, 23, 2169-2184.

Marques, L.G., Ferreira, M.C. & Freire, J.T. (2007). Freeze-drying of acerola (*Malpighia glabra* L.). Chemical Engineering and Processing, 46, 451-457.

Martins, M.C.P., Cunha, T.Y. & Silva, M.R. (2008). Effect of dehydration osmotic conditions on the quality of cashew apple from cerrado. Ciênc. Tecnol. Aliment., 28, 158-165.

Mazza, G. (1986). Anthocyanins and other phenolic compounds of Saskatoon berries (*Amelanchier alnifolia* Nutt.). Journal of Food Science, 51 (5), 1260-1264.

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

Mazza, G. & Cottrell, T. (2008). Carotenoids and cyanogenic glucosides in saskatoon berries (*Amelanchier alnifolia* Nutt.). Journal of Food Composition and Analysis, 21, 249-254.

Methakhup, S., Chiewchan, N. & Devahastin, S. (2005). Effect of drying methods and conditions on drying kinetics and quality of Indian gooseberry flake. *LWT*, 38, 579-587.

Michodjehoun-Mestres, L., Souquet, J., Fulcrand, H., Meudec, E., Reynes, M. & Brilouet, J. (2009). Characterisation of highly polymerised prodelphinidins from skin and flesh of four cashew apple (*Anacardium occidentale* L.) genotypes. *Food Chemistry*, 114, 989-995.

Mitra, P. & Meda, V. (2009). Optimization of microwave-vacuum drying parameters of Saskatoon berries using response surface methodology. *Drying Technology*, 27, 1089-1096.

Mohamed, S., Taufik, B. & Karim M.N.A. (1996). Effects of modified atmosphere packaging on the physicochemical characteristics of ciku (*Achras sapota* L) at various storage temperatures. *Journal of Science and Food Agriculture*, 70, 231-240.

Montri, N. (1998). In vitro propagation of *Phyllanthus emblica* L. M. Sc. Thesis. Kasetsart University; Thailand.

Morton, J.F. (1983). Why not select and grow superior types of canistel? *Proc. Amer. Soc. Hort. Sci.- Tropical Region* 27(A): 43-54.

Morton, J.F. (1987). Sapodilla. In *Fruits of warm climates*; Morton, J.F. Ed.; Creative Resources Systems, Miami, 1987, 393-398.

Murthy, Z.V.P. & Joshi, D. (2007). Fluidized bed drying of aonla (*Emblica officinalis*). *Drying Technology*, 25, 883-889.

Nanjundaswamy, A.M. & Madhkrishniak, S.G. (1989). Advances in dehydration processes for fruits, vegetables and their products. In *Trends in Food Science and Technology*, ed. Ragavenfra Rao M. R. et al. India, p. 369.

Nordin, M.F.M., Daud, W.R.W., Talib, M.Z.M. & Hassan, O. (2008). Effect of process parameters on quality properties of microwave dried red pitaya. *International Journal of Food Engineering*, 4, 1-17.

Ong, B.T., Nazimah, S.A.H., Osman, A., Quek, S.Y., Voon, Y.Y., Mat Hashim, D., Chew, P.M. & Kong, Y.W. (2006). Chemical and flavor changes in jackfruit (*Artocarpus heterophyllus* Lam.) cultivar J3 during ripening. *Postharvest Biology and Technology*, 40, 279-286.

Ong, S.P. & Law, C.L. (2009). Mathematical modeling of thin layer drying of salak. *Journal of Applied Sciences*, 9, 3048-3054.

Paull, R.E. (2001) *Advances in Postharvest Technology for Tropical and Subtropical Fruits*. Proceedings of the International Technical and Trade Seminar on Tropical and Subtropical Fruits. Kuala Lumpur. 2001.

Piga, A., Özer, K.B., Agabbio, M, Aksoy, U. (2004). Hot air dehydration of figs (*Ficus carica* L.) drying kinetics and quality loss. *International Journal of Food Science and Technology*, 39,793-799.

Pinto, A.B., Guedes, C.M., Moreira, R.F.A., De Maria, C.A.B. (2006). Volatile constituents from headspace and aqueous solution of genipap (*Genipapa Americana*) fruit isolated by the solid-phase extraction method. *Flavor and Fragrance Journal*, 21, 488-491.



Prasad, K.N., Yang, B., Yang, S., Chen, Y., Zhao, M., Ashraf, M. & Jiang, Y. (2009). Identification of phenolic compounds and appraisal of antioxidant and antityrosinase activities from litchi (*Litchi sinensis* Sonn.) seeds. *Food Chemistry*, 116, 1-7.

Pragati, Dahiya, S. & Dhawan, S.S. (2003). Effect of drying methods on nutritional composition of dehydrated aonla fruit (*Emblica officinalis* Garten) during storage. *Plant Foods for Human Nutrition*, 58, 1-9.

Pruthi, J.S. & Lal, G. (1959). Chemical composition of passion fruit (*Passiflora edulis*, Sims.). *Journal of Science of Food and Agriculture*, 10, 3, 188-192.

Pua, C.K., Sheikh Abd. Hamid, N., Rusul, G. & Abd. Rahman, R. (2007). Production of drum-dried jackfruit (*Artocarpus heterophyllus*) powder with different concentration of soy lecithin and gum Arabic. *Journal of Food Engineering*, 78, 630-636.

Queiroz, V.A.V., Berbert, P.A., Molina, M.A.B., Gravina, G.A., Queiroz, L.R. & Deliza, R. (2007). Desidratação por imersão-impregnação e secagem por convecção de goiaba. *Pesquisa Agropecuária Brasileira*, 42, 1479-1486.

Ramírez-Martínez, J.R. & Luh, B.S. (1973). Phenolic compounds in frozen avocados. *Journal of the Science of Food and Agriculture*, 24, 219-225.

Rangkadilok, N., Worasuttayangkurn, L., Bennett, R.N. & Satayavivad, J. (2005). Identification and quantification of polyphenolic compounds in Longan (*Euphoria longana* Lam.) fruit. *Journal of Agricultural and Food Chemistry*, 53, 1387-1392.

Reddy, L. (2006). Drying characteristics of Saskatoon Berries under microwave and combined microwave-convection heating. Thesis, Master, University of Sasjatchewan, Saskatoon. 1-82.

Reis, K.C., Azevedo, L.F., Siqueira, H.H. & Ferrua, F.Q. (2007). Avaliação físico-química de goiabas desidratadas osmoticamente em diferentes soluções. *Ciência Agrotecnológica*, 31, 781-785.

Roberts, K.T., Badrie, N. & Roberts-Nkrumah, L. (2007). Color and sensory characteristics of fried chips from three breadfruit (*Artocarpus altilis*) cultivars. *Acta Hort. (ISHS)* 757: 225-232.

Samaddar, H.N. (1985). Jackfruit. In T.K. Bose (Ed.). *Fruits of India: Tropical and subtropical*. Calcutta, Naya Prokash, 487-497.

Saxena, A., Bawaa, A.S. & Raju, P.S. (2008). Optimization of a multitarget preservation technique for jackfruit (*Artocarpus heterophyllus* L.) bulbs. *Journal of Food Engineering*, 91, 18-28.

Shah, N.S. & Nath, N. (2008). Changes in qualities of minimally processed litchis: Effect of antibrowning agents, osmo-vacuum drying and moderate vacuum packaging. *LWT – Food Science and Technology*, 41, 660-668.

Shui, G.H., Wong, S.H. & Leong, L.P. (2004). Characterization of antioxidants and change of antioxidant levels during storage of Manilkara zapota L. *Journal of Agriculture and Food Chemistry*, 52, 7834-7841.

Singh, R. (1992). Evaluation of dehydration techniques for different varieties of Ber fruit. Msc Thesis, CCS HAU, Hisar.

Solomon, A., Golubowicz, S., Yablowicz, Z., Grossman, S., Bergman, M., Gottlieb, H.E., Altman, A., Kerem, Z. & Flaishman, M.A. (2006). Antioxidant activities and anthocyanin content of fresh fruits of common Fig. (*Ficus carica* L.), 54, 7717-7723.

Suranant, S. (2001). Under-utilized tropical fruits of Thailand; RAP Publication: 2001/26. Bangkok, Thailand, pp. 16-17.

Tsami, E. & Katsioti, M. (2000). Drying kinetics for some fruits: predicting of porosity and color during dehydration. *Drying Technology*, 18, 1559-1581.

Varith, J., Dijkanarukkul, Achariyaviriya, A. & Achariyaviriya, S. (2007). Combined microwave-hot air drying of peeled longan. *Journal of Food Engineering*, 81, 459-468.

Vayalil, P.K. (2002). Antioxidant and antimutagenic properties of aqueous extract of date fruit (*Phoenix dactylifera* L. *Arecaceae*). *Journal of Agricultural and Food Chemistry*, 50, 610-617.

Vendramini, A.L. & Trugo, L.C. (2004). Phenolic compounds in acerola fruit (*Malpighia puniceifolia* L.). *Journal of the Brazilian Chemical Society*, 15, 664-668.

Vial, C., Guilbert, S. & Cuq, J.L. (1991). Osmotic dehydration of kiwi fruits: influence of process variables on the color and ascorbic acid content. *Science des Aliments*, 11, 63-84.

Vinson, J.A., Zubik, L., Bose, P., Samman, N., Proch, J. (2005). Dried fruits: Excellent in vitro and in vivo antioxidants. *Journal of the American College of Nutrition*, 24, 44-50.

Wall, M.M. (2006). Ascorbic acid and mineral composition of longan (*Dimocarpus longan*), lychee (*Litchi chinensis*) and rambutan (*Nephelium lappaceum*) cultivars grown in Hawaii. *Journal of Food Composition and Analysis*, 19, 655-663.

Witrowa-Rajchert, D. & Lewicki, P.P. (2006). Rehydration properties of dried plant tissues. *International Journal of Food Science and Technology*, 41, 1040-1046.

Wojdyło, A., Figiel, A. & Oszmiański, J. (2009). Effect of drying methods with the application of vacuum microwaves on the bioactive compounds, color and antioxidant activity of strawberry fruits. *Journal of Agricultural and Food Chemistry*, 57, 1337-1343.

Wong, D.W.S. (1989). Fruit Development and Ripening. Physiology. In "Avocado" AVI VanNostrand Reinhold, NY, pp. 229-245.

Xanthopoulos, G., Oikonomou, N. & Lambrinos, G. (2007). Applicability of a single-layer drying model to predict the drying rate of whole figs. *Journal of Food Engineering*, 81, 553-559.

Xanthopoulos, G., Yanniotis, S. & Lambrinos, G. (2009). Water diffusivity and drying kinetics of air drying of figs. *Drying Technology*, 27, 502-512.

Yang, X. (2005). Study on the processing of Jackfruit crisp chips by microwave puffing. *Chinese Journal of Tropical Crops*, 3,

Yong, C. K., Islam, Md. R. & Mujumdar, A.S. (2006). Mechanical means of enhancing drying rates: effect on drying kinetics and quality. *Drying Technology*, 24, 397-404.

Yusof, S. (1990). Physico-chemical characteristics of some guava varieties in Malaysia. *Acta Hort. (ISHS)* 269:301-306.

## **Chapter 2** **Drying of Roots**

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## ABSTRACT

Root is a part of a plant body that bears no leaves; often function in storage of food and nutrients. Starchy root vegetables are important staple foods, particularly in tropical regions. Drying is one of the ancient methods of root preservation. It is done by several methods like solar, osmotic, convective, freeze, vacuum and microwave drying. A lot of research findings are available on drying of various taproots, tuberous roots, corm, rhizome, tuber and bulbs. This chapter presents an overview of the recent developments in root drying. Various drying techniques suitable for roots and effect of drying method on the final quality of dehydrated roots are discussed in the chapter. The details on mathematical modeling of root drying process are also included. Further, the chapter highlights on future research needs on root drying.

## 2.1. INTRODUCTION

Roots are generally storage organs, enlarged to store energy in the form of carbohydrates. They differ in the concentration and the balance between sugars, starches, and other types of carbohydrate ([Kays 1996](#)). All of the root crops are utilized as staple foods, vegetables, raw materials for industry and medicinal purposes. Roots are perishable as higher temperature causes it to wilt and gives a poor appearance. Therefore, preservation of root is essential for keeping them for a long time without further deterioration in the quality of the product. Drying is one of the most common methods to enhance the shelf life of roots. The major aim of drying roots is to remove the moisture to a level at which microbial spoilage and deteriorative chemical reactions are greatly minimized. Drying extends the availability of seasonal roots, retaining their nutritive values, and adds variety to the otherwise monotonous diet. It also adds convenience to the products. Roots are thicker than seeds, flowers and leaves which make the drying process longer. Several drying methods have been employed on domestic and industrial scale to preserve the useful roots. Various roots are dried by several methods like sun, hot air, vacuum, freeze, infra-red and microwave hot air/vacuum drying.

## 2.2. PRE-PROCESSING OF ROOTS BEFORE DRYING

Roots are removed from soil; therefore it is required to remove the adhering soil particles and convert in to a suitable shape for drying. It includes preparation of raw roots and various pretreatments which are discussed below.

### 2.2.1. Preparation of Roots Suitable for Drying

Roots are generally washed in tap water to remove the dirt, dust and soil particles and then graded according to size and quality. Rotten and otherwise spoiled roots are sorted and removed. The skin of the roots is removed either manually or by peeling. Roots and tops may be removed before or after peeling. Peeling may be done by a hand-knife, flame treatment or abrasion peeler. In case of onions, the flame treatment is given and the charred skin is removed by tumbling in a vibrating washer. The tops, crown roots and cores are removed by hand positioning each end of the onion against a rotating knife or by semiautomatic equipment which carries the onion between two parallel

revolving circular blades. The onions are next sliced into 2.25-2.50 mm thick slices, at a right angle to the vertical axis. High-speed cutters or modifications of kraut-cutters or bread-slicing equipment are used. The losses in washing, cutting, trimming and slicing of the various roots are about 10-20 per cent. Some of the roots are dried as whole or transformed in to various shapes like cubes, shreds, spheres, cylinders etc ([Alexander Essers et al., 1996](#)). The shapes of various roots used during drying and dehydration are given in **Table 2.1**. It can be seen from **Table 2.1** that small roots are dried as it is, whereas, large size roots are converted in to various shapes. It shortens the diffusion path during drying and decreases the specific energy consumption.

**Table 2.1.** Shape of important roots used during drying

Name of Root	Shape	Reference
<b>Carrots</b>	Slices, Cubes, Shreds, Flakes	( <a href="#">Uddin et al., 2004</a> ; <a href="#">Cui et al., 2004</a> ; <a href="#">Baysal et al., 2003</a> ; <a href="#">Sutar et al., 2007b</a> )
<b>2004;</b>	Slices, Cubes	<a href="#">Alexander Essers et al., 1996</a>
<b>Chicory</b>	Slices, Crunched Tubers	<a href="#">Park et al., 2007</a>
<b>Echinacea</b>	Whole Roots	<a href="#">Kabganian et al., 2002</a>
<b>Garlic</b>	Slices, Cloves	( <a href="#">Cui et al., 2003</a> ; <a href="#">Sharma and Prasad, 2001</a> ; <a href="#">Baysal et al., 2003</a> ; <a href="#">Madamba et al., 1996</a> ; <a href="#">Madamba et al., 1994</a> ]
<b>Ginseng</b>	Whole Roots	<a href="#">Sokhansanj et al., 1999</a>
<b>Onion</b>	Slices, Rings, Flakes	( <a href="#">Rajkumar and Sreenayanan 2001</a> ; <a href="#">Sutar et al., 2007a</a> ; <a href="#">Praveen et al., 2006</a> ]
<b>Parsley</b>	Slices	<a href="#">Sobiech, 1980</a>
<b>Potato</b>	Cubes, Slices, Shreds, Spheres, Cylinders	( <a href="#">Khraisheh et al., 1997</a> ; <a href="#">Lebovka et al., 2007</a> ; <a href="#">Cui et al., 2004</a> ; <a href="#">Wang and Brennan 1995</a> ; <a href="#">Srikiatden and Roberts 2006</a> ; <a href="#">Sutar et al., 2009</a> )
<b>Purslane roots</b>	Whole Roots	<a href="#">Kashaninejad and Tabil, 2004</a>
<b>Sweet Potato</b>	Slices, Cubes	<a href="#">Singh et al., 2006</a> ; <a href="#">Bechoff et al., 2009</a>
<b>Ginger</b>	Flakes	<a href="#">Hawlder et al., 2006</a>
<b>Celery root</b>	Cylindrical Disks	<a href="#">Białobrzewski 2007</a> ; <a href="#">Białobrzewski and Markowski, 2004</a>
<b><i>H. tuberosus and C. intybus</i></b>	Crunched Tubers	<a href="#">Srikiatden et al., 2003</a>

### 2.2.2. Pretreatments

Almost all the roots are pre-treated before drying. The pre-treatments like blanching, alkaline dip, sulphiting, freezing, microwave treatment, high intensity electric field pulses (HELP) and high pressure treatment have been attempted by many researchers to enhance the dehydration characteristics and minimize the adverse changes in the root tissue during drying ([Ponting 1973](#); [Grabowski et al. 1994](#); [Ade-Omowaye et al. 2004](#)). The pre-treatments practiced during drying of important roots are given in **Table 2.2**. The roots like carrot and potato are subjected to several pre-treatments. Most commonly used pre-treatment for roots is hot water blanching. It helps to minimize the enzymatic reaction during drying, increases storage stability of dehydrated root product and accelerates the rate of drying. Also, final product results with better colour and organoleptic quality ([Lo et al. 2002](#); [Garnicki and Kaleta, 2007](#); [Galindo et al., 2005](#)). However, blanching causes tissue cell membrane disruption, protein denaturation, turgor loss and poor firmness. Heat treatments also cause loss of colour, flavour and nutrients. To overcome the drawbacks of water blanching, steam blanching can be used to inactivate the enzyme activity in roots like potato and carrots ([Litvin et al., 1998](#)). The pre-treatments like soaking of roots in solutions of NaCl, sucrose, NaHSO<sub>3</sub>, potassium metabisulphite and sodium metabisulphite are used to suppress the enzymatic reactions, to prohibit discolouration resulting from oxidation of polyphenolic compounds during root drying ([Ghosh et al., 2004](#); [Khraisheh et al., 1997](#)). The roots are also pre-treated using Pulsed Electric Field (PEF) at various electric field strengths and different pulse durations to enhance the drying rate ([Lebovka et al., 2007](#)). Recently, it is reported in literature pulsed microwave blanching with target product temperature retains nutrients better than conventional hot water blanching. The microwave blanching is comparable to water blanching with higher enzyme inactivation rate than water blanching ([Ramesh et al., 2002](#)).

**Table 2.2.** Pre-drying treatments of important roots

Name of Root	Pretreatment	Reference
<b>Onion</b>	Dipping in 0.2 % potassium metabisulphite solution	<a href="#">Sutar et al., 2007b</a>
<b>Carrots</b>	Blanching at 100°C for 5-6 min Steam blanching of carrots for 1 min Soaking in 10% NaCl for 30 min and at 20°C and blanching in the same solution for 2 min at 96°C. Blanching in boiling 5% brine solution, 3 to 6 min Blanching in water at 85°C for 4 min Blanching in 4.6°Brix sugar solution or 10% sucrose Blanching 40°Brix sugar solution at 80 °C for 14 min	( <a href="#">Srikiatden et al., 2003</a> ; <a href="#">Speck et al., 1977</a> ; <a href="#">Jayaraman and Gupta, 1992</a> )
	Blanching in 87°C for 2-4 min Blanching in water at 98±1°C for 3 min	
<b>Potato</b>	Dipping in 0.45-1% sodium metabisulphate solution for one minute Soaking in 2% NaHSO <sub>3</sub> solution for 5 min Blanching in water at 95 °C during 5 min	( <a href="#">Khraisheh et al., 1997</a> ; <a href="#">Lebovka et al., 2007</a> ; <a href="#">Sutar</a>

	Blanching in water at 95 °C for 4.5 min. Blanching in water at 85°C for 3.5 minutes Electric field strength (E) 400 V/cm, pulse duration 10 <sup>-3</sup> s, pulse repetition time 10 <sup>-2</sup> s Freezing thawing	<a href="#">et al., 2009;</a> <a href="#">Srikiatden and Roberts, 2003)</a>
	Blanching in water at 75°C for 15 min	
<b>Sweet Potato</b>	Immersion in 1 % NaCl solution Immersion in KMS and citric acid solutions in the concentrations 0.5:0.5%, 0.5:1.0%, 1.0:0.5% and 1.0:1.0% for 30 min Steam cooking at 85±2 °C for 20 min	( <a href="#">Singh et al., 2006)</a>
<b>Parsley Root Slices</b>	Blanching for 3 min in boiling 5% brine solution, 3 min in boiling water, and 6 min in boiling water	( <a href="#">Garnicki and Kaleta, 2007)</a>

### 2.3. TYPES OF ROOT DRYING METHODS

Roots are dried using several methods falling into various categories like hot air, freeze, dielectric, osmotic dehydration and hybrid drying. The drying methods being used for roots along with the process parameters are given in **Table 2.3**. It can be observed from the table that sun/solar drying, hot air, osmotic dehydration, microwave assisted drying, infra-red, freeze, vacuum and hybrid drying are most commonly used methods for majority of the roots. The foregoing sections illustrate these methods of root drying.



**Table 2.3.** Process parameters during drying of roots by various methods

Root	Drying Method and variables	Reference
<b>Onion</b>	<p>Hot air drying (Temperature 50°-80°C, Velocity 0.25-1 m/s, Rh 10-20%)</p> <p>Osmotic dehydration (NaCl concentration 5,12.5 and 20% w/w, Solution temperature 28,43 and 58°C)</p> <p>Fluidized bed drying (Air temperature 45°,55°,65°,75° and 85°C; Air velocity ranging from minimum fluidization velocity to 10 m/s)</p> <p>Multistage hot air dehydration (Temperature 50°-100 °C up to 30-60% moisture content level and second stage 50°C)</p> <p>Cross flow dryer (Temperature 50°-70 °C)</p> <p>Infrared radiation under vacuum</p> <p>Far-infrared radiation intensities (0.50, 0.80 and 1.00kW/kg of initial mass of onion), three initial thicknesses of onion slices (2, 4 and 6mm), 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%)</p>	<p>(<a href="#">Rajkumar and Sreenarayanan, 2001</a>; <a href="#">Munde et al., 1988</a>; <a href="#">Sutar et al., 2007b</a>; <a href="#">Sarsavadia et al., 1999</a>; <a href="#">Mongpraneet et al., 2002</a>; <a href="#">Wang, 2002</a>)</p>
<b>Carrots</b>	<p>Microwave Vacuum Drying (Microwave power density 2-12.66 W/g, Pressure 6.66,19.98 and 33.3 kPa)</p> <p>Osmotic Dehydration (NaCl 5,10, and 15 % along with sucrose 50°Brix at 30°C osmotic solution)</p> <p>Hot air drying (Temperature 50° to 70°C, Air velocity 0.5 - 1 m/s)</p> <p>Solar Cabinet Drying (Maximum air temperature 55°C and average air flow rate 0.492 m<sup>3</sup>/min)</p> <p>Microwave oven drying (Oven levels 2, 3 and 4 at 650 W power)</p> <p>Vacuum Drying (Temperature 65, 70, 75 °C at 5,10 and 15 kPa Pressure)</p> <p>Freeze drying (Pressure 1 mbar and temperature 30, 45 and 55°C)</p> <p>Hot air drying at 60°C in natural convection conditions (velocity&lt;0.01 m/s)</p>	<p>(<a href="#">Garnicki and Kaleta, 2007</a>; <a href="#">Ghosh et al., 2004</a>; <a href="#">Sutar et al., 2007b</a>; <a href="#">Prakash et al., 2004</a>; <a href="#">Baysal et al., 2003</a>; <a href="#">Maddamba and Bekki, 2001</a>; <a href="#">Srikiatden et al., 2003</a>; <a href="#">Baysal et al., 2003</a>)</p>

	Convective hot air drying (70 °C and 1.5 m/s air velocity)	
	Hot air tray drying (Air temperature 70 °C and 0.86 m/sec air velocity)	
<b>Sweet Potato</b>	Open sun and solar cabinet drying (4 h to 5 days drying time) Drum drying (Steam pressure 6 kg/cm <sup>2</sup> , Drum rpm 3 and drum clearance 0.3 mm) Hot air drying (Air temperature 50° to 80°C) Cross flow dryer (Drying air temperature 24° to 45°C) Greenhouse solar dryer (The temperature/humidity within the solar dryer ranged from 27° to 50 °C/14 to 52% ) Open sun drying (Ambient range of 24° to 36 °C and relative humidity 24 to 52% and air velocity 0.04 m/s)	( <a href="#">Singh et al., 2006</a> ; <a href="#">Bechoff et al., 2009</a> ; <a href="#">Yadav et al., 2006</a> )
<b><i>Echinacea angustifolia</i></b>	Hot air drying (Air temperatures 15°, 30° and 45 °C, with air flow velocities of 0.3, 0.7 and 1.1 m/s) A convection oven drying (The oven temperatures 30°, 40°, 50°, 60° and 70°C)	( <a href="#">Kabganian et al., 2002</a> ; <a href="#">Eren-turk et al., 2004</a> )
<b>Ginger</b>	Heat Pump Drying (Air temperature at 45°C, 10% relative humidity, the circulating air velocity 0.7m/s and the drying time 8 h) Freeze Drying (The freezing at -20°C for 24 h, a heating plate temperature 10°C and a pressure of 600 Pa for 24 h) Vacuum Drying (Pressure of 1500 Pa and a temperature of 45°C for 24 h)	( <a href="#">Hawllader et al., 2006</a> )

<b>Ginseng roots</b>	Hot air Drying (Three stage drying at 38°- 50-38 °C, 12 to 25% relative humidity and air velocity from 1 m/s to 3 m/s) Forced air drying (Air temperature 30°, 50° and 70 °C) Freeze drying (Freezing at -70 °C for 30 min and drying time from 30 min to 20 h) Far Infrared radiation drying (Temperature 50 °C, drying time 30 min to 20 h and the outlet air velocity 0.8m/s) Hot air Drying (Temperature 38° to 40°C)	( <a href="#">Sokhansanj et al., 1999</a> ; <a href="#">Martynenko, 2006</a> ; <a href="#">Kim et al., 2008</a> )
<b>Cassava roots</b>	Open Sun Drying	( <a href="#">Alexander Essers et al., 1996</a> )
<b>Celery Roots (<i>Apium graveolens</i>, cv. Diamond).</b>	Natural convection drying (Air temperature 49 ± 1°C, air humidity of 12.5%)	( <a href="#">Białobrzewski, 2007</a> )
<b>Potato</b>	Pulsed fluidized bed drying (Drying temperature 70° and 80°C, air velocity 1.9 and 2.4m/s, and rotating disk velocity 40 and 80 rpm) Hot air drying (70 °C and 1.5 m/s air velocity)	( <a href="#">Srikiatden et al., 2003</a> ; <a href="#">Reyes et al., 2007</a> )
<b>Chicory (<i>Cichorium intybus L.</i>)</b>	Hot air drying (Temperature 50° to 90°C, Air velocity 0.5 to 1.3 m/s)	( <a href="#">Park et al., 2007</a> )
<b><i>H. tuberosus</i> and <i>C. intybus</i></b>	Hot air drying (Temperature 30, 40 and 50°C, air velocity 1.5 m/s)	( <a href="#">Srikiatden et al., 2003</a> )
<b>Garlic</b>	Fluidized bed drying (Air temperature at 50 °C along with 0.93 m/s air velocity). Far infrared drying Temperature 80° to 85°C and 10 to 200 min time	( <a href="#">Cui et al., 2003</a> , <a href="#">Sharma and Prasad, 2001</a> ; <a href="#">Baysal et al., 2003</a> )

### 2.3.1. Sun/Solar drying

Sun drying is common method to preserve the root products in tropical countries. Sun drying consists of direct and indirect drying. Open sun drying is considered as direct sun drying process. It is generally used in the developing and undeveloped countries and carried out by spreading roots either on the floor or on supporting structures made

from locally available material like wood, bamboo etc. However, this technique is extremely weather dependent and has the problems of contamination with dust, wind-blown debris, sand particles and environmental pollution, insect infestation, damage to the product by rodents, birds and animals, growth of microorganisms and additional losses during storage due to insufficient or non-uniform drying. Also, degradation through exposure to direct irradiation of the sun and to rain, storm and dew takes place as well as the required drying time can be quite long. Losses during open sun drying can be estimated at more than 30% and could be reduced to a great extent by improved methods of solar drying. Therefore, indirect method of sun drying that is use of solar assisted mechanical dryers, which are far more rapid, providing uniformity and hygiene, are inevitable for root drying processes. The literature shows that sweet potatoes, onions, carrots and cassava roots can be dried using indirect type of solar drying with drying time from few hours to 5 days depending upon the root to be dried ([Singh et al., 2006](#)). The **Table 2.3** gives the brief overview of drying parameters of the selected roots dried using sun drying. Solar drying is a common method to dry onions. [Maini et al. \(1984\)](#) used "Forced indirect solar air dryer" with solar energy catchment area 6 m<sup>2</sup> painted with an ordinary black paint. Drying chamber, measuring 2 m × 1.5 m × 1.5 m which covered 45 trays with 5 mm thick slices spread on an aluminium tray at 4 kg/m<sup>2</sup> and blower forcing 56.85 m<sup>3</sup> of hot air/min were used. They reported drying ratio, re-constitution ratio, pyruvic acid loss and colour of dehydrated onions of four varieties by using solar dryer and concluded that variety 'Ropali' was better suited for dehydration because of its highest alcohol insoluble solids. [Pawar et al. \(1988\)](#) studied the suitability of various solar dryers for drying of sliced white onions and the influence of sulphitation on colour retention by the dried onion flakes. They compared physic-chemical characteristics after drying of white onion slices by mechanical dryer, different solar dryers and open air drying and found that the drying rates were fastest in mechanical solar cabinet dryer followed by those in matrix bed air heater, rock type air heater and open air drying. They also stated that sulphitation treatment with 0.25% potassium metabisulphite for five minutes led to virtually complete prevention of pink discolouration in onion flakes dried in solar dryer. [Rajkumar and Sreenarayanan, 2001](#) dehydrated white and red onions in a cross flow drier at different temperatures namely, 50°, 60° and 70°C with different sulphitation levels as pre-treatments. They reported that drying at 50°C and 0.4% sulphitation retained more ascorbic acid while, a temperature 60°C and 0.3% sulphitation showed less non-enzymatic browning and scored maximum points in organoleptic studies.

### 2.3.2. Hot Air Drying

Hot air drying is one of the most common methods of drying in which air is circulated by natural or forced convection though or over the bed of product. The product may be spread on the screened trays or in a controlled room or platform. The drying medium is air which is heated generally in the temperature range from ambient to 110°C during root drying depending upon the nature of roots. The most common methods of hot air drying include tray drying/cabinet drying and fluidized bed drying. There are several sizes of trays depending on type of product. The root products are generally spread on perforated trays in a single layer or multiple layers depending upon the required tray loading density in kg product/m<sup>2</sup> of the tray area. Air having tempera-

ture in the range ambient to 100°C is blown either in cross flow or parallel flow mode in the dryer in the velocity range 0.1 to 1.9 m/s. Roots like carrots, sweet potato, potato and onion are sensitive to temperature, the problem of darkening in colour, loss of flavour and decrease in rehydration ability of the dried product occur during hot air drying that can be solved by some pre-treatments like blanching, chemical dipping and osmotic dehydration. The range of air temperature and velocity used during hot air drying of various roots is given in **Table 2.3**. It can be observed the table that hot air drying is most common method of root drying as compared to other methods.

Hot air drying of roots can be carried out in single and multiple stages. Literature shows that multistage drying of root like onion is more effective than the single stage. [Munde et al. \(1988\)](#) developed a process for multistage dehydration of onion flakes. They dried 4 mm thick onion slices at 50°, 60°, 70°, 80°, 90° and 100°C temperatures up to 30, 40, 50 and 60 per cent cut-off moisture levels and the remaining moisture was removed at the control temperature 50°C. On the basis of quality factors and production time, they recommended the two stage dehydration process for onions and also stated that the four stage dehydration process saves 24% drying time at the cost of very marginal sacrifice in quality from the possible best two stage dehydration process.

### 2.3.3. Fluidized Bed Drying

Fluidized bed drying is carried out by passing the air at fluidization velocity through a bed of product so as to fluidize the material. In fluid bed drying, heat is supplied by the fluidization air, but the air flow need not be the only source. Heat may be effectively introduced by heating surfaces (panels or tubes) immersed in the fluidized layer. Uniform processing conditions are achieved by passing a gas (usually air) through a product layer under controlled velocity conditions to create a fluidized state. Some roots like onions, garlic, carrots can be dried using fluidized bed. [Sutar et al. \(2007\)](#) carried out fluidized bed drying of osmotically dehydrated onion slices at different temperatures. They reported that fluidized bed drying is faster method of drying for onions compared to other methods. [Prakash et al. \(2004\)](#) reported the drying characteristics and quality of 3 mm thick carrot slices (cv Pusa Kesar) by three drying methods viz., solar, fluidized and microwave drying. They used fluidized bed drier with 3 cm initial bed thickness, air temperatures of 50°, 60° and 70°C and air velocity 0.049 m<sup>3</sup>/s to dry the carrots. They found that in case of fluidized bed drying, after the initial falling rate period, temperature no longer controlled the drying rate. They also reported that the fluidized bed dried carrots show better colour, rehydration properties, greater retention of  $\beta$ -carotene and better overall sensory quality than those dried by solar and microwave oven methods.

### 2.3.4. Osmotic Dehydration

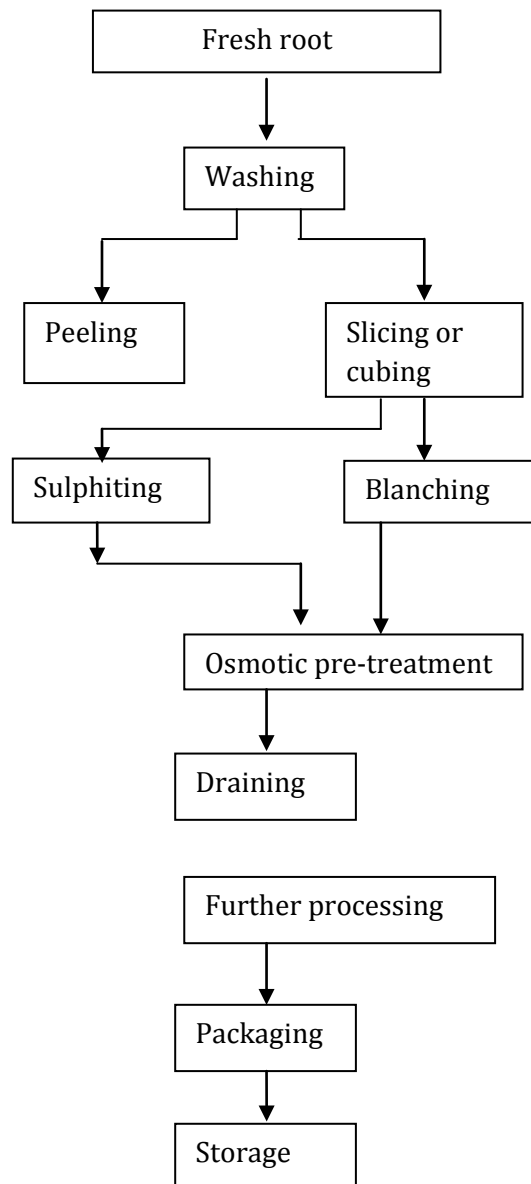
Osmotic dehydration is the process of water removal by immersion of water containing cellular solids in a concentrated aqueous solution. It is gaining attention due to its several advantages as a pre-treatment of other drying process. The osmotic pre-treatment is practiced for roots like potatoes and carrots to improve the organoleptic characteristics and to save energy of drying process. The sugar and salt is used as osmotic agent for roots. Several researchers ([Ghosh et al., 2004](#); [Sutar et al., 2007](#); [Uddin et al., 2004](#); [Singh et al., 2006](#)) investigated the mass transfer during osmotic dehydration of carrots, potatoes and onion. The product obtained by the osmotic process is more

stable during storage due to its low water activity by solute gain and water loss. At low water activity, the growth and toxin production by microorganisms and all the chemical reactions pertaining to deterioration of food are minimal. It also improves colour, flavour and texture of the dehydrated root product and it is less energy intensive process than air or vacuum drying as there is no phase change of water. Osmotic pre-treatment prior to drying is advantageous as sugar syrup prevents loss of flavour to some extent that is generally observed with hot air or vacuum drying. The enzymatic browning is also prevented as the product is surrounded by sugar, thus good colour is retained with little or no use of sulphur dioxide. Sugar uptake by the root pieces modify the composition (sugar to acid ratio) and improve the taste and acceptability of the final product. It partially removes water, reduces water removal load of the dryer and increases the drying rate ([Islam and Flink, 1982](#); [Chaudhari et al., 1993](#); [Karathanos et al., 1995](#); [Ertekin and Cakaloz, 1996](#)).

The schematic diagram of osmotic dehydration process is shown in **Figure 2.1**. All the steps given in the figure may not be followed as such and are subject to change considering the types of material being processed. It is usually not worthwhile to use osmotic dehydration technique for more than 50% weight reduction because of the decrease in the osmosis rate with time ([Islam and Flink, 1982](#); [Chaudhari et al., 1993](#)). Energy consumption in osmotic dehydration process arises from the heating of the material and osmoactive solution to the required temperature for solution mixing or pumping and recirculation, dissolution of hypertonic substance in a diluted solution, evaporation of excess water in an appropriate evaporator for reuse ([Lewicki and Lenart, 1990](#)).

### 2.3.5. Freeze Drying

Freeze drying is a process by which a solvent is removed from frozen foodstuff or a frozen solution by sublimation of the solvent by desorption of the sorbed solvent, generally under reduced pressure. The freeze drying involves freezing stage and sublimation stage. The roots like ginger, carrots, and ginseng are dried using freeze drying. The freeze drying parameters of the selected roots are given in **Table 2.3**. The freezing temperature ranges from -50° to -80°C and for sublimation the frozen roots are kept on heating plates having temperature 10° to 55°C with pressure less than 1 mbar. Freeze drying produces a high quality product, but being an expensive process, its application for root drying is limited. Literature shows several studies on freeze drying of carrots. Freeze dried root possess a preferable appearance, due to the excellent structural retention. [Litvin et al. \(1998\)](#) dried 7-10 mm thick carrot slices by combining the freeze drying with a short microwave treatment and air and vacuum drying. They first dried carrot slices by freeze drying at heating plate temperatures 30°, 45° and 55°C at 10-1 mbar to 50 % moisture content, then treated by microwaves at 637 W for 30, 40, 50, 60 and 70 s and finally dried to 5% moisture content by two drying methods namely, vacuum (45°C for 5 h) and air (50°C for 5 h). They concluded that during freeze drying, the rate of drying was temperature dependent and drying at lower temperature should be preferred. The sublimation process ceases at moisture content 45-50%.



**Figure 2.1.** Osmotic dehydration process

### 2.3.6. Microwave Assisted Drying

The application of microwave energy to dry roots is becoming more popular as it is a good approach for coping with certain drawbacks of conventional drying. In microwave heating, microwaves penetrate to the interior of food and heat is generated by absorption of electromagnetic radiation by dipolar molecules like water and fat present in foods to be heated. The microwave radiation is transformed into kinetic energy, which makes water molecules vibrate intensively causing friction and leading to rapid increase in temperature and consequently efficient water evaporation. This results in a greatly increased vapor pressure differential between the center and surface of the product, allowing fast transfer of moisture out of the food. Hence, microwave drying is rapid, more uniform and energy efficient compared to conventional hot air drying. The problems in microwave drying, however, include product damage caused by excessive heating due to poorly controlled heat and mass transfer ([Datta 1990](#); [Ramaswamy et al., 1991](#)). Guna-



sekarang ([Gunasekaran 1999](#)) proposed two strategies to apply microwaves effectively for drying and they are by creating a vacuum in the dryer to lower the drying temperature and applying microwave in a pulsed manner to maximize drying efficiency. In recent years, microwave-vacuum drying (MVD) has been investigated as a potential method for obtaining high quality dried food products. Microwave-vacuum drying combines the advantages of both vacuum drying and microwave heating. The low temperature and fast mass transfer conferred by vacuum combined with rapid energy transfer by microwave heating leads to rapid and low temperature drying and thus it has the potential to improve energy efficiency and product quality. Some roots have been successfully dried by microwave-vacuum drying techniques. The effect of vacuum in microwave drying operation is system specific and for successful design and operation of an industrial microwave-vacuum drying system, knowledge of the drying characteristics of the material under different conditions is important ([Drouzas and Schubert, 1996](#); [Durance and Wang, 2002](#); [Cui, 2003](#)). This reduces the time required for complete drying by more than 30% as compared to conventional methods [35]. Some researchers have reported the microwave vacuum drying studies of roots like garlic, carrots, potato, and parsley root and showed that microwave vacuum drying can be used to dry the roots for better product quality ([Sutar and Gupta, 2007](#); [Sobiech, 1980](#); [Yongsawatdigul and Gunasekaran, 1996a](#); [Kiranoudis et al., 1997](#); [Krokida and Maroulis, 1999](#); [Cui, 2004](#)). [Cui et al. \(2003\)](#) investigated combination of microwave-vacuum drying and air-drying as a potential mean for drying garlic slices. They concluded that the quality of garlic slices dried by these combination methods was close to that of freeze dried product and much better than those of hot air dried products. [Lin et al. \(1998\)](#) dried carrot slices by microwave vacuum drying and compared product quality to air and freeze dried carrots. They found that the microwave vacuum dried carrot slices had higher rehydration potential, higher  $\alpha$ -carotene and vitamin C content, lower density, and softer texture than those prepared by air drying. They also reported that less color deterioration occurred for vacuum-microwave drying. Although freeze drying of carrot slices yielded a product with improved rehydration potential, appearance, and nutrient retention, the microwave vacuum dried carrot slices were rated as equal as or better than freeze dried (FD) samples by sensory panel for color, texture, flavor and overall acceptability, in both the dry and rehydrated state.

Another approach to use microwaves is combining them with conventional hot air drying. Microwaves help to enhance the rate of moisture removal during hot air drying by evaporating moisture within product that generates additional pressure gradient for moisture movement. Researchers have attempted microwave convective drying of carrots, potatoes, garlic and onions. [Bouraoui et al. \(1994\)](#) dried potato slices using combined microwave and convective drying and concluded that microwave drying had a potential for producing better quality dried product than convective drying alone. The drying time was reduced considerably that is 10 min with microwave-convective drying as compared to 10 h in convective drying. No case hardening was observed and shrinkage was less than that found in convective drying. [Pravanjan et al. \(1995\)](#) evaluated the drying characteristics of carrot cubes by microwave hot air drying and reported that the microwave drying results in a substantial decrease (25-90%) in the drying time and better product quality than conventional hot air drying. [Sharma and Prasad \(2001\)](#) dried garlic cloves by combined microwave convective drying technique. They reported that



the microwave convective drying results in saving to an extent of about 91% of total drying time. Good quality dried garlic cloves were also obtained by the microwave convective drying technique. The details of microwave drying of various roots are given in [Table 2.3](#).

### 2.3.7. IR Drying

One of the ways to shorten the drying time is to supply heat by infrared radiation. This method of heating is especially suitable to dry thin layers of material with large surface exposed to radiation. Infrared radiation is transmitted through water at short wavelength, while at long wavelength; it is absorbed on the surface ([Sakai and Hanzawa, 1994](#)). Hence, drying of thin layers seems to be more efficient at far-infrared radiation-FIR (25–100  $\mu\text{m}$ ), while drying of thicker bodies should give better results at near-infrared radiation-NIR (0.75–3.00  $\mu\text{m}$ ) ([Sharma et al., 2005](#)). [Sharma et al. \(2005\)](#) dried onion slices at infrared power levels 300, 400 and 500 W, drying air temperatures of 35°, 40° and 45°C and inlet drying air velocities 1.0, 1.25 and 1.5 m/s. They reported that drying time reduced by about 2.25 times on increasing infrared power from 300 to 500 W, air temperature 35° to 45°C and air velocity from 1.0 to 1.5 m/s. Effective moisture diffusivity was significantly influenced by infrared power and air temperature. [Baysal et al. \(2003\)](#) dehydrated carrots in a tray drier at 70 °C with 0.86 m/s air velocity, in microwave oven at power density of 6 W/g (60 s power on and power off for 15 s) and by infrared drying at different time temperature combinations of 105°C for 15 min, 100°C for 30 min and 95°C for 40 min. The Infrared dehydrated carrot had the best rehydration capacity.

### 2.3.8. Vacuum Drying

Vacuum drying is an effective way to dry heat-sensitive roots having oxidative properties. Roots are dried in vacuum chamber having pressure less than 100 kPa at different temperatures. The heat is transferred by radiation or conduction to the product in vacuum. The lower pressure allows the moisture removal from roots at low temperature by preserving the quality. The vacuum drying parameters of carrot and ginger are given in [Table 2.3](#). [Madamba and Bekki, \(2001\)](#) studied the effect of vacuum level, slice thickness and drying air temperature on final product quality and drying rate for carrots. They used slices of 1, 2 and 3 mm and drying air temperatures of 65°, 70° and 75°C at 5, 10 and 15 kPa vacuum pressures. They found that final moisture content is affected by all the variables, average drying rate is affected by thickness while overall acceptability of product by pressure and thickness. The optimum drying conditions of 68°C and 10 kPa for drying 1.6 mm strips were established by them.

### 2.3.9. Hybrid Drying

The use of hybrid drying technologies is another approach to combine the advantages of different drying methods which are in practice. The combination of the osmotic dehydration and hot air drying is one of the important hybrid drying techniques. The osmotic dehydration of roots prior to hot air drying partially removes water and thus reduces water removal load at the dryer. Also, solute gain creates elevated temperature during hot air drying resulting in faster drying rates as well as solid uptake by the root pieces modify the composition (sugar to acid ratio), prevent the enzymatic and oxidative browning, and improves the sensory attributes (colour, flavour, texture, taste and over-

all acceptability) of the final product. Roots like onions can be dried using combination of osmotic dehydration and fluidized bed drying to get the better quality dehydrated onions with less energy consumption ([Sutar et al., 2007](#)). Recently, osmotic dehydration is combined with microwave drying. Microwave vacuum drying of osmotically pre-treated roots combines the benefits of both the operations and high quality product can be obtained. The combined osmotic and microwave drying results in more homogeneous heating of the product by modification of its dielectric properties due to the solute uptake, slightly reduced drying time, reduced shrinkage, high porosity and improved rehydration characteristics ([Ulrich and Schubert, 2001](#); [Torrington et al., 2001](#)). Literature shows some studies on the combined osmotic microwave vacuum dehydration of carrots and potatoes ([Sutar et al., 2007](#); [Sutar et al., 2008](#)). The value addition in the orange coloured carrots can be done by increasing its sweetness using osmotic pre-concentration and further it can be dried by microwave vacuum drying. The probable benefit of the osmotic pre-treatment using sucrose solution is simultaneous sugar gain and osmotic dehydration which reduces the water removal load during finish drying by microwave vacuum drying. The hybrid drying techniques of roots involve low energy unit operations and result into high quality product ([Yao and Le Maguer, 1997](#)).

## **2.4. MODELING ROOT DRYING PROCESS**

### **2.4.1. Modeling Osmotic Dehydration Process of Roots**

During osmotic dehydration, two resistances oppose mass transfer, one internal and the other external. The fluid dynamics of the solid fluid interface governs the external resistance whereas, the much more complex internal resistance is influenced by cell tissue structure, cellular membrane permeability, deformation of root pieces and the interaction between the different mass fluxes. Under the usual treatment conditions, the external resistance is negligible compared to the internal one. Variability in biological product characteristics produces major difficulties regarding process modeling and optimization. Mass transfer is affected by variety, maturity level and composition of product. The complex non-homogenous structure of natural tissues complicates any effort to study and understand the mass transport mechanisms of several interacting counter current flows (water, osmotic solute, soluble product solids). Literature shows the two basic approaches to model osmotic dehydration processes: macroscopic approach and microscopic approach ([Sutar et al., 2008](#)).

#### **2.4.1.1. Macroscopic approach**

The macroscopic approach assumes the tissue is homogeneous and the modelling is carried out on the lumped properties of cell wall, cell membrane and cell vacuole ([Yao and Le Maguer, 1997](#); [Azura et al., 1992](#)). The models available in literature can be classified under the following approaches:

1. Estimation of diffusion coefficients for water loss and solid gain by using Fick's second law of diffusion.
2. Estimation of water loss and solid gain as a function of time, temperature and initial concentration of the medium (Empirical models).
3. Based on cellular structure according to non-reversible thermodynamic principles.

4. Prediction of equilibrium moisture loss and solid gain on the basis of short period data.
5. Pressure gradient dependent modeling accounting the capillary and external pressure effects (Hydrodynamic mechanism).
6. Artificial Neural Network (ANN) modeling
7. Statistical modeling like stochastic approach, Weibull probabilistic distribution and multiple regressions.

The above models can be used in osmotic dehydration process of roots.

#### **2.4.1.2. Microscopic approach**

The microscopic approach recognizes the heterogeneous properties of the tissue and the complex cellular structure is represented by a simplified conceptual model ([Yao and Le Maguer, 1998](#)). As the solute penetrates the plant tissue, the internal cellular structure changes. The modeling of the cellular structural is attempted by very few researchers.

[Yao and Le Maguer \(1998\)](#) studied the multi-component mass transfer in biological tissues immersed in concentrated solutions. They developed a conceptual model to represent the cellular structure of a tissue consisting of individual cells embedded in a continuous cell wall matrix. The conceptual model comprised basically two layers that represent the intracellular and extra cellular volumes, and a semi permeable membrane that separates the two layers. The concept of volume average concentration and pressure within the intracellular volume was used to represent the discontinuous properties of the concentration and pressure as a continuous function of position. A mathematical model was developed that incorporates diffusion, bulk-flow, trans-membrane flux and shrinkage of the matrix. [Yao and Le Maguer \(1996\)](#) developed models by taking in to consideration the material properties like diffusivity, tortuosity and porosity, properties of the solution like density, diffusivity and viscosity and process conditions like temperature and shape of the sample with shrinkage consideration. In their models, water flow and advance of solute front as well as equilibrium conditions were calculated.

#### **2.4.1.3. Mass transfer kinetics during osmotic dehydration**

A mathematical model developed by [Azulara et al. \(1992\)](#) is being used by used by several researchers to study the mass transfer in osmotic dehydration of roots like onions, carrots, potatoes etc. The various parameters considered for the model are moisture loss at any time ( $ML_t$ ), moisture loss at equilibrium ( $ML_\infty$ ), solid gained at any time ( $SG_t$ ), solids gained at equilibrium ( $SG_\infty$ ) and the time of osmotic dehydration ( $t$ ). The models are as follows:

*For moisture loss:*

$$ML_t = \frac{S_1 t (ML_\infty)}{1 + S_1 t} = \frac{(ML_\infty)t}{\frac{1}{S_1} + t} \quad (2.1)$$

$$\frac{t}{ML_t} = \frac{1}{S_1 (ML_\infty)} + \frac{t}{ML_\infty} \quad (2.2)$$

For solid gain:

$$SG_t = \frac{S_2 t (SG_\infty)}{1 + S_2 t} = \frac{(SG_\infty)t}{\frac{1}{S_2} + t} \quad (2.3)$$

$$\frac{t}{SG_t} = \frac{1}{S_2 (SG_\infty)} + \frac{t}{SG_\infty} \quad (2.4)$$

The plots of  $\frac{t}{ML_t}$  vs.  $t$  and  $\frac{t}{SG_t}$  vs.  $t$  would be linear; the parameters could be determined from the intercept and slope. The Eqs. 2.1 and 2.3 could then be used to predict the mass transfer kinetics.  $S_1$  and  $S_2$  are the constants related to the rates of water and solid diffusion, respectively. The terms indicate that  $\frac{1}{S_1}$  or  $\frac{1}{S_2}$  represent the time required for half of the diffusible matter (water or solids) to diffuse out or enter in the product, respectively. Further, as the time  $t$  becomes much longer (that is,  $t \rightarrow \infty$ ) than the values of  $\frac{1}{S_1}$  or  $\frac{1}{S_2}$ , the water loss or the solid gain,  $ML_t$  or  $SG_t$ , approaches equilibrium value,  $ML_\infty$  or  $SG_\infty$ , asymptotically.

In above equations, the values of parameters  $S_1$ ,  $ML_\infty$ ,  $S_2$  and  $SG_\infty$  can be estimated from short duration osmotic kinetic data by performing linear regression or graphical plotting of the above equations in the linearized form.

#### 2.4.2. Modeling water and solid diffusion using transient solution of Fick's law of diffusion

The mathematical models used to describe mass transfer during osmotic dehydration are usually based upon various solutions to Fick's Law of Diffusion. The solution applies to unsteady one dimensional transfer between a plane sheet and a well stirred solution with a constant surface concentration, that is, infinite or semi-infinite medium. The following Fick's unsteady state diffusion model (Eq. 2.5) can be applied to describe the osmosis mechanism:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial Z^2} \quad (2.5)$$

The effective diffusivity can be determined by solving the above Fick's diffusion model using Newton Raphson method and Crank-Nicholson method ([Yao and Le Maguer, 1996](#)). There are some analytical solutions of Eq. 2.5 and are given by [Crank \(1979\)](#) for several geometries and boundary conditions. With the uniform initial water and solute concentration, the boundary conditions for a negligible external resistance and varying bulk solution concentration with the time, analytical solution of Fick's equation for infinite slab geometry being placed in a stirred solution of limited volume is given below by Eqs. 2.6 and 2.7 for moisture loss and solute gain, respectively.

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2 q_n^2} \exp\left[\frac{-D_{ew} q_n^2 t}{l^2}\right] \quad (2.6)$$

$$SR = \frac{S_t - S_e}{S_0 - S_e} = \sum_{n=1}^{\infty} \frac{2\alpha(1+\alpha)}{1+\alpha+\alpha^2q_n^2} \exp\left[\frac{-D_{es}q_n^2 t}{l^2}\right] \quad (2.7)$$

where, MR is the moisture ratio, SR is solid ratio,  $M_t$  is moisture in product at any time  $t$ (g),  $S_t$  is solids in the product at any time  $t$ (g),  $M_e$  is the equilibrium moisture in the product (g),  $S_e$  is the equilibrium solid in product (g),  $M_0$  is the initial moisture in the product (g),  $S_0$  is the initial solid in the product (g),  $D_{ew}$  is the effective water diffusivity in the product,  $D_{es}$  is effective solid diffusivity in the product,  $t$  is the time of osmosis (min),  $l$  is the half thickness of the slab (m) and  $q_n$  are the non-zero positive roots of the equation:

$$\tan q_n = -\alpha q_n \quad (2.8)$$

and

$$\alpha = m \frac{V_L}{V_s} \quad (2.9)$$

where,  $m$  is the partition coefficient and is defined as:

$$m = \frac{C_{\infty}^L}{C_{\infty}^S} \quad (2.10)$$

where,  $C_{\infty}^L$  is volumetric solute concentration (kg of solute/m<sup>3</sup>) in solution at infinite time and  $C_{\infty}^S$  is volumetric solute concentration (kg of solute/m<sup>3</sup>) in the product at infinite time.

Based on the model given by [Crank \(1979\)](#), [Azuara et al. \(1992\)](#) presented an expression from which the diffusion coefficient ( $D$ ) can be calculated at different times during the osmotic process:

$$D = \frac{\pi L^2}{4t} \left[ \left( \frac{St}{1+St} \right) \left( \frac{X_{\infty th}}{X_{\infty ex}} \right) \right]^2 \quad (2.11)$$

where,  $S$  is the constant related to the rate of ML or SG,  $X_{\infty th}$  is theoretical equilibrium value for ML or SG and  $X_{\infty ex}$  is experimental equilibrium value for ML or SG.

### 2.4.3. Modeling Drying Kinetics and Moisture Diffusivity during Root Drying

The literature shows the several theoretical, semi-theoretical and empirical models to study the drying kinetics during drying of foods. The most commonly used models are shown in [Table 2.4](#). In the analysis of falling rate drying period, a simple diffusion model based on Fick's second law of diffusion can be considered for the evaluation of moisture transport, which is given by the following equation ([Karathanos et al., 1990](#)).

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial M}{\partial x} \right) \quad (2.12)$$

**Table 2.4.** Mathematical models used to test the drying kinetics of roots

Model Name	Model	Reference
<b>Newton</b>	$MR = \exp(-kt)$	( <a href="#">Liu et al., 1997</a> ; <a href="#">Nellist, 1987</a> )
<b>Page</b>	$MR = \exp(-kt^n)$	( <a href="#">Agrawal and Singh, 1977</a> ; <a href="#">Bruce, 1985</a> )
<b>Henderson and Pebis</b>	$MR = a \exp(-kt)$	( <a href="#">Pal and Chakraverty, 1997</a> ; <a href="#">Rahman and Perera, 1996</a> )
<b>Two-Term</b>	$MR = a \exp(bt) + c \exp(dt)$	( <a href="#">Henderson, 1974</a> )
<b>Asymptotic Logarithmic</b>	$MR = a \exp(-kt) + b$	( <a href="#">Yaldyz and Ertekyn, 2001</a> )
<b>Wang and Singh</b>	$MR = 1 + at + bt^2$	( <a href="#">Wang and Singh, 1978</a> )
<b>Diffusion approximation</b>	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	( <a href="#">Henderson, 1974</a> )
<b>Two term Exponential</b>	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	( <a href="#">Wang and Singh, 1978</a> )
<b>Verma et. al.</b>	$MR = a \exp(-kx) + (1-a) \exp(-gt)$	( <a href="#">Verma et al., 1985</a> )
<b>Modified Henderson and Pabis</b>	$MR = a \exp(-kx) + b \exp(-gx) + c \exp(-gx)$	( <a href="#">Karathanos and Bessiotis, 1999</a> )

where,  $M$  is the free moisture content (kg water/kg dry matter),  $t$  is time (s),  $x$  is diffusion path or length (m) and  $D$  is moisture dependent diffusivity ( $m^2/s$ ). The diffusivity varies considerably with moisture content of the food and can be estimated by analyzing the drying data using the “method of slopes” technique.

For an infinite slab being dried from both sides and with the assumptions of (i) uniform initial moisture distribution throughout the mass of the sample and (ii) negligible external resistance to mass transfer, the following initial and boundary conditions are to be fixed for a solution of Eq. 2.12.

$$M = M_0 \text{ at } t = 0 \text{ for all } L$$

$$M = M_s = M_e \text{ at } t > 0, x = \pm L/2 \text{ at the surface}$$

where,  $M_0$  is the initial moisture content;  $M_s$  is the moisture content at the surface;  $M_e$  is the equilibrium moisture content and  $L$  is the thickness of the slab.

The solution of Eq. 2.12 for constant moisture diffusivity ( $D$ ) in an infinite slab is given by Eq. 13.

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[ -(2n+1)^2 \frac{\pi^2 Dt}{4l^2} \right] \quad (2.13)$$

where,  $l$  is half thickness of slab.

When the drying time becomes large and  $n > 1$ , Eq. 2.13 can be reduced to the following form after neglecting all other terms of right hand side except the first one.

For infinite slab

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left(-\frac{D\pi^2 t}{4l^2}\right) \quad (2.14)$$

The eq. 2.13 is evaluated numerically for Fourier number ( $F_0 = D.t / l^2$ ).

The diffusivity calculated would be a lumped value called apparent moisture diffusivity ( $D_a$ ) incorporating factors that are not considered separately but would affect the drying characteristics. During drying, moisture transport takes place by one or more combinations of the liquid diffusion, vapor diffusion, internal evaporation and surface diffusion. Since the exact mechanism of moisture transport is not known, an apparent diffusivity,  $D_a$ , instead of the true diffusivity, should be considered in equation 14. Therefore, the above equation is simply a model with empirical values for apparent diffusivity and not true diffusivity ([Sutar et al., 2007](#)).

## 2.5. Quality Evaluation of Dehydrated Root Products

The quality of dehydrated roots is usually accessed by rehydration characteristics, colour, shrinkage and density, texture, chemical and sensory quality. Several deteriorative reactions that affect these properties of dehydrated root products are initiated during pre-processing and dehydration operations, and continue during storage at a rate that is influenced by storage conditions. The above properties of roots are discussed in foregoing sections.

### 2.5.1. Rehydration Characteristics

The rehydration process is aimed at the restoration of raw material properties when dried materials are conducted with water. During rehydration process, the dry porous material submerged in water undergoes several simultaneous changes ([Krokida and Philippopoulos, 2005](#)). All the dehydrated root products are generally rehydrated in water at 25° and 100°C. During rehydration substantial amount of soluble solids can leach to solution, which may affect the nutritional quality of the products and simultaneously its ability to imbibe water ([Lewicki, 1998](#)). Hot air dried roots generally show rehydration ratio in the range 1:4 to 1:6 whereas microwave vacuum dried roots show very high rehydration ratio up to 1:10. Rehydration characteristics are affected by pre-treatment as well as method of drying. Osmotically dehydrated roots exhibit lower rehydration ratio than roots dried without osmotic pre-treatment. It is due to dissolution of salt/sugar during rehydration process ([Sutar et al., 2007](#)). [Lin et al. \(1998\)](#) dried the carrot slices by air, microwave vacuum and freeze drying methods and found that the microwave vacuum dried carrots shows higher rehydration ratio than air dried and lower than freeze dried carrots. They concluded that during the microwave vacuum drying the high internal vapour pressure generated by microwave heating and the low chamber pressure provided by vacuum caused the structure of carrot slices to expand and puff. Due to this puffing effect a less dense structure had higher capacity to absorb water when reconstituted.



### 2.5.2. Colour

Colour is an important criterion of acceptability of dehydrated root products. Dehydrated roots lose colour due to the oxidation of highly unsaturated molecules upon exposure to air. The measurement of colour is usually done by colorimetric techniques where the spectrum of light produced by an instrument and reflected on the products surface is analyzed. Colour is a three dimensional characteristics of appearance consisting of a lightness attributes, often called "Value", and two chromatic attributes, called "Hue" and "Chroma". Colour can be distinguished from one another by specifying these three attributes ([Giri, 2007](#)). Colour difference ( $\Delta E$ ) as described by Eq. 2.15 is used to describe the colour of dehydrated roots:

$$\Delta E = [(L-L^*)^2 + (a-a^*)^2 + (b-b^*)^2]^{0.5} \quad (2.15)$$

$\Delta E$  indicates the degree of overall colour change of a sample in comparison to colour values of an ideal sample having colour values of  $L^*$ ,  $a^*$  and  $b^*$ . Fresh roots are taken as ideal sample. Various methods of drying show significant effect on colour retention of dehydrated roots. Also, pre-treatments like blanching and osmotic dehydration helps to decrease the  $\Delta E$  values ([Krokida and Maroulis, 2000](#)). [Lin et al. \(1998\)](#) observed that the air dried carrot slices were darker, with less red and yellow hues than the freeze dried and microwave vacuum dried samples. The freeze dried samples had the highest degree of lightness with a slightly lower yellow hue than that of microwave vacuum dried samples. They concluded that the darker appearance of the air dried and microwave vacuum dried carrot slices compared to the freeze dried samples may be due to the exposure to heat during drying. According to [Howard et al. \(1996\)](#), the lightness of carrot was also affected by processing temperatures with higher temperatures causing darker colour.

### 2.5.3. Shrinkage and Density

Roots undergo volumetric changes upon water loss which is expressed as shrinkage. Such modifications occurring during drying process affect the moisture transport properties as well as structure of the product ([Hatamipour and Mowla, 2002](#)). Some of the researchers have shown a linear relation for shrinkage of foods as a function of moisture content. However, it is observed that there is no direct correlation between shrinkage and the amount of water evaporated. Rather the shrinkage behaviour is different for various systems, dependent on the material type, the characteristic cell and tissue structure, and also operating conditions ([Baysal, 2003](#); [Hatamipour and Mowla, 2002](#))

Roots classified as capillary porous are known to undergo volume changes upon uptake or loss of water. During drying, when there is loss of water, the volume change is expressed as shrinkage. Shrinkage is often considered negligible during modeling of the root drying processes. However, shrinkage is seldom negligible in these foods. [Rahman \(2001\)](#) presented various theories explaining the process of shrinkage and collapse during drying. Among the various factors affecting pore formation such as glass transition temperature, surface tension, structure, environmental pressure and mechanism of moisture transport, he hypothesized that the capillary force (suction) created by a receding liquid meniscus is the main force of collapse and counterbalancing this force causes formation of pores and lower shrinkage. The counterbalancing force could be strengthening the solid matrix (ice formation, case hardening, and matrix reinforcement), generation of internal pressure, mechanism of moisture transport, and environ-



mental pressure. Thus, the extent of shrinkage also depends upon methods and rate of drying, and drying environments like presence of air, vacuum or any inert gas ([Ratti, 1994](#); [Wang and Brennan, 1995](#); [Rahman and Perera, 1999](#)). Shrinkage affects the physical properties of materials such as bulk density and porosity. Changes in shape and size during drying modify both the dimensions and transport properties of individual particles and also thickness and porosity of the packed bed in the dryer ([Ratti, 1994](#); [Karithanos and Saravacos, 1993](#)). A study of the shrinkage phenomena is thus important for a better understanding of the drying process and to control the characteristics of the product. Shrinkage, density and porosity of garlic during drying were investigated by [Madamba et al. \(1994\)](#). Shrinkage was based on dimensional changes in garlic slabs and it was found to be fiber-oriented and different from the reported isotropic shrinkage of fruits and vegetables. They also proposed a general density model.

#### **2.5.4. Texture**

A compression test is one of the most common techniques for the estimation of the texture of dehydrated roots. The simplest approach is to measure the maximum applied force or stress at fracture of the root. The quantification of difficult terms such as hardness and chewiness has been made by a methodology called Texture Profile Analysis. Texture analyzer fitted with a load cell is used for textural analysis of the dehydrated roots. Compression test is carried out to generate a plot of force (N) vs. time (s) which is used to obtain hardness values. Compression plate is used to compress the dehydrated root slice to 30% of its original thickness. The pre-speed as well as post-speed of the probe are to be fixed during compression. For dehydrated slices, only hardness value is relevant. The hardness is expressed as peak force (N) in the first compression. The probes of various diameters are generally available with various texture analyzers. For rehydrated roots, puncture test is to be performed. Researchers have reported that osmotic pre-treatment to root can increase the hardness of root due to solid gain. Also microwave drying can result in to less hardness values ([Sutar et al., 2007](#); [Krokida and Maroulis, 2000](#)).

#### **2.5.5. Scanning Electron Microscopy (SEM)**

All drying techniques destroy or change the native structure with little hope of it being fully regained. Drying causes cells to rupture and dislocate which usually results in a dense, collapsed structure with varying porosity. Products with higher porosity have a higher rehydration value and moisture diffusivity also increases with porosity ([Marabi and Saguy, 2004](#)). The microstructure of roots dried by various techniques is observed to improve our understanding of the effect of drying on morphology. The structure of the dehydrated root sections is examined using a scanning electron microscope (SEM). Thin slices of dehydrated roots are cut and fixed on the SEM stub, which are subsequently coated with gold in order to provide a reflective surface for the electron beam. Gold coating is carried out in a sputter coater (BIO-RAD E-5200) under a low vacuum with the presence of the inert gas (argon). The gold coated samples are subsequently viewed under the scanning electron microscope ([Giri and Prasad, 2007](#)).

#### **2.5.6. Sensory Quality**

The sensory evaluation of dried root samples is carried out by panel of 50 members. The panelists are given a proforma for sensory evaluation and asked to indicate their

preference for each sample based on the quality attributes such as taste and overall acceptability. On 9-point hedonic scale, where 9 denotes "liked extremely" and 1 "disliked extremely" are used for all the attributes to be evaluated ([Ranganna, 1986](#)). Freeze dried roots possess a preferable appearance, which may be due to the excellent structural retention. Recent research trend shows that the microwave vacuum dried roots receive significantly higher ratings for texture and overall acceptability, and can be rated as high as freeze dried samples for colour and aroma/flavour by sensory panel. Colour, appearance, texture, aroma or flavour and overall acceptability of air dried carrot slices are greatly improved when rehydrated. Non-significant differences in texture and overall acceptability among the rehydrated microwave vacuum, air and freeze dried carrot samples is reported in literature ([Lin et al., 1998](#)).

### 2.5.7. Chemical Quality

Chemical quality of dehydrated roots includes the retention of vitamins (Vit. C, Carotenoids), sugars (total and reducing sugars) and other specific components for which root is used. Majority of dehydrated roots are analyzed for the retention of above chemical components. The various drying methods significantly affect the retention of ascorbic acid and  $\beta$ -carotene since the drying temperature degrades these vitamins. [Sutar et al. \(2007\)](#) studied effect of drying temperature on ascorbic acid and sugars retention of onions. They found that vit. C degradation takes place at higher drying temperature. [Lin et al. \(1998\)](#) compared the retention of  $\beta$ -carotene and ascorbic acid in the carrots dried by different techniques like air drying, freeze drying and microwave vacuum drying and found that the microwave vacuum dried carrots retained the  $\beta$ -carotene and ascorbic acid more than air dried and less than freeze dried. [Hawldar et al. \(2006\)](#) studied retention of 6-gingerol at various drying operations. Their evaluation included dried samples obtained by heat pump, modified atmosphere heat pump, freeze drying, and vacuum drying. They reported retention of 6-gingerol increased in the order of normal air drying, freeze drying, nitrogen drying, carbon dioxide drying, and vacuum drying.

## 2.6. Research Needs in Root Drying

Literature shows drying data of selected roots like carrots, potatoes, onions and sweet potatoes, whereas, remaining roots are still to be explored for drying by new methods. The roots like Parsley, Chicory, Cassava, Ginseng etc. require drying studies using modern drying technologies. It is needed to study the effects of pre-treatments on drying kinetics as well as moisture diffusivity of the roots. Also, the simulation studies of several roots are not available which leaves ample scope for researchers. Further, the physico-chemical and nutritional quality is to be evaluated for several roots.

## References

Ade-Omowaye, B.; Rastogi, N. K.; Angersbach, A.; Knorr, D. Effects of high hydrostatic pressure or high intensity electrical field pulse pre-treatment on dehydration characteristics of red paprika. *Innovative Food Science Emerging Technologies* 2001, 2, 1-7.

Agrawal, Y. C.; Singh, R. D. Thin layer drying studies for short grain rice. ASAE, St. Joseph (MI), Paper 1977.

Alexander Essers, A. J.; Remco M. Van der Grift; Alphons G. J. Voragen. Cyanogen removal from cassava roots during sun-drying. *Food Chemistry* 1996, 55(4), 319-325.

Attiyate, Y. Microwave vacuum drying: first industrial application. *Food Engineering International* 1979, 4(1), 30-31.

Azuara, E.; Cortes, R.; Garcia, H.S.; Speck Berstian C.I. Kinetic model for osmotic dehydration and its relationship with Fick's second law. *International Journal of Food Science and Technology* 1992, 27, 409-418.

Baysal, T. ; Icier, F. ; Ersus, S. ; H., Yildiz. Effects of microwave and infrared drying on the quality of carrot and garlic. *European Food Research and Technology* 2003, 218, 68-73.

Baysal, T.; Icier, F.; Ersus, S.; Yildiz, H. Effects of microwave and infrared drying on the quality of carrot and garlic. *European Food Research and Technology* 2003, 218, 68-73

Bechoff, A.; Dufour, D.; Dhuique-Mayer, C.; Marouz Effect of hot air, solar and sun drying treatments on provitamin A retention in orange-fleshed sweetpotato. *Journal of Food Engineering* 2009, 92, 164-171.

Białobrzewski, I. Determination of the mass transfer coefficient during hot-air-drying of celery root, *Journal of Food Engineering* 2007, 78, 1388-1396.

Białobrzewski, I.; Markowski, M. Mass transfer in the celery slice: Effects of temperature, moisture content, and density on water diffusivity. *Drying Technology* 2004, 22, 1777-1789.

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

Bruce, D. M. Exposed-layer barley drying: three models fitted to new data up to 150 °C. *Journal of Agricultural Engineering Research* 1985, 32, 337-348.

Chaudhari, A.P; Kumbhar, B.K; Singh, B.P.N; Maharaj, N. Osmotic dehydration of fruits and vegetables – a review. *Indian Food Industry* 1993, 12 (1), 20-27

Crank, J. *The mathematics of diffusion*; Oxford University Press, USA, 1979.

Cui, Z.W.; Shi-Ying, X.; Sun, D.W. Effect of Microwave-Vacuum Drying on the Carotenoids Retention of Carrot Slices and Chlorophyll Retention of Chinese Chive Leaves, *Drying Technology* 2004, 22(3), 563 – 575

Cui, Z.W; Xu, S.Y; Sun, D.W. Dehydration of garlic slices by combined microwave-vacuum and air drying. *Drying Technology* 2003, 21(7), 1173-1184.

Datta, A.K. Heat and mass transfer in the microwave processing of food. *Chemical Engineering Progress* 1990, 86(6), 47-53.

Doymaz, I. Convective air drying characteristics of thin layer carrots. *Journal of Food Engineering* 2004, 61, 359–364.

Drouzas, A.E; Schubert, H. Microwave application in vacuum drying of fruits. *Journal of Food Engineering*, 1996, 28, 203–209.

Durance, T.D.; Wang, J.H. Energy consumption, density and rehydration rate of vacuum microwave and hot air convection dehydrated tomatoes. *Journal of Food Science* 2002, 67(6), 2212-2216.

Erenturk, K.; Erenturk, S.; Tabil, L.G. A comparative study for the estimation of dynamical drying behavior of *Echinacea angustifolia*: regression analysis and neural network, *Computers and Electronics in Agriculture* 2004, 45, 71-90.

Ertekin, F.K; Cakaloz, T. Osmotic dehydration of peas: I. Influence of process variables on mass transfer. *Journal of Food Processing and Preservation* 1996, 20(1), 105-119.

Galindo, F.G; Toledo, R.T; Sjöholm, I. Tissue damage in heated carrot slices Comparing mild hot water blanching and infrared heating. *Journal of Food Engineering* 2005, 67, 381-385.

Garnicki, K.; Kaleta, A. Drying curve modelling of blanched carrot cubes under natural convection condition. *Journal of Food Engineering* 2007, 82, 160-170

Ghosh, P.K; Agrawal, Y.C; Jayas, D.S; Kumbhar, B.K. Mass transfer kinetics model of osmotic dehydration of carrots. *Transactions of ASAE* 2004, 47(4), 1179-1185.

Giri, S.K. Microwave-Vacuum Drying of Button Mushroom (*Agaricus bisporus*), unpublished PhD Thesis 2007, Indian Institute of Technology Kharagpur India.

Giri, S.K.; Prasad, S. Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms. *Journal of food Engineering* 2007,78, 512-521.

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

Gunasekaran, S. Pulsed microwave-vacuum drying of food materials. *Drying Technology*, 1999, 17(3), 395-412.

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

Hawllader, M.; Perera, C. O.; Tian, M. Comparison of the retention of 6-gingerol in drying of ginger under modified atmosphere heat pump drying and other drying methods. *Drying Technology* 2006, 24, 51-56.

Henderson, S. M. Progress in developing the thin layer drying equation [for maize]. *Transactions of the ASAE* 1974, 17, 1167-1168/1172.

Howard, L.R.; Braswell, D.D.; Aselage, J. Chemical composition and color of strained carrots as affected by processing. *Journal of Food Science* 1996, 61, 327-330.

Islam, M.N; Flink, J.M. Dehydration of potato. II. Osmotic concentration and its effect on drying behaviour. *Journal Food Technology* 1982, 17(1), 387-392.

Jayaraman K.S.; Gupta, D.K. Dehydration of fruits and vegetables-recent developments in principles and techniques. *Drying Technology* 1992; 10, 1-50.

Kabganian, R.; Carrier, D.J.; Sokhansanj, S.; Physical Characteristics and Drying Rate of *Echinacea* Root. *Drying Technology* 2002, 20(3),637 - 649.

Karathanos, V. T.; Belessiotis, V. G. Application of a thin-layer equation to drying data of fresh and semi-dried fruits. *Journal of Agricultural Engineering Research* 1999, 74, 355-361.

Karathanos, V.T., Villalobos, G; Saravacos, D.G. Comparison of two methods of estimation of the effective moisture diffusivity from drying data. *Journal of Food Science* 1990, 55(1), 218-231.

Karathanos, V.T.; Saravacos, G.D. Porosity and pore size distribution of starch materials. *Journal of Food Engineering* 1993, 18 (3), 259-280.

Karathanos, V.T; Kostaropoulos, A.E; Saravacos, G.D. Air-drying behaviour of osmotically dehydrated fruits. *Drying Technology* 1995,13 (5), 1503-1509.

Kashaninejad, M.; Tabil, L. G. Drying characteristics of purslane (*Portulaca oleraceae* L.). *Drying Technology* 2004, 22, 2183-2200.

Kays, S.J.; Silva Dias, J.C. *Cultivated Vegetables of the World*. 1996, Exon Press, Athens,GA.

Khraisheh, M.; Cooper, T.; Magee, T. Shrinkage characteristics of potatoes dehydrated under combined microwave and convective air conditions. *Drying Technology* 1997, 15, 1003-1022.

Kim, S. J.; Murthy, H. N.; Hahn, E. J.; Lee, H. L.; Paek, K. Y. Effect of processing methods on the concentrations of bioactive components of ginseng (*Panax ginseng* CA Meyer) adventitious roots. *LWT-Food Science and Technology* 2008, 41, 959-964.

Kiranoudis, C.T.; Tsami, E; Maroulis, Z.B. Microwave vacuum drying kinetics of some fruits. *Drying Technology* 1997,15(10), 2421-2440.

Krokida, M. K.; Philippopoulos, C. Rehydration of Dehydrated Foods. *Drying Technology* 2005, 23(4): 799-830.

Krokida, M.; Maroulis, Z. Quality changes during drying of food materials. *Drying Technology in Agriculture and Food Sciences* 2000: 61-98.

Krokida, M.K; Maroulis, Z.B. Effect of microwave drying on some quality properties of dehydrated products. *Drying Technology* 1999,17(3), 449-466.

Lebovka, N. I.; Shynkaryk, N. V.; Vorobiev, E. Pulsed electric field enhanced drying of potato tissue. *Journal of Food Engineering* 2007, 78, 606-613.

Lewicki, P. P. Effect of pre-drying treatment, drying and rehydration on plant tissue properties: a review. *International Journal of Food Properties* 1998, 1, 1-22.

Lewicki, P.; Lenart, A. Energy Consumption During Osmo-Convection Drying of Fruits and Vegetables. In *Drying of Solids*; Mujumdar, A.S, Ed., 1992, 354-366.

Lin, T.M.; Durance, T.D.; Scaman, C.H. Characterization of vacuum microwave, air and freeze-dried carrot slices. *Food Research International* 1998, 31(2), 111-117.

Litvin, S.; Mannheim, C.H; Miltz, J. Dehydration of Carrots by a Combination of Freeze Drying, Microwave Heating and Air or Vacuum Drying. *Journal of Food Engineering* 1998, 36, 103- 111.

Liu, Q.; Bakker-Arkema, F. W. Stochastic modelling of grain drying: Part 2. Model development. *Journal of Agricultural Engineering Research* 1997, 66, 275-280.

Lo, C. M.; Grn, I. U.; Taylor, T. A.; Kramer, H.; Fernando, L. N. Blanching effects on the chemical composition and the cellular distribution of pectins in carrots. *Journal of Food Science* 2002, 67, 3321-3328.

Madamba, P. S.; Driscoll, R. H.; Buckle, K. A. The thin-layer drying characteristics of garlic slices. *Journal of Food Engineering* 1996, 29, 75-97.

Madamba, P.S.; Bekki. E. Optimization of the vacuum dehydration of carrot (*Daucus carota* L.) strips. Paper Number: 01-6065. In proceedings of An ASAE Meeting CA, USA during July 30-August 1, 2001.

Madamba, P.S.; Driscoll, R. H.; Buckle, K. A. 1994. Shrinkage, density and porosity of garlic during drying, *Journal of Food Engineering*, 23(3): 309-319.

Madamba, P.S.; Driscoll, R. H.; Buckle, K. A. Shrinkage, density and porosity of garlic during drying, *Journal of Food Engineering* 1994, 23( 3), 309-319 .

Maini, S.B.; Brijesh, D.; Anand, J.C. Storage behaviour and drying characteristics of commercial cultivars of onion. *Journal of Food Science and Technology* **1984**, 21, 417-419.

Marabi, A.; Saguy, I.S. Effect of porosity on rehydration of dry food particulates. *Journal of the Science of Food and Agriculture* 2004, 84, 1105-1110.

Martynenko, A. I. Computer-Vision System for Control of Drying Processes. *Drying Technology* 2006 , 24(7), 879-888.

Mongpraneet, S.; Abe, T., Tsurusaki, T. Accelerated drying of welsh onion by far infrared radiation under vacuum conditions. *Journal of Food Engineering* 2002; 55, 147-156.

Munde, A.V.; Agrawal, Y.C.; Shrikande, V.J. Process development for multistage dehydration of onion flakes. *Journal of Agricultural Engineering* **1988**, 25 (1), 19-24.

Nellist, M. E. Modelling the performance of a cross-flow grain drier. *Journal of Agricultural Engineering Research* 1987, 37, 43-57.

Pal, U. S.; Chakraverty, A. Thin layer convection-drying of mushrooms. *Energy Conversion and Management* 1997, 38, 107-113.

Park, K. J.; de Oliveira, R. A.; Brod, F. Drying Operational Parameters Influence on Chicory Roots Drying and Inulin Extraction. *Food and Bioproducts Processing* 2007, 85, 184-192.

Pawar, V.N.; Singh, N.I.; Dev, D.K.; Kulkarni, D.N. and Ingle, U.M. Solar drying of white onion flakes. *Indian Food Packer* **1988**, Jan.-Feb., 15-28.

Ponting, J.D. Osmotic dehydration of fruits: recent modifications and applications. *Process Biochemistry* 1973, 8(12), 12-22.

Prakash, S.; Jha, S.K.; Datta, N. Performance evaluation of blanched carrots dried by three different driers. *Journal of Food Engineering* 2004, 62, 305-313.

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

Praveen, K. D.G.; Hebbar, H.U.; Ramesh, M.N. Suitability of thin layer models for infrared-hot air-drying of onion slices. *LWT-Food Science and Technology* 2006;39, 700-705.

Rahman, M. S.; Perera, C. O. Effect of pre-treatment on air drying rate and thin-layer drying characteristics of fresh cheery. *Proc. 10th Intl. Drying Symposium* 1996, 1053-1060.

Rahman, M.S. Towards prediction of porosity in foods during drying: a brief review. *Drying Technology* 2001, 19(1), 1-13.

Rahman, M.S.; Perera, C.O. Drying and Food Preservation. In *Handbook of Food Preservation*, Rahman, M.S., Ed., Marcel Dekker: New York 1999.

Rajkumar, P.; Sreenarayanan, V.V. Studies on dehydration and pre-treatment level to control browning and storage of onion flakes. *Journal of Food Science* **2001**, 38 (6), 625-628.

Ramaswamy, H.S; Wil, T.P; Fakhauri, M. Distribution and equalization of temperature in a microwave heated food model. ASAE paper No. 91-3518, ASAE, St. Joseph, MI 49085 1991

Ramesh, M.N; Wolf, W; Tevini, D; Bognár, A. Microwave blanching of vegetables. *Journal of Food Science* **2002**, 67(1), 390-398.

Ranganna, M.S. *Handbook of Analysis and Quality Control for Fruits and Vegetables Products* 1986, McGraw Hill Publishing Co. Ltd., New Delhi.

Ratti, C. Shrinkage during drying of foodstuffs. *Journal of Food Engineering* 1994, 25, 91-105.

Reyes, A.; Moyano, P.; Paz, J. Drying of Potato Slices in a Pulsed Fluidized Bed. *Drying Technology* 2007, 25(4), 581-590.

Sakai, N. and Hanzawa, T. Applications and advances in far-infrared heating in Japan. *Trends in Food Science and Technology* 1994, 5 (11), 357-362

Sarsavadia, P.N., Sawhney, R.L., Pangavhane, D.R., Singh, S.P. Drying behaviour of brined onion slices. *Journal of Food Engineering* 1999, 40, 219-226.

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

Sharma, G.P; Prasad, S. Drying of garlic (*Allium sativum*) cloves by microwave-hot air combination. *Journal of Food Engineering* 2001, 50, 99-105.

Singh, B; Panesar, P.S; Nanda, V; Gupta, A.K; Kennedy, J.F. Application of Response surface methodology for the osmotic d rehydration of carrots. *Journal of Food Process Engineering* 2006, 29, 592-614.

Singh, S.; Raina, C. S.; Bawa, A. S; Saxena, D. C. Effect of Pretreatments on Drying and Rehydration Kinetics and Color of Sweet Potato Slices. *Drying Technology* **2006**, 24, 1487-1494.

Sobiech, W. Microwave-vacuum drying of sliced parsley root. *Journal of Microwave Power* 1980, 15(3), 143-54.

Sokhansanj, S.; Bailey, W. G.; Van Daltsen, K. B. Drying of North American ginseng roots (*Panax quinquefolius* L.). *Drying Technology* 1999, 17, 2293-2308.

Speck, P., Escher, F.; Solms, J. Effect of salt pretreatment on quality and storage stability of air-dried carrots. *LWT-Food Science and Technology* 1977, 10, 308-313.

Srikiatden, J., Roberts, J.S. Moisture transfer in potato, apple and carrot (core and cortex) during convective hot air and microwave convective hot air drying. *IFT Annual Meeting-Chicago*, 2003.

Srikiatden, J.; Roberts, J.S. Measuring moisture diffusivity of potato and carrot (core and cortex) during convective hot air and isothermal drying. *Journal of Food Engineering* 2006, 74, 143-152.

Srikiatden, J.; Roberts, J.S. Predicting moisture profiles in potato and carrot during convective hot air drying using isothermally measured effective diffusivity. *Journal of Food Engineering* 2008; 84, 516-525.

Srikiatden, J.; Roberts, J.S.; Shene, C.; Cabezas, M. J. Bravo, S. Effect of Drying Air Temperature on Drying Kinetics Parameters and Fructan Content in *Helianthus tuberosus* and *Cichorium intybus*. *Drying Technology* 2003, 21(5), 945-956.

Sutar, P. P.; Prasad, S. Modeling Microwave Vacuum Drying Kinetics and Moisture Diffusivity of Carrot Slices. *Drying Technology* 2007, 25(10), 1695-1702.

Sutar, P.P. Combined Osmotic and Microwave Vacuum Dehydration of carrots, Unpublished PhD Thesis, Indian Institute of Technology Kharagpur, India 2008.

Sutar, P.P.; and Gupta, D.K. Mathematical Modeling of Mass Transfer in Osmotic Dehydration of Onion Slices. *Journal of Food Engineering* 2007, 78 (1), 90-97.

Sutar, P.P.; Prasad, S.; Gupta, D.K. Modeling Fluidized Bed Drying of Osmotically Dehydrated Onion Slices and Product Quality Evaluation. *Transactions of American Society of Agricultural and Biological Engineers* 2007, 51(2), 567-572.

Sutar, P.P.; Raghavan, G.S.V.; Garipey, Y.; Prasad, S. Optimization of Osmotic Dehydration of Potato Cubes Under Pulsed Microwave Vacuum Environment in Ternary Solution. In *Proceedings of 6th Asia Pacific Drying Conference - (ADC 2009)*, Bangkok, Thailand, 2009, 165-173.

Torrington, E.; Esveld, E.; Scheewe, I., Van den Berg, R.; Bartels, P. Osmotic dehydration as a pre-treatment before combined microwave-hot-air drying of mushrooms. *Journal Food Engineering* 2001, 49(2/3), 185-191.

Uddin, M.B; Paul, A; Ibanoglu, S. Evaluation of mass exchange during osmotic dehydration of carrots using response surface methodology. *Journal of Food Engineering* 2004, 65 (4), 473-477.

Ulrich, E.; Schubert, H. Combined osmotic and microwave- vacuum dehydration of apples and strawberries. *Journal of Food Engineering* 2001, 49, 193-199.



Verma, L. R.; Bucklin, R. A.; Endan, J. B.; Wratten, F. T. Effects of drying air parameters on rice drying models. *Transactions of the ASAE* 1985, 85, 296–301.

Wang, J. A Single-Layer Model for Far-Infrared Radiation Drying of Onion Slices. *Drying Technology* 2002, 20(10), 1941 -1953.

Wang, N.; Brennan, J.G. Changes in structure, density and porosity of potato during dehydration. *Journal of Food Engineering* 1995, 24, 61-76.

Wang, C. Y.; Singh, R. P. A single layer drying equation for rough rice. *ASAE, St. Joseph (MI)*, 1978, ASAE Paper No: 78-3001.

Yadav, A.R.; Guha, M.; Tharanathan, R.N.; Ramteke, R.S. Changes in characteristics of sweet potato flour prepared by different drying techniques, *LWT-Food Science and Technology*, 2006, 39 (1), 20-26.

Yaldyz, O.; Ertekyn, C. Thin layer solar drying of some vegetables. *Drying Technology* 2001, 19, 583-597.

Yao, Z.; Le Maguer M. Mathematical modeling and simulation of mass transfer in osmotic dehydration processes. Part I: Conceptual and mathematical models, *Journal Food Engineering* 1996, 29, 349-360.

Yao, Z.; Le Maguer, M. Mathematical modelling and simulation of mass transfer in osmotic dehydration processes. Part II: Simulation and model verification. *Journal of Food Engineering* **1997**, 32, 21-32.

Yao, Z.; Le Maguer, M. Possibility of using pseudo-diffusion approach to Model mass transfer in osmotic dehydration, *Transactions of ASAE* 1998, 41(2), 409-414.

Yongsawatdigul, J.; Gunasekaran, S. Microwave vacuum drying of cranberries: Part I: Energy use and efficiency. *Journal of Food Processing and Preservation* 1996a, 20, 121-143.



## **Chapter 3**

### **Innovations in Paddy Drying and Rice Parboiling Processes**

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### 3.1. INTRODUCTION

Rice, which is an important food crop in the world, can be categorized based on its amylose content into four groups, namely, high-amylose rice (> 25% amylose content), medium-amylose rice (20% < amylose content < 25%), low-amylose rice (10% < amylose content < 20%) and waxy rice (0 < amylose content < 2%). High- to medium-amylose rice is mainly consumed around the world, while waxy rice is consumed only in some of the South East Asian countries; however, waxy rice is widely used as a raw material for producing various kinds of food products such as sweets, desserts, rice cakes and rice crackers.

After harvesting, rice needs to be dried in order to avoid deterioration of its quality, mainly due to microorganisms and respiration. However, if the selected drying methods and conditions are not suitable, the supplied energy may be utilized ineffectively and the rice quality may be very poor. Crack formation inside rice kernels during drying is indeed an important problem in the rice industry. The cracked kernels may be broken during subsequent milling and thus decrease the head rice yield; this naturally leads to a significant loss of the commercial value of dried rice. In addition to cracks, drying can induce interactions amongst moisture and other components such as lipid, starch and proteins, which subsequently lead to changes in the physicochemical properties of rice; the susceptibility of rice to hydrolysis by amylase enzyme would also be altered and hence the modified glyceemic response of rice.

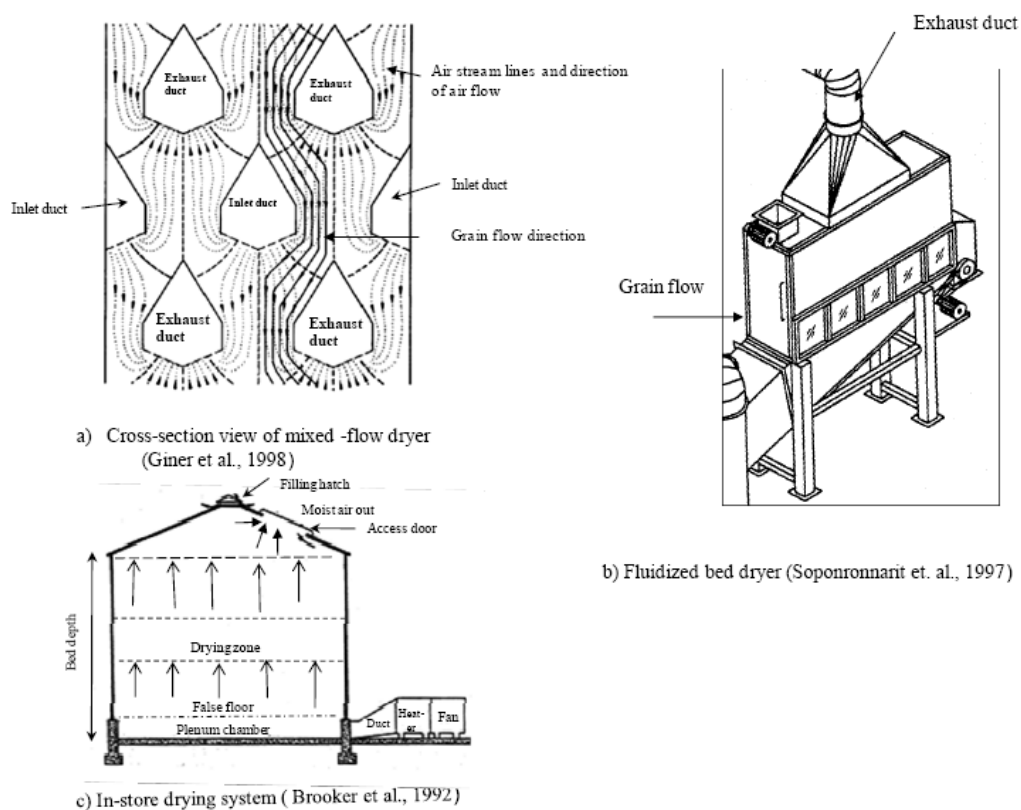
In order to obtain higher quality of rice with minimal energy consumption, selection of drying methods and conditions is very important. Suitable drying conditions can vary for different types of dryers; nevertheless, this chapter focuses mainly on fluidized bed drying of rice. The chapter firstly describes various grain dryer types as well as the working principles and performance of a fluidized bed grain dryer. This is followed by a brief discussion of a heat- and mass-transfer model as well as a model for head rice quality prediction. Applications of fluidized bed drying for waxy rice and the use of the technology to accelerate rice aging as well as to produce healthy rice with low-glyceemic response and parboiled rice are also discussed.

### 3.2. GRAIN DRYER TYPES

Convective drying of grains may be carried out using either continuous grain flow dryers or fixed bed grain dryers. Both techniques have certain advantages and disadvantages. The types of continuous grain flow dryers frequently used in Thailand are cross flow dryers, mixed flow dryers and fluidized bed dryers. Illustrations of the mixed flow and fluidized bed dryers are given in **Figure 3.1a** and **b**, respectively. A mixed flow dryer is designed to provide uniform heat treatment of grain when it flows down through the dryer. Mixed flow dryer has rows of ducts through which air is supplied to and removed from the moving grain bed. The ducts are aligned in a horizontal plane and every inlet duct is surrounded by four exhaust ducts. A part of air entering the grain bed below each inlet duct flows upwards and towards the two exhausts located above. A contact between the drying grain and the air in this area is called counter flow. The other part of the air moves downward to the two exhausts in the row located below, thus creating concurrent flow between the grain and the air. Drying temperature ranging

from 65 to 85°C is normally recommended for grains. The airflow rate of 45-78m<sup>3</sup>/min-ton grain is commonly used in this type of dryer.

A fluidized bed dryer differs from a mixed flow dryer in that grain kernels are suspended in the drying air; good contact between the kernels and the drying air is achieved. This allows a fluidized bed dryer to operate at a high temperature, thus enhancing the drying capacity and reducing the equipment size. In a fluidized bed dryer (**Figure 3.1b**), grain moves across the air stream and exits at the dryer end. Since exhaust air still has capability to carry more moisture (low-relative humidity and high-temperature exhaust air), the exhaust air is generally recycled. By recycling the exhaust air, energy consumption of a fluidized bed dryer is minimized compared to the other types of dryers.



**Figure 3.1.** Typical grain dryer types

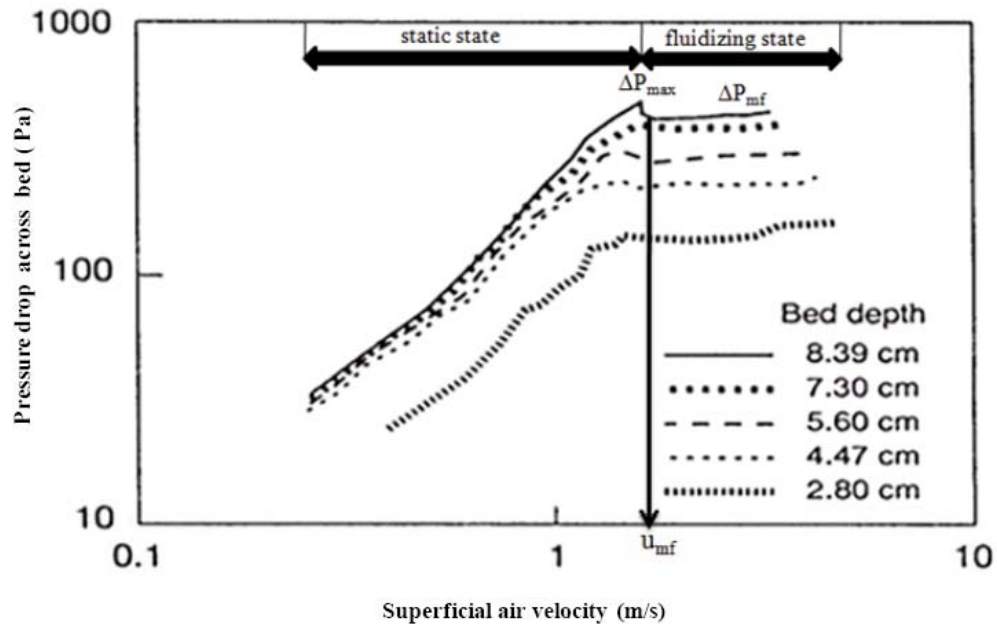
In-store drying or fixed-bed grain drying system shown in **Figure 3.1c** has numerous advantages such as effective energy utilization, less mechanical parts and lower possibility of stress cracking of grain since low-temperature drying is performed. Besides, the system has a capability of storing dried grain for a long period without much deterioration of quality. This can be achieved by ventilating ambient air only for 2 or 3 h per week through the grain bulk in order to remove heat being generated by the respiration of the grain. A major limitation of this drying system is that it cannot be applied with high temperature and high air flow rate because of high pressure drop and high moisture gradient that may be generated in the grain bed. With such a limitation, this drying technique is not suitable for drying grain at high initial moisture content since drying may take excessively long (several weeks) and this may lead to risk of grain spoilage. It

is recommended that the initial moisture content of grain should be lower than 18% w.b. (wet basis) and air flow rate should be around 1.0 m<sup>3</sup>/min per ton of paddy when this drying technique is to be used.

### 3.3. WORKING PRINCIPLE OF FLUIDIZED BED GRAIN DRYERS

In addition to knowing the minimum fluidization velocity for a certain grain drying application, the pressure drop across the bed of particles during the fluidization state is also very important primary information for sizing of a fan and duct system. If the fan can generate sufficient air flow but cannot provide adequate pressure, the particles in the bed or drying chamber cannot be fluidized. This information also provides a rough indication of the fluidization quality, especially when visual observation is not possible. The pressure drop can simply be approximated by the weight of particles in the bed or drying chamber divided by the cross sectional area of the bed. **Figure 3.2** shows a typical change of the pressure drop across the bed of paddy at different superficial air velocities and different bed depths. Initially, the pressure drop rises rapidly with increasing air velocity; nevertheless the bed of particles still remains in a static state. When the superficial air velocity increases to a certain value, depending on the bed depth, the pressure drop reaches the highest value,  $\Delta P_{max}$ . With further increase in the air velocity, the pressure drop starts to decrease to the steady pressure of the bed,  $\Delta P_{mf}$ , as the voidage increases from  $\epsilon_m$  (voidage of particles in the static bed) to  $\epsilon_{mf}$ . The superficial air velocity at  $\Delta P_{mf}$  is called the minimum fluidization velocity,  $u_{mf}$ , at which the bed of particles expands slightly and the particles start behaving like a fluid. At air velocities beyond the minimum fluidization value, the bed expands and gas bubbles in the bed can be differentiated, resulting in an inhomogeneous bed. In spite of the increased air velocity, the pressure drop remains unchanged during this stage of fluidization.

The minimum fluidization velocity shown in **Figure 3.2** is approximately 1.6 m/s for paddy with a moisture content of 16% d.b. (dry basis), which is safe for prolonged storage. However, the moisture content of paddy after harvesting ranges between 28 and 33% d.b. and in this moisture range paddy kernels tend to agglomerate. Agglomeration results in difficult fluidization at a superficial air velocity of 1.6 m/s. In order to have complete mixing between paddy kernels and drying air, the superficial air velocity should be in the range of 2.2-2.4 m/s. Using higher superficial air velocity than the recommended range may not improve drying and instead lead to higher energy consumption due to excessive pumping and heating of the drying air.



**Figure 3.2.** Relationship between bed pressure drop and superficial air velocity at different bed depths (Prachayawarakorn, 1991)

**Table 3.1** shows the performance of two commercial fluidized bed dryers, with drying capacities of 2.5-5 t/h and 5-10 t/h. The recycle of exhaust air ranged between 53 and 69% for these particular dryers; most energy was consumed for the fluidized bed drying, approximately 90% of the total supplied energy. The thermal energy consumption was in the range of 2.2-2.6 MJ/kg water evaporated for drying paddy with initial moisture contents of 28-30% d.b. at 120-130°C. The thermal energy consumption was higher, about 7.8 MJ/kg water evaporated, when the paddy had an initial moisture content of 22% d.b. and the drying air temperature was 115°C. The larger energy consumption indicates that the drying technique is inappropriate for paddy with lower initial moisture content.

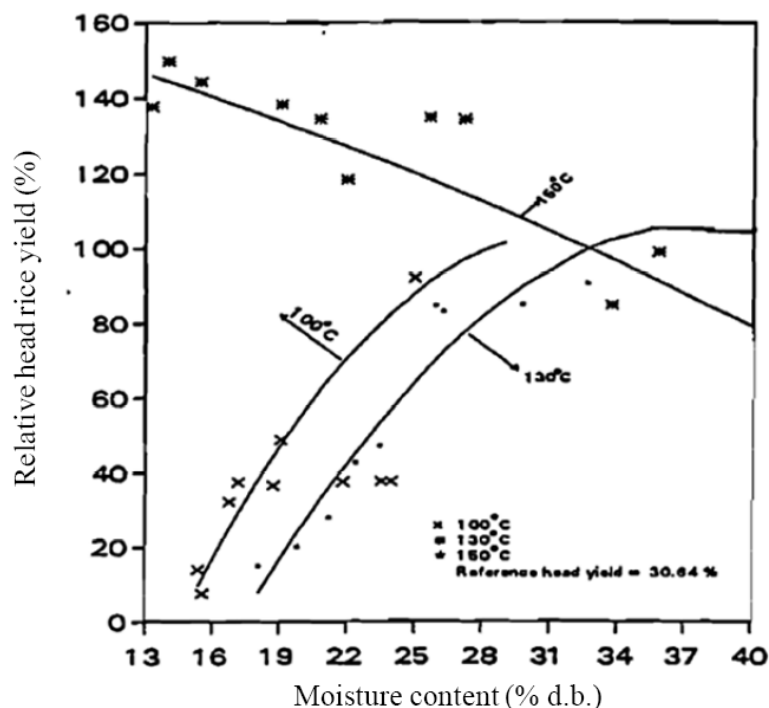
In addition to the energy consumption, the quality of a dried product is an important factor to evaluate the dryer performance. Any dryer types that result in the poor product quality are not suitable. In rice drying, the important parameters used to assess the dryer performance are the yield of head rice and rice color. As presented in **Table 3.1**, fluidized bed drying slightly affected the head rice yield; the head rice yields of all the tested samples, except for Test sample no. 5, were slightly lower than the reference head rice yield obtained by ambient air drying. The drop in the head rice yield was due to stresses induced by moisture gradients, which led to cracks in the kernels, resulting in less resistance to abrasive force during subsequent milling.



**Table 3.1.** Performance test results of commercial fluidized bed paddy dryers (a = 2.5-5 t/h; b = 5-10 t/h) (Soponronnarit et al., 1996)

Test condition	Test no.				
	1	2	3	4	5
Drying air temperature (°C)	115	116	120	130	150
Drying air recycled (%)	69	69	69	69	53
Inlet moisture content of paddy (% dry basis)	22.0	26.0	28.7	30.6	27.0
Outlet moisture content of paddy (% dry basis)	20.1	22.5	22.5	23.0	21.0
Outlet paddy temperature (°C)	54.0	52.0	54.0	57.0	63.0
Electrical energy consumed (MJ/kg-water evap.)	0.83	0.43	0.26	0.21	0.15
Thermal energy consumed (MJ/kg-water evap.)	7.80	3.13	2.57	2.21	3.90
Head rice yield (%)					
- Dried in fluidized bed dryer	53.2	54.3	53.9	57.0	48.1
- Dried by ambient air (reference)	57.4	57.2	53.9	57.0	56.2
Rice whiteness					
- Dried in fluidised bed dryer	40.3	40.7	40.0	43.7	36.8
- Dried by ambient air (reference)	44.4	44.2	40.1	43.8	42.6
Test time (h)	5.0	35.0	46.0	51.0	29.0
Drying capacity (tons/h)	9.5 <sup>b</sup>	9.5 <sup>b</sup>	9.5 <sup>b</sup>	9.5 <sup>b</sup>	4.8 <sup>a</sup>

The color of milled rice after high-temperature drying changed slightly as compared to the color of the reference rice. The milled rice was pale yellow as indicated by the lower whiteness values. The change of the milled rice color is due to non-enzymatic browning reactions. These browning reactions are generally enhanced when higher drying temperatures are used. However, the color of milled rice after drying at the reported temperatures was still acceptable from a commercial point of view.



**Figure 3.3.** Relationship between head rice yield and final moisture content in fluidized bed drying at different temperatures (initial moisture content = 45.3% d.b.) (Soponronnarit and Prachayawarakorn, 1994)

Using a drying temperature of 150°C to reduce the paddy moisture content from 27% to 21% d.b. resulted in 8% reduction of the head rice yield, which was the higher reduction than at other test conditions. Nevertheless, when the initial moisture content of paddy increased to 45% d.b., drying at 150°C could improve the head rice yield as shown in **Figure 3.3**. The relative head rice yield, defined as the ratio of head rice yield of paddy after drying to the reference head rice yield, was significantly higher than 100%, approximately 1.4 times of the reference sample. The improved head rice yield is due to starch gelatinization where the starch granules swelled and disrupted. Amylose subsequently leached out to the outer spaces inside the kernels, providing strong intermolecular binding forces between granules hence the higher head rice yield (Atwell et al., 1988; Adhikaritanayake and Noomhorm, 1998).

Soponronnarit and Prachayawarakorn (1994) recommended that for production of high-quality head rice, the drying temperature should be limited to 115-120°C, and the paddy should not be dried to below 23-25% d.b. (from an initial moisture content lower than 30% d.b.) When the initial moisture content of paddy is higher than 30% d.b., the drying temperature can be increased up to 150°C without any drop in the head rice quality even if the grain after fluidized bed drying is not tempered. In addition, it is also recommended that the exhaust air should be recycled since the exhaust air temperature is generally still high; otherwise the energy consumption would be very high. The fraction of the recycled air could be up to 0.8, with no effect on the drying capacity. The recommended bed height is in the range of 10-15 cm.

### 3.4. MATHEMATICAL MODELS FOR DRYING, TEMPERING AND VENTILATION OF PADDY

During drying of paddy, the moisture gradient exists inside the kernels, leading to development of stresses; stresses are more severe as the moisture content of the grain decreases. The stresses provoke grain fissuring and posterior breakage ([Kunze, 1979](#); [Cnossen et al., 2003](#)). To reduce the stresses and the number of cracked kernels, tempering is commonly required between drying stages ([Shei and Chen, 1998](#); [Li et al., 1999](#); [Poomsa-ad et al., 2002](#)). During tempering, the moisture gradient created during drying would reduce and diminish if the paddy is tempered for a sufficiently long period of time. To calculate the required tempering time, a model of heat and mass transfer is needed. A model to predict the level of head rice yield can also be coupled to the heat and mass transfer model.

It can be assumed that the paddy drying process consists of a drying unit, tempering unit and ambient-air ventilation unit. A mathematical model for each stage needs to be developed.

The formulation of the mathematical model is based on the following assumptions:

- Paddy kernels have a uniform size of a finite cylindrical shape.
- The bed kernels are perfectly mixed such that each individual kernel has the same moisture content at any time.
- Internal diffusion is the dominant mechanism for moisture transport within each kernel.
- The drying air is in thermal equilibrium with the exiting kernels, so that the kernel temperature is equal to the exhaust air temperature.
- The temperature gradient inside the kernel as well as the kernel shrinkage are negligible.

A model of the drying process with the above-mentioned assumptions consists of three governing equations, i.e., mass balance, energy balance between air and grain bed and the drying-rate equation.

#### 3.4.1. Heat and mass balances

Over a small interval of time  $\Delta t$ , a certain amount of moisture evaporates from the grain bed into the drying air, resulting in a change in the humidity ratio. This moisture balance can be written as

$$W_f = R(M_i - M_f) + W_{in} \quad (3.1)$$

where	$W_f$	=	exhaust-humidity ratio of air, kg water/kg dry air
	$W_{in}$	=	inlet-humidity ratio of air, kg water/kg dry air
	$M_i$	=	average moisture content at time t, decimal d.b.
	$M_f$	=	average moisture content at time t+ $\Delta t$ , decimal d.b.
	$R$	=	ratio of dry mass of grain to mass of air , Decimal

The exhaust air temperature can be determined by Eq. (3.2),

$$T_f = (C_a T_{in} + W_{in}(h_{fg} + C_v T_{in}) - W_i h_{fg} + R C_{pw} \theta_{in}) / (C_a + W_f C_v + R C_{pw}) \quad (3.2)$$

where	$T_f$	=	exhaust air temperature, °C
	$T_{in}$	=	inlet air temperature, °C
	$\theta_{in}$	=	inlet grain temperature, °C
	$C_a$	=	specific heat of dry air, kJ/kg °C
	$C_v$	=	specific heat of water vapor, kJ/kg °C
	$C_{pw}$	=	specific heat of moist grain, kJ/kg °C
	$h_{fg}$	=	latent heat of moisture evaporation, kJ/kg

At inlet, the grain temperature is equal to the ambient-air temperature.

### 3.4.2. Drying kinetics of a single kernel

Moisture migration within a kernel is described by mass diffusion both during the drying and tempering stages. For a finite cylinder, the partial differential equation for moisture diffusion in a single paddy kernel can be written as:

$$\frac{\partial M}{\partial t} = D \left[ \frac{\partial^2 M}{\partial r^2} + \left( \frac{1}{r} \right) \frac{\partial M}{\partial r} + \frac{\partial^2 M}{\partial z^2} \right] \quad (3.3)$$

where	$D$	=	effective moisture diffusion, m <sup>2</sup> /s
	$M$	=	moisture content, decimal d.b.
	$r$	=	co-ordinate along the radius of cylinder, m
	$t$	=	time, min or s
	$z$	=	length of cylinder, m

The expression for  $D$  as proposed by [Poomsa-ad et al. \(2002\)](#) is given as:

$$D = 5.41141 \times 10^{-6} \exp \left( - \frac{28436.4}{T_{abs}} \right) \quad (3.4)$$

where  $T_{abs}$  is the absolute air temperature (K). Equation (3.4) is valid over the temperature range of 373.15 to 443.15 K. The average air temperature between the inlet and exhaust conditions is used to calculate the effective diffusion coefficient.

### 3.4.3. Initial and boundary conditions for drying kinetics simulation

Moisture content within a paddy kernel at the dryer inlet can be assumed to be spatially uniform. The gas-film resistance around the kernel surface is presumed negligible, allowing the moisture content at the surface to equilibrate with the drying air:

$$\begin{aligned} t = 0, \quad 0 \leq r \leq r_o & \quad M = M_{in} \\ -l \leq z \leq +l & \quad M = M_{in} \\ t > 0, \quad r = r_o & \quad M = M_{eq} \end{aligned}$$

$$\begin{aligned} z &= \pm l & M &= M_{eq} \\ t > 0, \quad r &= 0 & \frac{\partial M}{\partial r} &= 0 \end{aligned}$$

where  $M_{in}$  = initial moisture content, decimal d.b.  
 $M_{eq}$  = moisture content at the equilibrium, decimal d.b.  
 $l$  = half height of cylinder representing the kernel, m

The moisture equilibrium equation used in the present study is given by:

$$1 - \Phi = \exp\left\{-4.584 \times 10^{-6} T_{abs} (100M_{eq})^{2.397}\right\} \quad (3.5)$$

Eq. (3.3) can be solved by various numerical methods, e.g., the finite difference method. The average moisture content of a single kernel can then be determined by

$$M_{av} = \frac{1}{V_p} \iint 2\pi M(r, z, t) dr dz \quad (3.6)$$

where  $M_{av}$  = average moisture content at time t, decimal d.b.  
 $V_p$  = volume of a single kernel, m<sup>3</sup>

By assuming the exhaust air temperature, the amount of water evaporated from a paddy kernel into the air can be determined by Eqs. (3.3)-(3.6). The value of  $W_f$  in Eq. (3.1) allows recalculation of the exhaust air temperature  $T_f$  using Eq. (3.2). Iterative calculation eventually leads to the final values of  $M_f$  and  $T_f$  at time t.

#### 3.4.4. Initial and boundary conditions for tempering stage simulation

During the tempering stage, moisture inside a paddy kernel transports to the exterior surface but does not evaporate due to lack of air movement. The validity of this assumed behavior has been noted by [Sabbath \(1970\)](#) and [Steffe \(1979\)](#). The initial and boundary conditions for the tempering period are as follows:

$$\begin{aligned} t &= 0 & M &= M(r, z) \\ t > 0, \quad r &= r_o & \frac{\partial M}{\partial r} &= 0 \\ z &= \pm l & \frac{\partial M}{\partial z} &= 0 \\ t > 0, \quad r &= 0 & \frac{\partial M}{\partial r} &= 0 \end{aligned}$$

#### 3.4.5. Head-rice yield prediction

The relative head rice yield equation was proposed by [Poomsa-ad et al. \(2005\)](#) as:

$$RHY = A + B t + C t^2 \quad (3.7)$$

where  $RHY$  = relative head-rice yield  
 $t$  = tempering time, min  
 $A$  =  $-39.232 + 8.4227 M - 0.34060 T - 0.029105 T M$

$$\begin{aligned}
 B &= 25.945 - 1.1878 M - 0.24443 T + 0.012302 T M \\
 C &= -0.33610 + 0.015028 M + 0.0032590 T - 0.00015762 T M \\
 M &= \text{preset moisture content, per cent dry basis}
 \end{aligned}$$

$t$ ,  $M$  and  $T$  are the tempering time in min; moisture content in percent dry basis; and tempering temperature in °C, respectively. The equation is valid over 15.5% d.b. <  $M$  < 30% d.b. After determining the required tempering time, head rice can be calculated by Eq. (3.7).

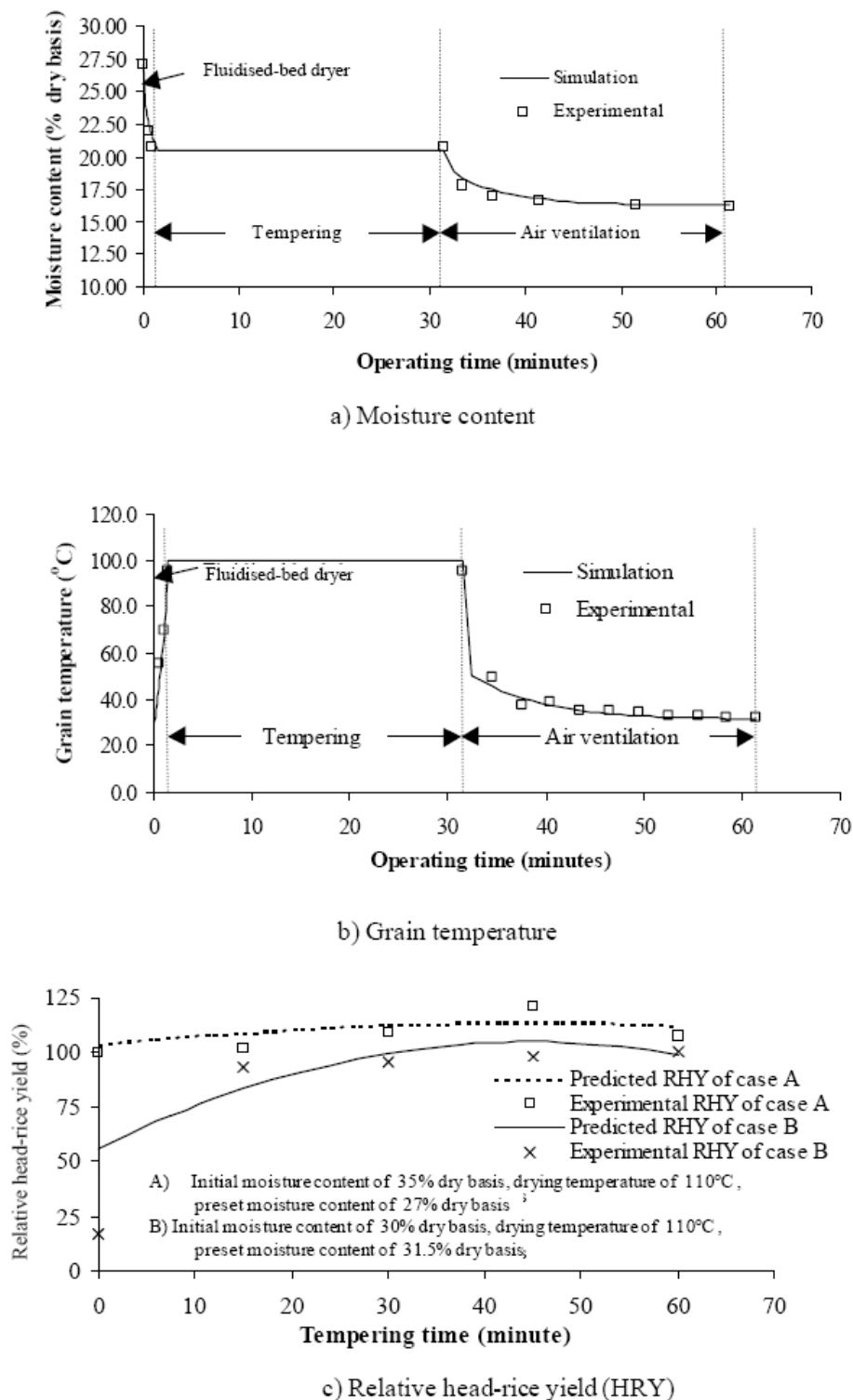
### 3.4.6. Ambient-air ventilation simulation

The analogous equations of heat and mass balances throughout the thin bed as previously represented can also be used during the ventilation stage by replacing  $\theta_{in}$  in Eq. (3.2) by the tempering temperature or grain temperature after the first stage; the moisture content is then solved via the use of Eq. (3.3). At this stage, the grain temperature is much higher than the ambient air temperature, so the grain temperature is used as an input parameter for calculating the effective diffusion coefficient. The grain temperature and the inlet air humidity are used to calculate the equilibrium moisture content using Eq. (3.5). Initial and boundary conditions for a single paddy kernel during this step are given by:

$$\begin{aligned}
 t = 0 & & M &= M(r, z) \\
 t > 0, \quad r = r_o & & M &= M_{eq} \\
 z = \pm l & & M &= M_{eq} \\
 t > 0, \quad r = 0 & & \frac{\partial M}{\partial r} &= 0
 \end{aligned}$$

### 3.4.7. Mathematical model validation

Experimental data of [Soponronnarit et al. \(1999\)](#) were used to validate the above-mentioned models. **Figure 3.4** shows a comparison between the experimental and predicted data for kernel moisture content, kernel temperature and head-rice yield during the drying, tempering and ambient-air ventilation stages. The results show that the predictions are in good agreement with the experimental observations. As is seen in Fig. 4b, the temperature dropped sharply during the small interval of ventilation, thus causing high reduction in the head rice yield if the grain did not pass through the tempering stage (even though the first-stage outlet moisture content of paddy was not low). This behavior can be seen clearly in **Figure 3.4c** for case (B) where the initial moisture content of paddy was 30% d.b. However, such behavior is not significant for case (A) where the initial moisture content was relatively higher than in case (B). This is because the high kernel moisture content, along with the high kernel temperature, enhances the development of a polymeric network of starch in the paddy structure, thus making the kernel more strengthened.



**Figure 3.4.** Comparison between simulated and experimental moisture content, grain temperature and relative head rice yield (Poomsa-ad et al., 2005)

Poomsa-ad et al. (2002) used the above-mentioned mathematical model to suggest a suitable way to dry paddy. The drying time and energy consumption along with the head rice yield were used as decisive factors for optimization. From the simulation results,

paddy after fluidized bed drying at 110-150°C should be tempered for 35 min and the moisture content of paddy before tempering should not be lower than 19.5% d.b. for the paddy that has the initial moisture in the range of 26-32% d.b. Under these operating conditions, the thermal energy consumptions was noted to be 5-7 MJ/kg water evaporated, while the electric energy consumed was 0.5-0.6 MJ/kg water evaporated ([Prachayawarakorn et al., 2005](#)).

### 3.5. SENSORY EVALUATION OF COOKED RICE

The texture of cooked rice is a very important parameter besides the head rice yield and the color for consumer's acceptability. The drying temperature may detrimentally affect the textural property of the dried rice. [Tirawanichakul et al. \(2004\)](#), for example, studied the effects of drying temperature and initial moisture content of paddy on the acceptability of cooked rice. Two paddy varieties, Pathumthani and Suphanburi 1, having amylose contents of 15-18% and 25-27%, respectively, were fluidized bed dried at 40-150°C to a moisture content of 22% d.b., tempered for 30 min and dried by ambient air until the samples reached moisture content of 16% d.b. The rice was then cooked and its texture was evaluated by the trained panelist using a hedonic scale ranging from 1 to 9. The results presented in **Table 3.2** show the overall acceptability of the cooked rice. The overall acceptability of the cooked rice was insignificantly different among the paddy samples obtained either from high- or low-temperature drying, indicating that the drying temperature did not affect the cooked rice texture.

Based on the aforementioned results, higher drying temperatures are preferred for paddy drying in order to enhance the drying capacity. Drying temperature of 150°C is recommended. However, the recommended temperature may not be used with other types of grain dryers since the characteristics of heat and mass transfer of other grain dryers are different from those of the fluidized bed dryer. Any dryer types that provide poor contact between the drying medium and grain would affect the quality of paddy, in particular color, if the grain is subject to high-temperature drying for a long period of time.

**Table 3.2.** Effects of drying air temperature and initial moisture content on overall acceptability of cooked rice for Suphanburi 1 and Pathumthani 1 varieties ([Tirawanichakul, 2004](#))

Overall acceptability of cooked rice						
Inlet air temperature (°C)	Initial moisture content (% d.b.)					
	Pathumthani 1			Suphanburi 1		
	25.0	28.8	32.5	25.0	28.8	32.5
Control	6.94 <sup>b</sup>	5.98 <sup>a</sup>	4.96 <sup>b</sup>	6.46 <sup>a</sup>	4.53 <sup>a</sup>	4.97 <sup>a</sup>
40	7.54 <sup>a</sup>	6.40 <sup>a</sup>	8.38 <sup>a</sup>	5.54 <sup>a</sup>	4.57 <sup>a</sup>	4.43 <sup>b</sup>



60	7.21 <sup>b</sup>	5.44 <sup>b</sup>	7.92 <sup>a</sup>	5.17 <sup>b</sup>	4.55 <sup>a</sup>	5.05 <sup>a</sup>
80	7.18 <sup>b</sup>	5.27 <sup>b</sup>	7.83 <sup>a</sup>	5.58 <sup>a</sup>	4.46 <sup>a</sup>	4.67 <sup>a</sup>
100	7.37 <sup>a</sup>	6.32 <sup>a</sup>	4.96 <sup>b</sup>	5.38 <sup>b</sup>	4.05 <sup>b</sup>	4.38 <sup>b</sup>
120	7.52 <sup>a</sup>	5.82 <sup>b</sup>	6.63 <sup>b</sup>	4.63 <sup>b</sup>	4.05 <sup>b</sup>	4.67 <sup>a</sup>
140	7.52 <sup>a</sup>	5.77 <sup>b</sup>	4.92 <sup>b</sup>	4.58 <sup>b</sup>	4.51 <sup>a</sup>	4.13 <sup>b</sup>
150	7.37 <sup>a</sup>	5.86 <sup>a</sup>	7.08 <sup>a</sup>	4.67 <sup>b</sup>	4.86 <sup>a</sup>	4.09 <sup>b</sup>

Different superscripts in the same column mean that the values are significantly difference ( $p < 0.05$ ). Control = Rewetted rice which was gently dried by ambient air ventilation in thin layer. The meaning of hedonic score is as follows: Hedonic scale from 1-9: 1 = Extremely dislike; 2 = Very much dislike; 3 = Moderately dislike; 4 = Slightly dislike; 5 = Like nor dislike; 6 = Slightly like; 7 = Moderately like; 8 = Very much dislike; 9 = Extremely like

### 3.6. DRYING OF WAXY RICE

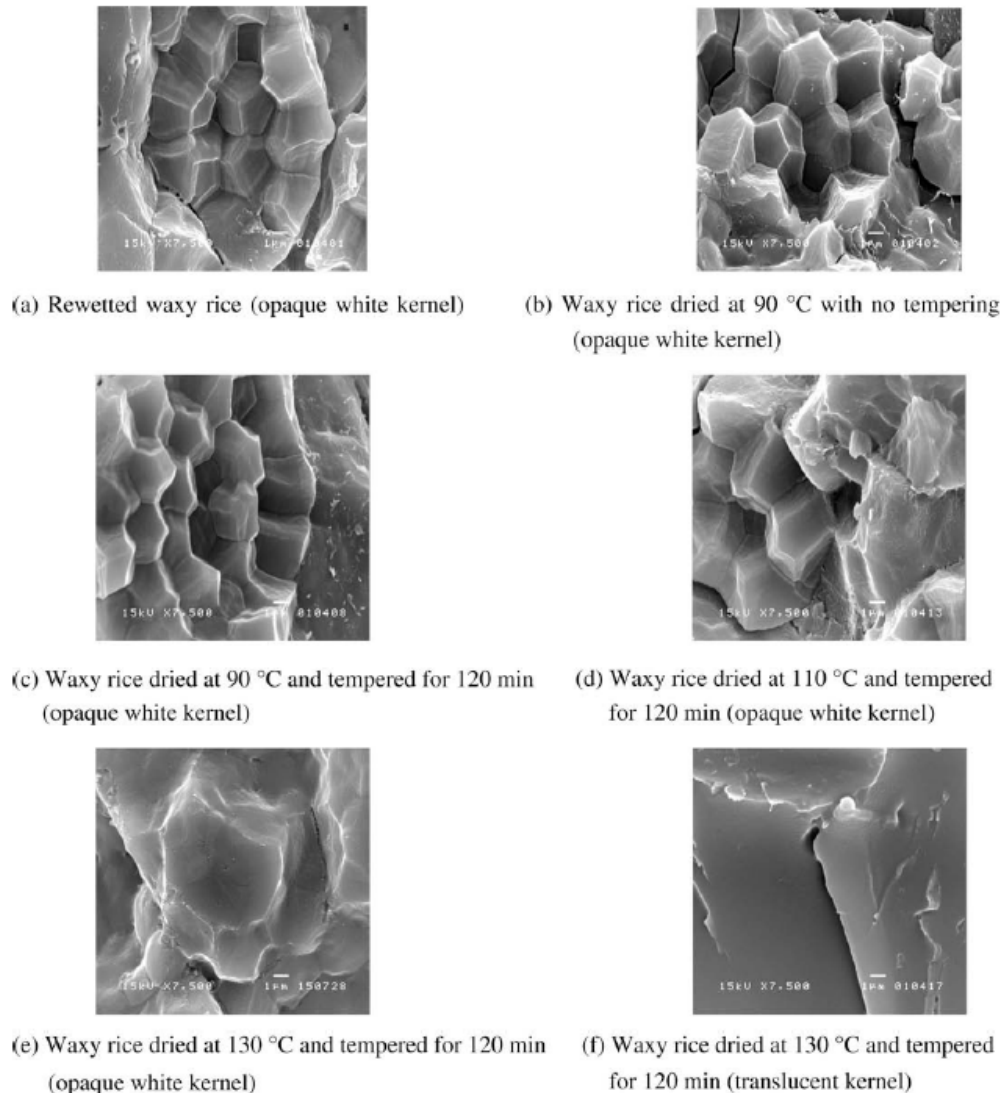
The above suitable conditions for drying rice containing amylose in the range of 15 to 28% are not suitable for drying waxy rice, which mostly consists of amylopectin. This is because waxy kernels would change from opaque to translucent kernels when being dried at temperatures above 130°C; such appearance is not acceptable to rice mills. The formation of translucent kernels is caused by starch gelatinization during drying. [Jai-boon et al. \(2009\)](#) reported that the quantity of translucent kernel formation depended on the drying temperature and tempering time as presented in **Table 3.3**. Drying waxy rice at temperatures of 90 and 110°C did not lead to translucent kernels throughout the tempering time of 120 min. As the temperature increased to above 130°C, however, translucent kernels were formed, around 3% or higher depending on the tempering time. **Figure 3.5** shows the morphology of opaque and translucent waxy rice kernels obtained at different conditions. The starch granules of reference waxy rice, obtained by shade drying, showed characteristically irregular polygons with diameters of approximately 2  $\mu\text{m}$ . (see **Figure 3.5a**). When waxy rice was dried at 90°C, the morphology of most starch granules (as shown in **Figure 3.5b** and **Figure 3.5c**) was rather similar to that of the reference waxy rice although there was some degree of starch gelatinization (3.8-10.4%). Irreversible loss of their shape was evident when the drying temperatures of 110 and 130°C were used (see **Figure 3.5d-Figure 3.5e**); some starch granules were fused and closely connected. Such starch granule modification enabled the kernels to withstand abrasive forces during subsequent milling.

**Figure 3.5f** shows the microstructure of translucent kernels obtained under the same drying conditions as that shown in **Figure 3.5e**; the polygonal shape of starch granules disappeared in the translucent kernels. This implies that all starch granules in waxy rice were disrupted and completely gelatinized.

To prevent translucent kernel formation, it is recommended to dry waxy rice at a temperature lower than 130°C. At the recommended temperature, the head rice yield and color of milled waxy rice is also noted to be acceptable.

**Table 3.3.** Percentage of translucent kernels at various drying temperatures and tempering time (Jaiboon et al., 2009)

Condition	Translucent kernels (%)
$T = 90\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., without tempering	0
$T = 90\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., tempering 30 min	0
$T = 90\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., tempering 120 min	0
$T = 110\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., without tempering	0
$T = 110\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., tempering 30 min	0
$T = 110\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., tempering 120 min	0
$T = 130\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., without tempering	$2.9 \pm 0.2$
$T = 130\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., tempering 30 min	$7.8 \pm 0.0$
$T = 130\text{ }^{\circ}\text{C}$ , $M_i = 28.8\%$ d.b., tempering 120 min	$10.4 \pm 0.3$



**Figure 3.5.** Morphology of waxy rice at various drying temperatures and tempering time (Jaiboon et al., 2009)

### 3.7. ACCELERATED RICE AGING AND PRODUCTION OF HEALTHY RICE

In addition to the preservation of head rice yield, high-temperature fluidized bed drying can also change the rice property in a way similar to the aging process, which generally takes about 4-6 months. Aged rice has important characteristics of non-stickiness and large volume expansion; both properties are preferred by people in some Asian countries including Thailand. The changes of such cooking properties are caused by changes in lipid, protein and other substances produced by enzymatic activities and oxygen during rice storage (Chrastil et al., 1994). In addition to the conventional storage method, thermal processing such as steaming in an autoclave and high-temperature fluidized bed drying is an alternative method to produce aged rice (Bhattacharya et al., 1964; Soponronnarit et al., 2008). During thermal processing, some starch granules in rice are gelatinized; this results in changes in the cooking properties. To accelerate rice

aging via the use of a fluidized bed drying technique, the initial moisture content, tempering time and drying temperature are the important parameters. **Table 3.4** shows the cooking properties of Khao Dawk Mali 105 after high-temperature fluidized bed drying and tempering. The water uptake and volume expansion of the cooked rice increased, while the solid loss decreased. The increase in the water uptake and the corresponding volume of the cooked rice can be explained by the fact that the cell walls of the accelerated aged rice are more strengthened, due to starch gelatinization, and could maintain the hexagonal shape, which provides higher water absorption ([Desikachar & Subrahmanyan, 1959](#)). These cooking property changes are similar to those changes of rice during conventional storage (see **Table 3.5**), indicating that high-temperature fluidized bed drying, in combination with tempering, can accelerate the rice aging process. Drying temperature and tempering time was noted to influence the cooking properties, while the initial moisture content of rice in the range of 27-33% d.b. did not affect the cooking properties. To achieve the cooking properties similar to those obtained from the conventional aging process, paddy at such initial moisture content should be dried at 150°C and tempered for at least 90 min.

**Table 3.4.** Water uptake, volume expansion and solid loss of Khao Dawk Mali 105 after processing under different conditions ([Soponronnarit et al., 2008](#))

Drying temperature (°C)	Initial moisture (% d.b.)	Tempering time (min)	Water uptake (%)	Volume expansion (mm <sup>3</sup> )	Solid loss (%)
<b>130</b>	27.7	0	331.04 ± 8.89 <sup>a</sup>	466.89 ± 1.4 <sup>ab</sup>	2.74 ± 0.03 <sup>rm</sup>
		30	341.44 ± 12.08 <sup>abcd</sup>	474.17 ± 1.4 <sup>ab</sup>	2.67 ± 0.02 <sup>lm</sup>
		60	357.21 ± 5.17 <sup>cde</sup>	481.72 ± 14.43 <sup>cdef</sup>	2.55 ± 0.04 <sup>ij</sup>
		90	356.75 ± 15.97 <sup>cde</sup>	505.06 ± 4.80 <sup>fgh</sup>	2.28 ± 0.02 <sup>ef</sup>
		120	369.15 ± 13.51 <sup>fg</sup>	505.52 ± 12.08 <sup>fgh</sup>	2.15 ± 0.03 <sup>d</sup>
	33.2	0	341.2 ± 14.96 <sup>abcd</sup>	426.17 ± 14.52 <sup>a</sup>	2.80 ± 0.04 <sup>n</sup>
		30	341.44 ± 7.25 <sup>abcd</sup>	454.60 ± 12.36 <sup>bc</sup>	2.65 ± 0.03 <sup>kl</sup>
		60	358.19 ± 5.2 <sup>de</sup>	477.94 ± 10.11 <sup>cdef</sup>	2.47 ± 0.02 <sup>hi</sup>
		90	355.81 ± 10.89 <sup>bcde</sup>	490.71 ± 11.92 <sup>defg</sup>	2.34 ± 0.08 <sup>fg</sup>
		120	371.52 ± 14.06 <sup>ef</sup>	502.31 ± 14.50 <sup>fg</sup>	2.04 ± 0.06 <sup>c</sup>
<b>150</b>	27.7	0	335.45 ± 9.27 <sup>abc</sup>	460.34 ± 22.86 <sup>bc</sup>	2.74 ± .05 <sup>rmn</sup>
		30	356.14 ± 12.5 <sup>cde</sup>	478.05 ± 14.81 <sup>cdef</sup>	2.62 ± 0.08 <sup>ijkl</sup>
		60	357.85 ± 10.02 <sup>cde</sup>	477.63 ± 17.51 <sup>cdef</sup>	2.46 ± 0.03 <sup>h</sup>
		90	375.01 ± 10.92 <sup>ef</sup>	509.46 ± 22.09 <sup>gh</sup>	2.31 ± 0.06 <sup>ef</sup>
		120	383.92 ± 11.59 <sup>f</sup>	539.42 ± 27.42 <sup>i</sup>	1.92 ± 0.09 <sup>b</sup>
	33.2	0	330.75 ± 4.87 <sup>a</sup>	428.67 ± 10.81 <sup>a</sup>	2.60 ± 0 <sup>ijkl</sup>
		30	342.88 ± 8.26 <sup>abcd</sup>	467.20 ± 11.31 <sup>bcd</sup>	2.56 ± 0.03 <sup>jk</sup>

	60	361.9 ± 6.31 <sup>de</sup>	498.39 ± 3.87 <sup>efg</sup>	2.42 ± 0.07 <sup>gh</sup>
	90	377.38 ± 12.98 <sup>ef</sup>	511.85 ± 8.66 <sup>gh</sup>	2.25 ± 0.04 <sup>e</sup>
	120	402.50 ± 11.05 <sup>g</sup>	531.37 ± 6.41 <sup>hi</sup>	1.78 ± 0.04 <sup>a</sup>

Different superscripts in the same column mean that the values are significantly different ( $p < 0.05$ ). Cooking properties of reference rice at: Mi = 27.7% (d.b.), water uptake (%) =  $333.92 \pm 14.39^{ab}$ , volume expansion ( $\text{mm}^3$ ) =  $461.37 \pm 12.57^{bc}$ , solids loss (%) =  $2.74 \pm 0.02^{mn}$ , Mi = 33.2% (d.b.), water uptake (%) =  $342.01 \pm 6.99^{abcd}$ , volume expansion ( $\text{mm}^3$ ) =  $58.94 \pm 14.73^{bc}$ , solid loss (%) =  $2.81 \pm 0.05^n$

**Table 3.5.** Cooking properties of Khao Dawk Mali 105 after ambient storage for 6 months (Soponronnarit et al., 2008)

Storage time (month)	Water uptake (%)	Volume expansion ( $\text{mm}^3$ )	Loss of solids (%)
0	$377.38 \pm 11.21^a$	$474.30 \pm 8.22^a$	$2.60 \pm 0.02^f$
1	$381.93 \pm 1.39^{ab}$	$481.07 \pm 22.14^{ab}$	$2.52 \pm 0.05^e$
2	$402.13 \pm 20.3^{abc}$	$505.98 \pm 4.62^{bc}$	$2.43 \pm 0.05^d$
3	$397.5 \pm 17.56^{abc}$	$526.89 \pm 19.28^{cd}$	$2.38 \pm 0.01^d$
4	$404.62 \pm 7.11^{bc}$	$532.86 \pm 14.54^{cd}$	$2.27 \pm 0.02^c$
5	$414.44 \pm 7.88^c$	$547.36 \pm 0.28^d$	$2.17 \pm 0.06^b$
6	$418.83 \pm 11.32^c$	$548.81 \pm 27.42^d$	$1.84 \pm 0.06^a$

Different superscripts in the same column mean that the values are significantly different ( $p < 0.05$ ).

In addition to the ability to accelerate the rice aging process, high-temperature fluidized bed drying, in combination with tempering, can induce formation of amylose-lipid complexes in rice. [Laisut et al. \(2008\)](#) studied the effects of the drying temperatures and tempering time on amylose-lipid complexes formation in Khao Dawk Mali 105 brown rice. It was found that the first phase transition temperature (see [Table 3.6](#)) was in the range of 69-83°C, representing the melting of starch; and in the range of 109 to 137°C for the second transition, corresponding to the melting of amylose-lipid complexes ([Derycke et al., 2005](#)). The enthalpy of the second transition peak of a reference sample was 0.9 J/g; the enthalpy was observed to increase when the sample was dried and tempered. The largest amount of the enthalpy for melting amylose-lipid complexes was 3 J/g when using the drying temperature of 150°C and tempering time of 120 min. Although it is still not clear about the amount of complexes formed during drying and tempering, the results from the thermograms showed that the total enthalpy for complexes melting was higher than for the treated brown rice. Thus, the total complexes formation was hypothesized to be enhanced by the higher drying temperature and longer tempering time.

**Table 3.6.** Effect of inlet drying temperature, initial moisture content and tempering times on gelatinization and amylose-lipid complex properties of Khao Dawk Mali 105 brown rice (Jaisut et al., 2008)

Condition	Transition temp. of the first peak (°C)			$\Delta H_1$ (J/g)	% SG	Transition temp. of the second peak (°C)			$\Delta H_2$ (J/g)
	$T_{o1}$	$T_{p1}$	$T_{c1}$			$T_{o2}$	$T_{p2}$	$T_{c2}$	
$T = 130\text{ °C}$ , $M_i = 33.3\%$ d.b., tempering 30 min	69.2	73.8	81.5	$4.4 \pm 0.05$	$34.7 \pm 0.3$	109.5	114.5	123.9	1.4
$T = 130\text{ °C}$ , $M_i = 33.3\%$ d.b., tempering 60 min	69.4	73.9	81.8	$4.2 \pm 0.05$	$36.6 \pm 0.4$	N/A	N/A	N/A	N/A
$T = 130\text{ °C}$ , $M_i = 33.3\%$ d.b., tempering 120 min	69.5	74.2	82.2	$4.1 \pm 0.07$	$38.9 \pm 0.5$	111.0	119.3	124.0	1.5
$T = 150\text{ °C}$ , $M_i = 33.3\%$ d.b., tempering 30 min	69.7	74.5	82.7	$3.8 \pm 0.04$	$43.3 \pm 0.2$	123.0	130.4	136.8	2.5
$T = 150\text{ °C}$ , $M_i = 33.3\%$ d.b., tempering 60 min	69.8	74.7	82.7	$3.7 \pm 0.01$	$44.7 \pm 0.1$	N/A	N/A	N/A	N/A
$T = 150\text{ °C}$ , $M_i = 33.3\%$ d.b., tempering 120 min	69.9	74.9	82.9	$3.7 \pm 0.01$	$45.1 \pm 0.1$	120.0	130.0	137.0	3.0
Reference, $M_i = 33.3\%$ d.b.	64.0	71.7	79.6	$6.5 \pm 0.40$	0	127.0	132.0	134.0	0.9

Reference: paddy dried by ambient air aeration from  $M_i = 33.3\%$  (d.b.) to  $16\%$  (d.b.), N/A: not available

The glycemic index (GI) has been used to indicate the effects of carbohydrates on the blood glucose levels ([Jenkins et al, 1981](#)). Carbohydrate-based foods that can be digested easily, providing rapid release of glucose into blood stream, have high values of GI, while slowly digested carbohydrates are considered to have lower values of GI. The amylose-lipid complexes formed during drying of brown rice were found to limit starch digestibility and, in turn, improve the glucose control in blood stream of consumers who suffer from Type 2 diabetes mellitus. The GI value of reference brown rice obtained by shade drying was 70. After thermal processing, the GI values of the treated brown rice samples were found to be in the range of 59 to 64 (see [Table 3.7](#)). The effect of drying temperature on the GI was remarkable, whilst the effect of tempering time was smaller. It is therefore suggested to dry brown rice at temperatures higher than 130°C to reduce the GI of brown rice.

**Table 3.7.** Effects of drying temperature and tempering time on glycemic index (GI) of Khao Dawk Mali 105 brown rice starch samples ([Jaisut et al., 2008](#))

Condition	glycemic index (GI)
Reference, $M_i = 33.3\%$ d.b.	$70.3 \pm 0.00^g$
$T = 130\text{ }^\circ\text{C}$ , $M_i = 33.3\%$ d.b., tempering 30 min	$63.6 \pm 0.01^f$
$T = 130\text{ }^\circ\text{C}$ , $M_i = 33.3\%$ d.b., tempering 60 min	$62.9 \pm 0.01^e$
$T = 130\text{ }^\circ\text{C}$ , $M_i = 33.3\%$ d.b., tempering 120 min	$62.6 \pm 0.00^d$
$T = 150\text{ }^\circ\text{C}$ , $M_i = 33.3\%$ d.b., tempering 30 min	$61.0 \pm 0.02^c$
$T = 150\text{ }^\circ\text{C}$ , $M_i = 33.3\%$ d.b., tempering 60 min	$60.7 \pm 0.00^b$
$T = 150\text{ }^\circ\text{C}$ , $M_i = 33.3\%$ d.b., tempering 120 min	$59.9 \pm 0.03^a$

Different superscripts in the same column mean that the values are significantly different ( $p < 0.05$ ).

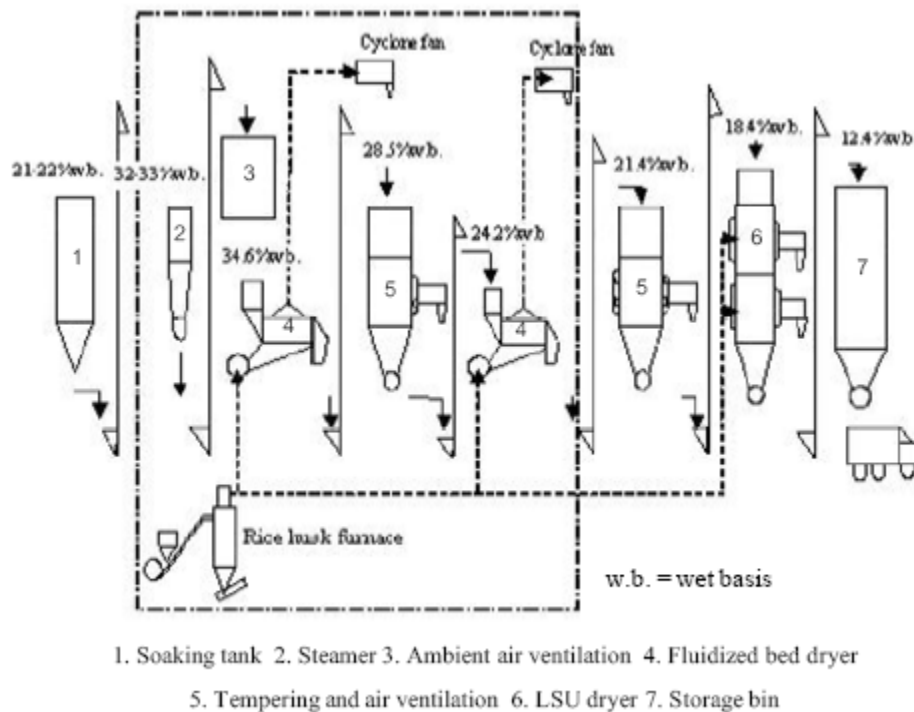
### 3.8. APPLICATION OF FLUIDIZED BED DRYING FOR PRODUCING PARBOILED RICE

Parboiled rice provides several advantages over non-parboiled rice. Some of the advantages are strengthening of kernel integrity, high milling yield and decreased solid loss upon cooking. Other important characteristics of parboiled rice are that it is firmer and has less sticky texture. Conventionally, parboiled rice is produced by first soaking paddy in excess water to a moisture content of 33-50% d.b. The steeping water is drained and the soaked paddy is steamed at a temperature of 100-130°C to gelatinize the rice starch. The steamed paddy is then dried and cooled. To obtain white parboiled



rice, the husk and outer bran layer are removed by dehusking and milling processes. The white parboiled rice contains 78% starch, 4.5-10% protein and a small quantity of lipid (0.5%) (Champagne et al., 2004).

**Figure 3.6** shows an example of a conventional parboiling process that is currently operated in some countries including Thailand. Several units of hot air fluidized bed dryers (No. 4), which are attached to tempering and air ventilation units (No. 5), are first used to dry paddy from an initial moisture content of 50% d.b. to 21% d.b, after which an LSU dryer is used to dry the rice until the moisture content reaches 16% d.b. This process takes about 3-4 h.



**Figure 3.6.** Conventional parboiled rice production process (Rordprapat et al., 2005b)

Recently, Taechapairoj et al. (2004) found that if paddy with initial moisture content in the range of 41-42.5% d.b. was subject to superheated-steam fluidized bed drying at a temperature of 150-170°C, gelatinization of rice starch and evaporation of water occurred simultaneously. The gelatinization kinetics of rice starch in this drying system could adequately be described by a zero-order reaction:

$$\frac{C(t)}{C_o} = kt \quad (3.8)$$

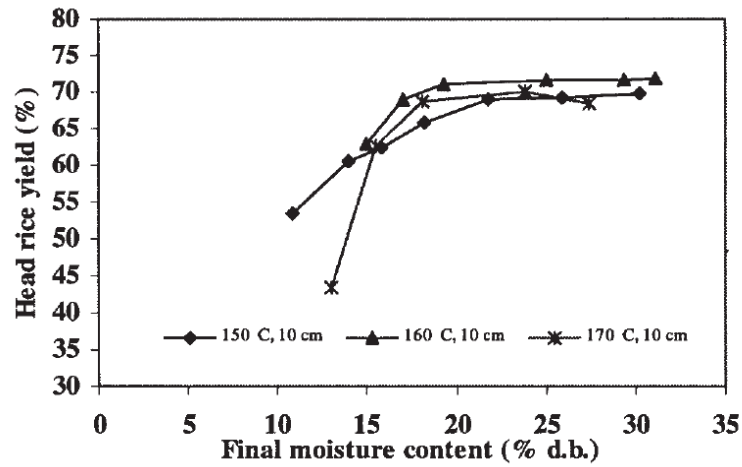
where C is the percentage of non-gelatinized starch (%), k is the rate constant (s<sup>-1</sup>) and t is drying time (s). The rate constant was related to the bed depth and drying temperature through the following correlation:

$$k = -30.34026 + 3.1920113H_{bed} - 0.109836H_{bed}^2 - \exp\left(-\frac{1518.626}{T}\right) \quad (3.9)$$

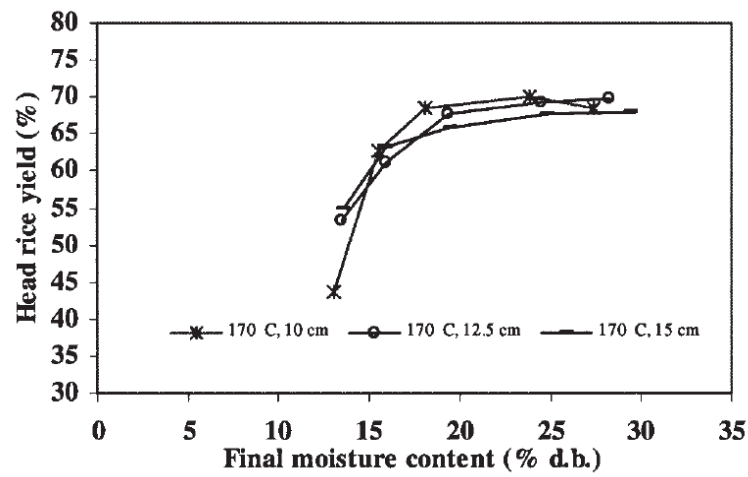


where  $H_{bed}$  is the static bed depth (cm) and  $T$  is the drying temperature (K). The rate of starch gelatinization could be accelerated by increasing the drying temperature or using thinner bed depth; the latter factor nevertheless has only a minor effect. The gelatinization occurred completely within 5-6 min at temperature of 150-160°C and within 4 min at 170°C for a bed depth of 10-15 cm. At these conditions the corresponding moisture content of paddy was around 18% d.b, at which the head rice yield was still as high as 65-70% (see **Figure 3.7**). Further decrease in the moisture content led to a rapid drop in the head rice yield due to moisture-induced stresses, which led to the kernel cracks. Therefore, it is recommended to decrease the moisture content of paddy to 18% d.b.

[Rordprapat et al. \(2005a\)](#) compared the conventional method and the newly-proposed superheated steam drying method to produce parboiled rice. It was found that the head rice yield of a sample from the superheated steam drying method was significantly higher than that of a sample produced conventionally (see **Figure 3.8**). The improved head rice yield reflected the fact that the rice starch gelatinized more completely during superheated steam drying as steam condensation during an early period of superheated steam drying allowed rapid rise in the kernel temperature and induced gel formation. From the superheated steam drying experiments, the kernel temperature reached slightly above 80°C during the first minute of drying and then rose to 100°C within 3-4 min. Such temperature history, in combination with the adequate availability of moisture during an early period of drying, promoted starch gelatinization.

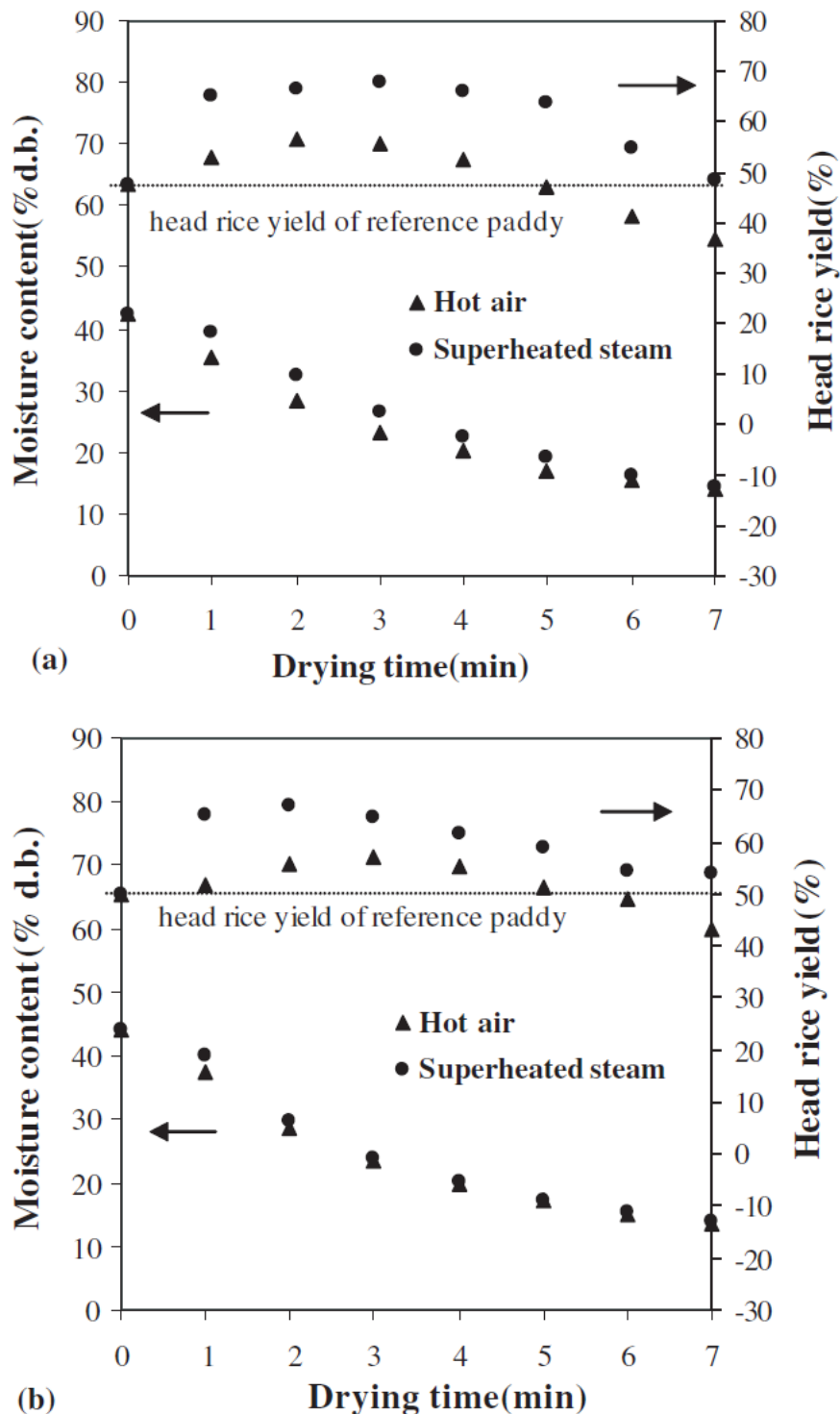


a) Bed depth 10 cm



b) Superheated steam temperature 170 C

**Figure 3.7.** Relationship between head rice yield and final moisture content during superheated steam fluidized bed drying (Taechapairoj et al., 2004)

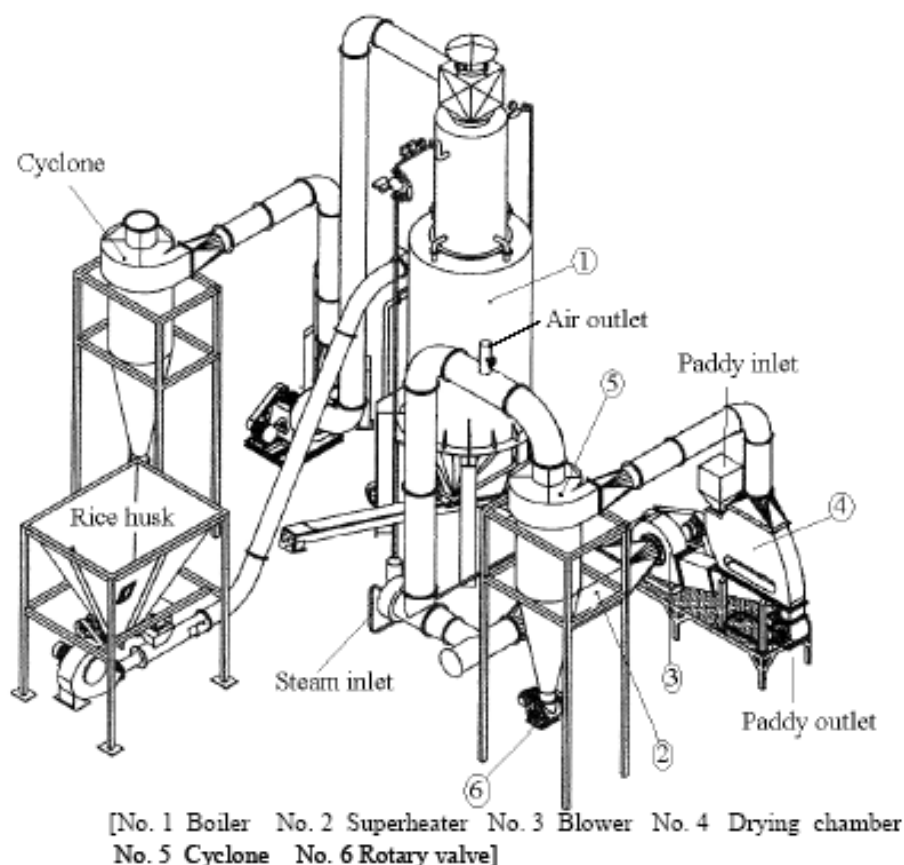


**Figure 3.8.** Drying curves and head yield of rice dried by hot air and superheated steam. (a) Superficial velocity of  $1.3 u_{mf}$  and (b) Superficial velocity of  $1.5 u_{mf}$  (Rordprapat et al., 2005a)

The above-mentioned superheated steam paddy drying process represents a significant progress in the parboiling process as superheated steam itself can act as both steaming and drying media at the same time, thereby reducing some of the steps involved in the parboiling process. With superheated steam as the drying medium, the

steaming and drying can be combined into one step. Thus, all the units from No. 2 to No. 5, inter-connected in **Figure 3.6** by the dotted line, could be replaced by a single superheated steam dryer. Additionally, the processing time would be much shorter compared to the conventional method; it takes only 5 min to reduce the moisture content of paddy from 41% d.b. to 18% d.b.

[Soponronnarit et al. \(2006\)](#) successfully fabricated and tested a pilot-scale continuous superheated steam fluidized bed dryer with a capacity of 100 kg/h. A cyclonic rice husk furnace was used as a heating source to generate steam for the dryer. A schematic diagram of the pilot-scale dryer is shown in **Figure 3.9**. The equipment was also installed and demonstrated to some parboiled rice factories. **Table 3.8** shows the paddy quality after drying with superheated steam. Before drying, paddy was soaked with hot water at 70°C for 7-8 h. The head rice yield of the reference paddy, which was dried in shade, was 56.6%, and the white belly, representing incomplete gelatinization, was 5.6%. After drying, the head rice yield improved, being in the range of 63 to 68%, and the white belly was not observed. Moreover, the hardness of dried parboiled rice significantly increased, while less water was adsorbed upon cooking.



**Figure 3.9.** Schematic diagram of a pilot-scale superheated-steam fluidized bed dryer ([Soponronnarit et al., 2006](#))

**Table 3.8.** Quality of paddy (Chainat 1 variety) soaked at 70 °C for 7-8 h and dried at different inlet steam temperatures ([Soponronnarit et al., 2006](#))

Drying Con- dition	Feed rate (kg/h)	Moisture content (kg/kg dry basis)	Head rice yield (%)	Whiteness	White belly (%)	Hardness (N)	Water adsorp- tion (g water/g rice)
After soaking		0.456 ± 0.008	56.6 ± 1.1 <sup>a</sup>	39.0 ± 0.2 <sup>a</sup>	5.7 ± 0.6 <sup>*a</sup>	37.9 ± 1.3 <sup>a</sup>	3.51 ± 0.07 <sup>a</sup>
128 °C	106	0.290 ± 0.008	63.5 ± 0.6 <sup>b</sup>	32.2 ± 0.8 <sup>b</sup>	0 <sup>b</sup>	48.6 ± 0.9 <sup>b</sup>	2.82 ± 0.05 <sup>b</sup>
144 °C	98	0.230 ± 0.004	66.9 ± 0.6 <sup>c</sup>	29.4 ± 0.5 <sup>c</sup>	0 <sup>b</sup>	51.9 ± 0.6 <sup>c</sup>	2.19 ± 0.01 <sup>c</sup>
160 °C	120	0.218 ± 0.004	67.9 ± 0.6 <sup>c</sup>	28.0 ± 0.6 <sup>c</sup>	0 <sup>b</sup>	55.0 ± 1.3 <sup>d</sup>	1.99 ± 0.05 <sup>d</sup>

### 3.9. Concluding remarks

- Fluidized bed drying technique can be applied to dry paddy without any adverse effect on head rice and color when the technique is managed properly. To preserve the quality, it is recommended that paddy should be dried to the lower moisture content of 22-23% d.b. and tempered for at least 30 min before drying again using ambient air to decrease the moisture content of paddy to 16% d.b. Under such conditions, the utilized drying temperature can be up to 150°C for high- or medium-amylose paddy. Drying paddy at such a temperature affects the cooked rice texture insignificantly as indicated by sensory evaluation. For low-amylose paddy or waxy rice, on the other hand, the drying temperature should be lower than 130°C. This is because some waxy kernels change their appearance from opaque to transparency due to starch gelatinization.
- Fluidized bed drying, in combination with the tempering step, can modify the rice properties, i.e. elongation ratio, whiteness, volume expansion, water uptake, solids loss and pasting properties, to be similar to those of naturally aged paddy. Appropriate condition for accelerating the rice aging process is the use of the drying temperature of 150°C; this should be followed by tempering for at least 90 min. The paddy initial moisture content should be around 33% d.b. In addition to the modified properties, drying paddy at such recommended conditions could reduce the GI value of brown rice from high to low-medium category because of the formation of amylose-lipid complexes.
- Paddy dried by superheated steam fluidized bed drying has physicochemical properties similar to those of parboiled rice. The drying temperature of 150°C is recommended. To maintain high head rice yield, the final moisture content of paddy should not be lower than 18% d.b.

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### References

- Adhikaritanayake, T.B., Noomhorm, A. (1998). Effect of continuous steaming on parboiled rice quality. *Journal of Food Engineering*, 36, 135-143.
- Atwell, W.A., Hood, L.F., Lineback, D.R., Varriano-Marston, E., Zobel, H.F. (1988). The terminology and methodology associated with basic starch phenomena. *Cereal Foods World*, 33, 306-311.
- Bhattacharya, K.R., Desikachar, H.S.R., Subrahmanyam, V. (1964). Curing of freshly harvested rice by heat treatment. *Indian Journal of Technology*, 2, 378-380.
- Brooker, D.B., Bakker-Arkema, F.W., Hall, C.W. (1992). *Drying and storage of grains and oilseeds*. Van Nostrand Reinhold, New York.

- Prachayawarakorn, S., Devahastin, S. and Soponronnarit, S. Paddy Drying and Rice Parboiling
- Champagne, E.T., Wood, D.F., Juliano, B.O. (2004). The rice grain and its gross composition. In E.T. Champagne (Ed.), *Rice chemistry and technology* (pp. 77-107). St. Paul, Minnesota: The American Association of Cereal Chemists.
- Chrastil, J. (1994). Effect of storage on the physicochemical properties and quality factors of rice. In W.E. Marshall, J.I. Wadsworth (Eds.), *Rice science and technology* (pp. 49-81). Marcel Dekker, New York.
- Cnossen, A.G., Jiménez, M.J., Siebenmorgen, T.J. (2003). Rice fissuring response to high drying and tempering temperatures. *Journal of Food Engineering*, 59, 61-69.
- Derycke, V., Vandeputte, G.E., Vermeylen, R., Man, W.De, Goderis, B., Koch, M.H.J., Delcour, J.A. (2005). Starch gelatinization and amylose-lipid interactions during rice parboiling investigated by temperature resolved wide angle X-ray scattering and differential scanning calorimetry. *Journal of Cereal Science*, 42, 334-343.
- Desikachar, H.S.R., Subrahmanyam, V. (1959). Expansion of new and old rice during cooking. *Cereal Chemistry*, 36, 385-391.
- Giner, S.A., Bruce, D.M., Mortimore, S. (1998). Two-dimensional simulation model of steady-state mixed-flow grain drying. part 1: the model. *Journal of Agricultural Engineering Research*, 71, 37-50.
- Kunze, O.R. (1979). Fissuring of the rice grain after heated air drying. *Transactions of the ASAE*, 22, 1197-1202, 1207.
- Jaiboon, P., Prachayawarakorn, S., Devahastin, S., Soponronnarit, S. (2009). Effects of fluidized bed drying temperature and tempering time on quality of waxy rice. *Journal of Food Engineering*, 95, 517-524.
- Jaisut, D., Prachayawarakorn, S., Varayanond, W., Tungtrakul, P., Soponronnarit, S. (2008). Effects of drying temperature and tempering time on starch digestibility of brown fragrant rice. *Journal of Food Engineering*, 86, 251-258.
- Jenkins, D.J.A., Wolever, T.M.S., Taylor, R.H., Baker, H., Fielden, H., Baldwin, J.M., Bowling, A.C., Newman, H.C., Jenkins, A.L., Goff, D.V. (1981). Glycemic index of foods: a physiological basis for carbohydrate exchange. *The American Journal of Clinical Nutrition*, 34, 362-366.
- Li, Y.B., Cao, C.W., Yu, Q.L., Zhong, Q.X. (1999). Study on rough rice fissuring during intermittent drying. *Drying Technology*, 17, 1779-1793.
- Poomsa-ad, N., Soponronnarit, S., Prachayawarakorn, S., Terdyothin, A. (2002). Effect of tempering on subsequent drying of paddy using fluidisation technique. *Drying Technology*, 20, 195-210.
- Poomsa-ad, N., Terdyothin, A., Prachayawarakorn, S., Soponronnarit, S. (2005). Investigations on head-rice yield and operating time in the fluidised-bed drying process: experiment and simulation. *Journal of Stored Products Research*, 41, 387-400.
- Prachayawarakorn, S. (1991). Drying of high moisture paddy by fluidization technique. M.Eng. Thesis, King Mongkut's University of Technology Thonburi, Bangkok, Thailand. (in Thai)

Prachayawarakorn, S., Poomsa-ad, N., & Soponronnarit, S. (2005). Quality maintenance and economy with high-temperature paddy-drying processes. *Journal of Stored Products Research*, 41, 333-351.

Rordprapat, W., Nathakaranakule, A., Tia, W., & Soponronnarit, S. (2005a). Comparative study of fluidized bed paddy drying using hot air and superheated steam. *Journal of Food Engineering*, 71, 28-36.

Rordprapat, W., Nathakaranakule, A., Tia, W., & Soponronnarit, S. (2005b). Development of a superheated-steam-fluidized-bed dryer for parboiled rice. *The Journal of the Royal Institute of Thailand*, 30, 363-378. (in Thai)

Sabbath, M.A. (1970). Convective heat transfer coefficient and tempering effects on cooling rate of shelled corn. Ph.D. Thesis, Purdue University, West Lafayette, Indiana.

Shei, H.-J., & Chen, Y.-L. (1998). Intermittent drying of rough rice. *Drying Technology*, 16, 839-851.

Soponronnarit, S., Chiawwet, M., Prachayawarakorn, S., Tungtrakul, P., & Taechapairoj, C. (2008). Comparative study of physicochemical properties of accelerated and naturally aged rice. *Journal of Food Engineering*, 85, 268-276.

Soponronnarit, S., Kittiporn, K., & Prachayawarakorn, S. (1997). Appropriate operating parameters for fluidized bed corn drying. *RERIC International Energy Journal*, 19, 1-13.

Soponronnarit, S., & Prachayawarakorn, S. (1994). Optimum strategy for fluidized bed paddy drying. *Drying Technology*, 12, 1667-1686.

Soponronnarit, S., Prachayawarakorn, S., Rordprapat, W., Nathakaranakule, A., & Tia, W. (2006). A superheated-steam fluidized-bed dryer for parboiled rice: testing of a pilot-scale and mathematical model development. *Drying Technology*, 24, 1457-1467.

Soponronnarit, S., Prachayawarakorn, S., & Wangji, M. (1996). Commercial fluidized bed paddy dryer. In *Proceedings of the Tenth International Drying Symposium*, Krakow, Poland.

Soponronnarit, S., Wetchacama, S., Swasdisevi, T., & Poomsa-ad, N. (1999). Managing moist paddy by drying, tempering and ambient air ventilation. *Drying Technology*, 17, 335-344.

Steffe, J.F. (1979). Moisture diffusion and tempering in the drying of rough rice. Ph.D. Thesis, University of California, Davis.

Taechapairoj, C., Prachayawarakorn, S., & Soponronnarit, S. (2004). Characteristics of rice dried in superheated-steam fluidized-bed. *Drying Technology*, 22, 719-743.

Tirawanichakul, S., Prachayawarakorn, S., Varanyanond, W., Tunktrakul, P., & Soponronnarit, S. (2004). Effect of fluidized bed drying temperature on various quality attributes of paddy. *Drying Technology*, 22, 1731-1754.



## **Chapter 4**

### **Drying of medicinal plants**

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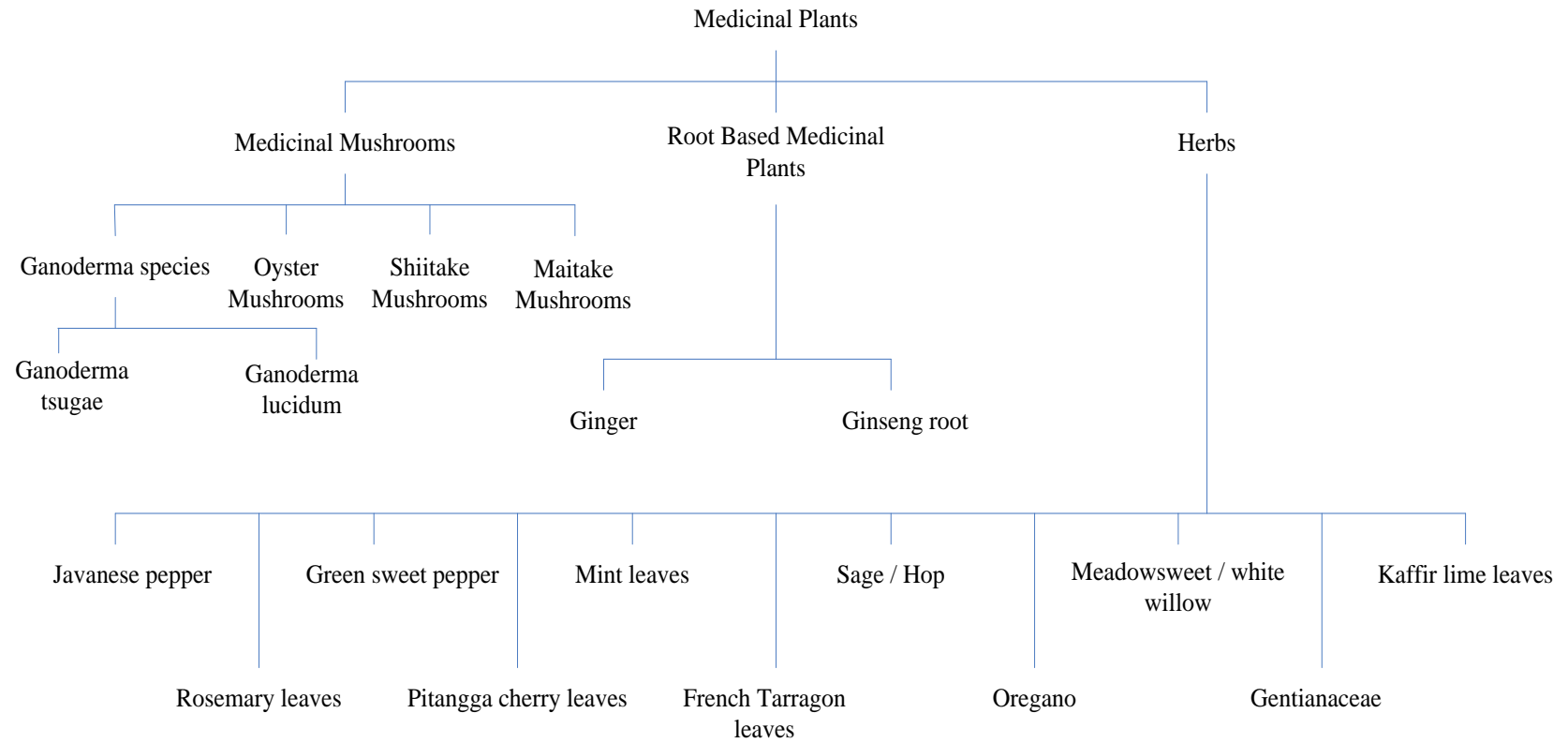
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## 4.1. INTRODUCTION

Medicinal plants are usually used as medicines, spices, flavors, etc. To date, a world-wide increasing demand for medicinal plants has been observed ([Tambunan et al., 2001](#); [Souza and Oliveira, 2006](#); [Perumal, 2009](#)). Bioactive ingredients in medicinal plants are essential for human's health. As prevention is better than curing, people nowadays are paying more attention to improve the body immune system to prevent the attack of diseases. According to a World Health Organization survey, about 70% - 80% of the world's population relies on non-conventional medicine for their primary health care, instead of consuming synthetic drugs ([Cordeiro and Oliveira, 2005](#)). Medicinal plants can be classified as medicinal mushrooms, root based medicinal plants and herbs (**Figure 4.1**). Drying is one of the important post harvest processes for medicinal plants to prevent spoilage of the plants by lowering the amount of moisture in the products during storage. In addition, drying of medicinal plants must be accomplished immediately after harvesting to retain the quality of the plants and to prevent contamination and losses caused by insects, birds and fungi ([Yahya et al., 2001](#)). However, improper thermal drying can cause a significant loss of the active ingredients in medicinal plants as they are thermolabile. Furthermore, adverse effect on the quality of medicinal plants such as browning and degradation of essential oil content occur when they are exposed to high temperatures (e.g. hot air drying) during the drying process ([Arabhosseini et al., 2007](#); [Arslan and Ozcan, 2008](#)). Hence, proper drying techniques are important to enhance the quality of the dried medicinal plants especially in terms of the contents of active ingredients. **Table 4.1** shows the thermolabile active ingredients of selected medicinal plants reported by researchers.



**Figure 4.1.** Classification of medicinal plants

**Table 4.1.** Medicinal plants and thermolabile active ingredients of interest

Medicinal plants	Thermolabile Nutrient / active ingredients	Therapeutic effects	Reference	
Medicinal mushrooms	<i>Ganoderma tsugae</i> Murrill	Water – soluble polysaccharides,  Crude ganoderic acids, total phenolic content	Anti-tumor, anti-cancer, antiviral, anti-HIV, anti-inflammatory, antioxidant.	<a href="#">Paterson, 2006</a> ; <a href="#">Mau et al., 2005</a>
	Oyster mushrooms ( <i>Pleurotus sp.</i> )	Protein, carbohydrate, free amino acid.	Anti-kwashiorkor.	<a href="#">Gothandapani et al., 1997.</a>
	Maitake mushrooms ( <i>Gri-fola frondosa</i> )	Polysaccharides	Anti-cancer, anti-tumor, antiviral and immunomodulating.	Yoshikawa et al., 1999; <a href="#">Wasser and Weis, 1999</a> ; <a href="#">Mau et al., 2002</a>
	Shiitake mushrooms ( <i>Lentinus edodes</i> )	Ergosterol, Vitamin D.	Treatment of rickets disease, hyperproliferative disease, malignancies, osteomalacia and osteoporosis.	<a href="#">Perera et al., 2003</a> ; <a href="#">Peleg, 1997</a> ; <a href="#">Easter and Riggs, 1997</a>
Root based medicinal plants	Ginger rhizomes ( <i>Zingiber officinale Roscoe</i> )	6-Gingerol.	Antioxidant and anti-cancer.	<a href="#">Yogeshwer and Madhulika, 2007</a>
	Ginger leaves ( <i>Alpinia zerumbet, Etlingera elatior, Curcuma longa,</i>	Total phenolic content (TPC), ascorbic acid content (AA),	Antioxidant.	<a href="#">Chan et al., 2009</a>

	<i>Kaempferia galangal</i>			
	America ginseng ( <i>Panax quinquefolius</i> ) roots	Ginsenoside	Anti-fatigues, anti-cancer, anti-inflammatory, immunosuppressive and platelet inhibition.	<a href="#">Jung et al., 1998</a> ; <a href="#">Cho et al., 2002</a> ; <a href="#">Surh et al., 2002</a> ; <a href="#">Lee et al., 2003</a>
	Green sweet peppers	Ascorbic acid.	Antioxidant.	<a href="#">Pal et al., 2008</a>
	Mint ( <i>Mentha piperita</i> ), sage ( <i>Salvia officinalis</i> ) and Hops ( <i>Humulus lupulus</i> )	Ethereal oil, alpha acid.	Antioxidant.	<a href="#">Muller et al., 1989</a>
	Meadowsweet ( <i>Filipendula ulmaria L.</i> ), White willow ( <i>Salix alba</i> )	Total phenols, simple phenols, flavonoids, Hydrolysable tannins, condensed tannins.	Antioxidant, anti-inflammatory.	<a href="#">Harbourne et al., 2009</a>
	Kaffir lime leaf ( <i>Citrus hystrix DC.</i> )	Citronellal.	Antioxidant, anti-cancer.	<a href="#">Yoshida et al., 2005</a>
	Betel leaves ( <i>Piper betle L.</i> )	Hydroxychavicol and eugenol.	Anti-mutagenic and anti-diabetic.	<a href="#">Amonkar et al., 1986</a> ; <a href="#">Arambewala et al., 2005</a>
	Mint ( <i>Mentha longifolia L.</i> )	Essential oil such as pulegone, menthone and limonene.	Decongestant, antispasmodic and antibiotic.	Wyk and Gericke, 2000; <a href="#">Mimica et al., 2003</a> ; <a href="#">Oyediji and Afolayan, 2006</a>
	Rosemary leaves ( <i>Rosma-</i>	Essential oils and mineral con-	Antioxidant and basic source	<a href="#">Lozak et al., 2002</a> ; <a href="#">Mah-</a>

Herbs	<i>rinus officinalis</i> L. Lamia- ceae)	tent (such as K, Ca, Na, Mg, P etc.).	of minerals for human health.	<a href="#">moud et al., 2005</a>
	Pitanga cherry ( <i>Eugenia uniflora</i> ) leaves	Total phenolic contents, flavo- noids	Antioxidant, xanthine-oxidase inhibitory (treatment of gout).	<a href="#">Schmeda-Hirschmann et al., 1987; Amic et al., 2003</a>
	French Tarragon ( <i>Arte- misia dracunculus</i> L.) leaves	Camphene, Sabinene, Myrcene, <i>E-β</i> -ocimene, Estragole, Gera- nyl acetate, Methyl eugenol.	Anti-bacterial, anti-fungal, anti-tumor	<a href="#">Deans and Svobada, 1988; Meepagala et al., 2002</a>
	Oregano ( <i>Origanum vul- gare</i> )	Total phenolic content (TPC)	Antioxidant, anti-bacterial.	<a href="#">Sagdic and Oscan, 2003; Jaloszynski et al., 2008</a>
	Gentianaceae ( <i>Enicos- temma littorale</i> )	Total phenolic content (TPC)	Antioxidant	<a href="#">Sthishkumar et al., 2009</a>

#### 4.1.1. Medicinal mushrooms

Mushrooms are in increasing demand due to its extensive used in culinary preparation. It is now regarded as an important export commodity. They are orient for their flavor and reputed medicinal values. Most of the edible mushrooms such as oyster (*Pleurotus flavus*), button (*Agaricus bisporus*) and shiitake mushrooms (*Lentinus edodes*) are rich in nutrients including free amino acids, protein, carbohydrate, vitamins and minerals ([Casalicchio et al., 1975](#); [Bano and Rajarathnam, 1988](#); [Gothandapani et al., 1997](#)). Besides nutritional values, mushrooms are also found to be medically active in several therapeutic effects such as anti-cancer, anti-tumor, anti-viral, antioxidant and immunomodulating ([Wasser and Weis, 1999](#); [Mau et al., 2002](#)) due to their bioactive ingredients content.

Ganoderma is a famous Chinese medicinal mushroom which belongs to the basidiomycotina class of fungi. Over the past two millennia, Ganoderma has been used as a folk medicine especially in Asian countries to cure various human diseases based on the bioactive ingredients in the fruit bodies, cultured mycelia and basidiospores ([Shiao et al., 1994](#); [Lai and Yang, 2007](#)). It contains pharmacologically active constituents, including polysaccharides, triterpenoids, nucleosides, protein, organic germanium and other trace elements such as fiber ([Cui et al., 2006](#); [Wang et al., 2006](#)). These active constituents could lower blood pressure, blood sugar, enhance immune function, exhibit anti cancer, anti inflammatory, anti oxidant, anti tumor and anti HIV effects ([Paterson, 2006](#); [Mau et al., 2005](#)).

#### 4.1.2. Medicinal Gingers

Ginger is the rhizome of *Zingiber officinale* Roscoe (Zingiberaceae). It is famous for its culinary and medicinal properties. Ginger is exported in the form of volatile oil and powder. Apart from flavoring, it is normally used as an ingredient for traditional herb medicines which could stimulate the appetites, calm the stomach and to prevent vomiting ([Hawlder et al., 2006](#)). [Balladin et al., \(1998\)](#) reported that ginger contains phytochemical groups such as n-gingerol, zingerone, n-shogaol and paradols (main pungent principles of gingers) which are good sources of antioxidant. Besides ginger rhizomes, ginger leaves of different species such as *Alpinia zerumbet*, *Etingera elatior*, *Curcuma longa* and *kaempheria galangal* are also used as food flavoring, traditional medicine and herbal tea.

#### 4.1.3. Ginseng roots

Ginseng, the genus *Panax* which belongs to the family of Araliaceae is known as high value herbal medicine among Asian. Asian ginseng (*Panax ginseng* C. A. Meyer) and North America ginseng (*Panax quinquefolius* L.) are commercially important species in Asian markets ([Sokhansanj et al., 1999](#)). Ginseng roots are the most valuable part of the plants which contain active ingredients namely Rb group ginsenosides (majority), Rg group ginsenosides, and polyacetylenes ([Davidson et al., 2004](#); [Christensen and Jensen, 2009](#)). These active ingredients are found to be medically active with therapeutic effects such as anti-fatigues, anti-cancer, anti-inflammatory, immunosuppressive and platelet inhibition ([Jung et al., 1998](#); [Cho et al., 2002](#); [Surh et al., 2002](#); [Lee et al., 2003](#)). The market value of ginseng roots (USD31.30/kg in 2007) is dependent on a number of factors



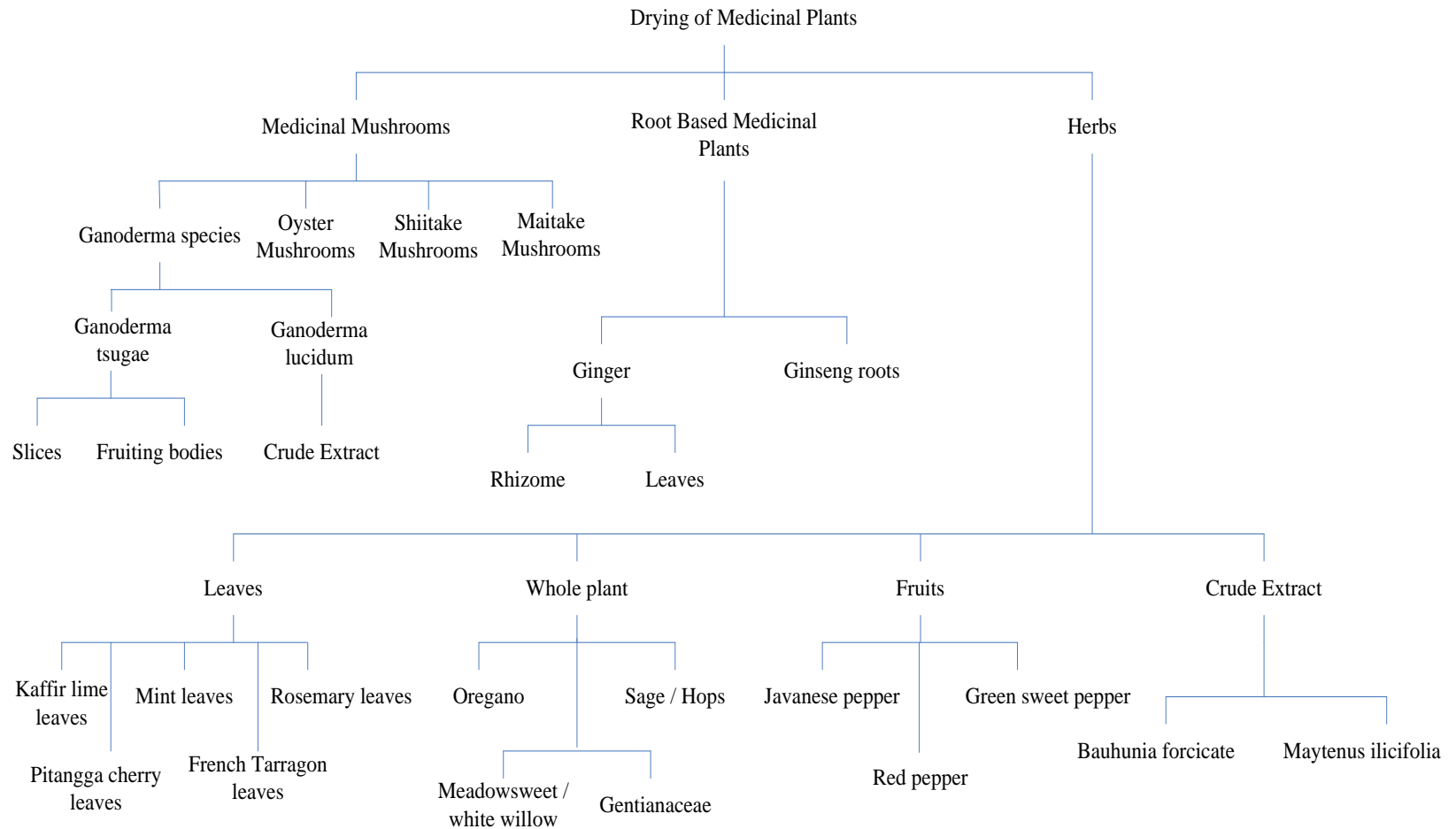
including age of roots, moisture content, shape of dried roots and ginsenoside levels ([Davidson et al., 2004](#); [Davidson et al., 2009](#)).

#### 4.1.4. Herbs

Herbs are medicinal plants which provide the raw material for food, cosmetic and pharmaceutical industries to produce spice, essential oil and drugs ([Oztekin et al., 1999](#)). They are harvested as leaves, blooms or roots. Herb leaves are usually use in culinary to enhance taste and appearance due to their attractive color, aroma and flavor. They are excellent source of mineral constituents which is important in human diet ([Arslan and Ozcan, 2008](#)). Peppers, mint leaves, lime leaves and Meadowsweets are some of the herbs which contain bioactive ingredients such as piper, ethereal oil, phenolic contents, carotinoid, citronellal and ascorbic acid. Most of these active ingredients are function as antioxidant and anticancer ([Phoungchandang et al., 2008](#)).

## 4.2. DRYING OF MEDICINAL PLANTS

Drying is the most important operation in postharvest processing to preserve the quality of those valuable, but perishable medicinal plants. Most bioactive ingredients in the medicinal plants are heat sensitive, hence drying techniques which could retain the bio-active ingredients is essential in the medicinal plants processing industry. To date, many drying methods have been investigated and used for drying of medicinal herbs, such as hot air tray drying, vacuum drying, freeze drying, jet spouted bed drying, microwave-convective drying and heat pump drying ([Tambunan et al., 2001](#); [Soysal and Oztekin, 2001](#); [Cordeiro and Oliveira, 2005](#); [Fatouh et al., 2006](#); [Chan et al., 2009](#); [Harbourne et al., 2009](#); [Pal et al., 2008](#); [Soysal et al., 2009](#)). The effect of drying methods and drying parameters is prominent in terms of quality of dried medicinal plants. Generally, the selection of proper drying methods or drying strategies in handling the drying of medicinal plants are depending on the classification and the part of the medicinal plant (e.g. fruiting body, slices, leaves, root based materials, etc.), the classification of the medicinal plant is shown in **Figure 4.2**. Traditional drying methods such as open air drying and sun drying are still practicing in tropical and subtropical countries, due to the abundant solar energy which is renewable, cheap and environmental friendly ([Basunia and Abe, 2001](#); [Akpinar, 2006](#)). Despite of this, these drying methods are unable to achieve the high quality standards required for the medicinal plants due to contamination and long drying time, which cause inverse effect to the quality of dried medicinal plants. ([Fargali et al., 2008](#)).



**Figure 4.2.** Classification for drying of medicinal plants

#### 4.2.1. Drying of medicinal mushrooms

Drying of medicinal mushrooms is simple and economical as compared to canning and freezing ([Rama and Jacob John, 2000](#)). Pre-drying treatment of medicinal mushrooms such as washing in water with chlorine, pretreatment with potassium metabisulphite (KMS), blanching with salt solution, soaking in curd and fermented whey are normally applied in order to stabilize the color, enhance flavor retention and maintain the texture properties during the drying process ([Gothandapani et al., 1997](#); [Walde et al., 2006](#)). However, most of the pre-drying treatment tends to prolong the total drying time ([Gothandapani et al., 1997](#); [Pal et al., 1997](#); [Martinez-Soto et al., 2001](#); [Walde et al., 2006](#)). In addition, [Gothandapani et al. \(1997\)](#) reported that blanching increased the loss of certain nutrients of mushrooms such as protein, carbohydrate and free amino acid content due to the removal of soluble nutrients. Hence, untreated medicinal mushroom is preferable for preservation of soluble nutrients and reduction of total drying time during the drying process. In this regard, sun drying which requires pretreatment is not a preference.

Research findings on drying of different species of medicinal mushrooms are shown in [Table 4.2](#). Heat pump drying, fluidized bed drying and microwave vacuum drying are reported to be suitable for drying of medicinal mushrooms which are in the form of fruiting body. These methods can be carried out at low drying temperature (28 to 40°C) but higher drying rate can be obtained which results in shorter total drying time; as compared to other drying methods. This in turn produces good product quality in terms of active ingredients content (e.g. water soluble polysaccharides in *Ganoderma* species), rehydration characteristics and color of dried products.

Medicinal mushrooms in form of slices can be dried by microwave vacuum drying. It has been reported that low microwave power level and operating pressure improved the quality attribute of mushrooms slices in terms of internal structure and lead to a better rehydration characteristics ([Giri and Prasad, 2007](#)). On the other hand, hot air drying of *Ganoderma* slices at mild temperature (e.g. 60°C) is suitable for the preservation of basidiospores, which is a valuable medicinal product. However it should be noted that hot air drying at 60°C may cause nutrient loss to the bioactive ingredients that are contained in the mushroom slices. In addition, medicinal mushroom also contains water soluble active ingredients such as polysaccharides and triterpenes in crude extract of medicinal mushrooms. Rapid drying can minimize the loss of these ingredients. Since high temperature is detrimental to heat sensitive ingredients. High temperature is ruled out from the drying strategy. In this regard, two stage drying method could be considered to allow rapid drying at the initial stage for a short period of time followed by low temperature drying such as heat pump drying.

**Table 4.2.** Research findings on drying of medicinal mushrooms in the form fruiting body, slices and crude extract.

Medicinal mushrooms		Drying method	Findings	Reference
<b><i>Gandoerma tsu-gae</i> Murrill</b>	Fruiting bodies	Oven drying.	Drying at low temperature (50°C) with air circulation could retain higher amount of crude ganoderic acids.	<a href="#">Chin et al, 2009</a>
		Heat pump (HP) drying (continuous / intermittent).	Continuous HP drying preserved higher amount of water soluble polysaccharides with shorter total drying time required as compared to intermittent HP drying.	<a href="#">Chin and Law, 2010</a>
	Slices	Oven drying.	Drying of <i>Ganoderma</i> slices at 60°C produced better quality of basidiospores as compared to drying temperature of 50°C and 70°C.	<a href="#">Chin et al, 2008</a>
<b><i>Ganoderma lucidum</i></b>	Crude Extract	Vacuum drying, freeze drying, combined microwave – vacuum and vacuum drying.	Combined microwave – vacuum and vacuum drying resulted in 90% shorter drying time than the conventional drying methods with high retention of total water soluble polysaccharides and triterpenes.	<a href="#">Cui et al., 2006</a>
		Hot air drying, vacuum drying, freeze drying.	The effect of drying methods on the rheological properties and chemical compositions of polysaccharides did not differ significantly except for Uronic acid.	<a href="#">Lai and Yang 2007</a>
<b>Oyster mushrooms</b>	Fruiting body	Hot air cabinet drying, fluidized bed drying, vacuum drying and microwave oven drying.	Fluidized bed drying is a better choice as it required shorter drying time compared to hot air and vacuum drying. Microwave drying caused case hardening although short drying time was required.	<a href="#">Walde et al., 2006</a>
		Hot air drying.	Drying at air temperature of 50°C and at an air velocity of 0.9 ms <sup>-1</sup> appears to be suitable for drying of both	<a href="#">Pal et al., 1997</a>

			treated and untreated oyster mushrooms. The rehydration ratio, texture and appearance of untreated mushrooms were better but treated mushrooms were better in terms of color and flavor.	
		Sun drying, fluidized bed drying and hot air drying.	Drying methods and pretreatment did not have significant effect over the constituents of mushrooms, except blanching which retained lesser amount of protein and carbohydrate, and decreased free amino acid content by nearly 75%.	<a href="#">Gothandapani et al., 1997</a>
		Hot air drying.	Increasing hot air drying temperature enhanced the hardness but reduced the cohesiveness of dried products. Pre-drying treatment such as sulphitation helped in reduction of darkening of mushrooms during drying process whereas blanching caused deterioration of color and texture of dried mushrooms.	<a href="#">Kotwaliwale et al., 2007</a>
<b>Button mushrooms</b>	Slices	Microwave vacuum drying, hot air drying.	Microwave – vacuum drying resulted in a 70 – 90% decrease in drying time and the dried products had better rehydration characteristics as compared to hot air drying. Microwave power level affected the drying rate whereas system pressure was found to be strongly affected the quality attribute. 202 W microwave power level, 6.5 kPa pressure and 7.7 mm slices are the optimum drying conditions for this drying method.	<a href="#">Giri and Prasad, 2007</a>
		Microwave vacuum drying, freeze drying.	Freeze drying and microwave vacuum drying with internal controlled temperature produced dried slices with excellent internal structure. Freeze dried slices at 3 mm	<a href="#">Rodriguez et al., 2005</a>

			Hg pressure produced favorable rehydration value whereas satisfactory sorption values were obtained for microwave vacuum dried slices with temperature controlled at 30°C.	
		Low temperature De-humidified air drying.	Drying of thicker samples at higher temperature showed more than one falling rate period implying that the water diffusivity was not constant and drying rate decreases with time.	<a href="#">Seyhan and Evranuz, 2000</a>
<b>Shiitake mushrooms</b>	Fruiting body	Vacuum heat pump drying.	Low drying temperature and high vacuum pressure enhanced the color degradation of dried product due to long drying time required. The rehydration capacity of vacuum heat pump dried mushroom does not affect significantly by drying temperature but it was found to increase with decreases in vacuum pressure.	Artnaseaw et al., 2009
		Vacuum desiccator drying with UV-B irradiation.	During drying, optimum conversion of ergosterol to vitamin D was found when the moisture content of shiitake mushrooms reached 70% (wet basis). Beyond this level of moisture, the conversion of ergosterol to vitamin D decreased significantly.	Perera et al., 2003
Maitake Mushrooms	Fruiting body	Bubbling type thermohygrostatic drying.	A simulation method was developed by using modified plate drying model and it was found to simulate the drying characteristics of maitake mushrooms accurately for both continuous and intermittent drying process in this dryer for all drying conditions.	<a href="#">Cao et al., 2003</a> ; <a href="#">Cao et al., 2004</a>

#### 4.2.2. Drying of medicinal gingers

Ginger rhizomes are normally dried to extend their shelf life and for the ease of transportation due to the excess of production in certain countries such as Thailand. Matured ginger rhizome contains about 82.6% to 90% moisture content and it is normally dried until about 10% (wet basis) final moisture content ([Hawllader et al., 2006](#)). However, the moisture content of ginger rhizome has been found to decrease with the age of the plant ([Phoungchandang et al., 2009](#)).

**Table 4.3** summarizes the research findings reported in the literature. Based on the findings given in **Table 4.3**, heat pump drying of ginger rhizomes could retain higher amount of 6-gingerol as compared to other drying methods. Heat pump drying using inert gas such as nitrogen and carbon dioxide replacing atmospheric air could improve water diffusivity, consequently enhanced the drying rate of ginger rhizomes. In addition, low oxygen level during heat pump drying of ginger rhizomes in modified atmosphere could preserve most of 6-gingerols by prohibiting the destruction of gingerols. Osmotic dehydration pretreatment can be applied to assist the removal of moisture. It has been reported that the concentration of osmotic solution affects the drying kinetics. Higher concentration of permeating agent could reduce the total drying time where the initial transient period is shortened in the subsequent drying operation. For drying of ginger leaves, non thermal drying methods such as normal air drying are preferable as it could preserve higher amount of antioxidants. In addition, its operating cost is relative lower but drying time is longer; as compared to thermal drying methods. In this aspect, low temperature drying such as freeze drying and heat pump drying can be considered as well.

#### 4.2.3. Drying of ginseng roots

Ginseng is normally grown wild in the forest and in the mountains. It is a delicate herb which quality is mostly dependent on the age and the content of bioactive ingredients. Most of the harvested ginseng roots are dried and sold for export to Asian countries. Fresh ginseng roots contain approximately 70% moisture content (wet basis). In typical industrial operations, they have to be dried to a low moisture content of about 8 – 10% (wet basis) in a short time after harvested ([Chen and Mujumdar, 2007](#); [Davidson et al., 2004](#)). However, Dalfsen, (1998) suggested that good quality of dried roots should have final moisture content in the range of 5.5 to 7.5% depending on the size of roots.

In terms of the color of the dried roots, the suitable drying temperature for drying of ginseng roots was ranged from 29.4°C to 43°C and 38°C was found as optimum temperature to avoid color degradation (Dalfsen et al., 1995; Li and Morey, 1987). However, hot air drying at low drying temperature requires long drying time, which may promote the browning effect of dried roots. In this regard, heat pump drying may be considered. Combined drying methods such as microwave convective drying) and variable temperature drying (e.g. 38-50-38°C) has been reported to reduce the drying time of ginseng drying up to 55.2% as compared to continuous hot air drying at 38°C ([Ren and Chen 1998](#); [Davidson et al., 2004](#)). Moreover, the color of the dried ginseng roots were found to be improved without having significant effect on the retention of ginsenoside if compared to continuous hot air dried ginseng roots.

**Table 4.3.** Research findings on drying of root based medicinal plants, ginger and ginseng

Root Based Medicinal Plants	Drying method	Findings	Reference	
<b>Ginger</b>	Rhizomes	Tray drying, heat pump dehumidified drying, mixed mode solar drying.	Mixed mode solar drying of ginger at 62.82°C required shorter total drying time up to 42.3% as compared to other drying methods and it could retain 6-gingerol as high as heat pump dehumidified dried product.	<a href="#">Phoungchandang et al., 2009</a>
	Rhizomes	Modified atmosphere heat pump drying, normal air drying, freeze drying, vacuum drying.	Modified atmosphere heat pump drying using inert gas such as nitrogen and carbon dioxide improved the effective diffusivity and resulting in better retention of 6-gingerol, which is 43.5 and 45.4% as compared to normal air dried products.	<a href="#">Hawllader et al., 2006</a>
	Rhizomes	Freeze drying.	Short primary drying time was observed with an increase in the sample surface temperature under constant chamber pressure and freezing rate. As compared to the fresh ginger, there was a slight decrease in the quality of freeze dried ginger such as the content of ashes insoluble in acid and solute in alcohol. However, the content of solute in water was increased.	<a href="#">Tambunan et al., 2001</a>
	Rhizomes	Osmotic dehydration pretreatment following oven drying.	Drying time was reduced as shorter “warm up” period can be observed when higher concentration of permeating agent was used, as compared to those pretreated with lower concentration of permeating agents and without osmotic dehydration pretreatment.	<a href="#">Pan et al., 2003</a>
	Leaves	Microwave, oven and sun drying.	Microwave drying gave a prominent effect on the decomposition of antioxidants as compared to other drying	<a href="#">Chan et al., 2009</a>



			methods. Non thermal drying such as normal air drying preserved higher amount of antioxidants. Freeze drying of <i>Alpinia zerumbet</i> and <i>Etingera elatior</i> leaves had significant gains in TPC and antioxidant activity as compared to fresh leaves and dried leaves of other species.	
<b>Ginseng Roots</b>	Hot air drying, combined microwave-hot air drying.	Combined microwave-hot air drying (60W and 38°C) reduced the drying time significantly by 55.2% and 28.7% for both large and small roots as compared to hot air drying at 38°C. This method produced better quality of dried roots in terms of color, as compared to hot air dried products.	<a href="#">Ren and Chen, 1998</a>	
	Cabinet hot air drying.	Drying of ginseng roots (38 to 40°C) with skin epidermis delayed the drying and act as barrier in controlling the moisture loss and center temperature of ginseng root. This in turn controls the degree of root shrinkage.	<a href="#">Sokhansanj et al., 1999</a>	
	Three stage air convective drying.	Three stage drying process (38-50-38°C) of ginseng roots in a force air convection dryer was found to reduce the drying time to about 40% as compared to drying at constant temperature of 38°C. The color and degradation of ginsenoside components in three stage dried ginseng roots have no significant difference with those dried at constant drying temperature. For three stage drying process, the suitable point to change the drying air temperature was found at the area ratio (AR) of 0.70 and 0.50 of the roots which equivalent to moisture content of 1.0 and 0.3 g / g (d.b.).	<a href="#">Davidson et al., 2004</a> ; <a href="#">Davidson et al., 2009</a>	

#### 4.2.4. Drying of herbs

The demand for medicinal herbs and spices increased worldwide during the last decade whereas the total world production of herbs was amounted to 378,000 tons with a value of USD 8.42 billion in 2003 ([Khairallah, 2006](#)). Drying is one of the important post harvest processes for the herbs for storage and export purpose. Hence, good drying technique should be adopted to enhance the quality of herbs. The quality of herbs depends very much on the contents of active ingredients ([Chen and Mujumdar, 2007](#)). As most of the active ingredients are temperature sensitive, the drying temperature for herbs is always limited to 35 to 50°C, at atmospheric pressure. Herbs contain high initial moisture content up to 85% (wet basis) and usually are dried until the final moisture content which is less than 11% (wet basis). Since the amount of moisture in drying of herbs is huge, it is indeed an energy intensive process ([Muller et al., 1989](#)).

Several drying methods such as solar drying, normal air drying, hot air drying with step up drying temperatures, heat pump dehumidified air drying and microwave drying have been reported for the drying of herbal leaves (**Table 4.4**). High drying capacity and relatively low specific energy consumption exhibited by these drying methods promote energy saving for drying of leafy materials.

In terms of product quality, low temperature drying and short heat treatment time by these drying methods could produce dried leaves with low color degradation and higher retention of phytochemical content as compared to sun dried and continuous tray drying. In addition, microwave drying of herbal leaves shows optimum color values in dried products as this method could minimize browning reaction resulted from short heat treatment time. However, the retention of phytochemicals in microwave drying of herbal leaves remains unknown.

For drying of whole medicinal plants such as meadowsweet and willow, oregano and Gentianaceae, convective air drying at low temperature could retain higher amount of total phenolic content in the dried medicinal plants. Low temperature convective air drying rapidly inactivates the degradative enzymes of polyphenols, namely polyphenols oxidases (PPO) in medicinal plants, which in turn preserves higher amount of polyphenols and flavonoids as compared to sun drying and microwave drying. Solar drying has been suggested for drying of sage and hops as the dried products contain higher amount of ethereal oil and alpha acid content compared to continuous air drying.

Heat pump drying and intermittent microwave convective drying are emerging drying methods for drying of fruits of medicinal plants such as pepper. High drying rate and high specific moisture extraction rate reduce the energy consumption and produce relatively good product quality as compared to conventional drying methods.

On the other hand, spray drying and jet spouted drying have been suggested for the drying of crude extracts of herbs. In this regard, retention of nutrient in powder as well as the retention of flavanoid is important quality attributes. Process parameters are to be optimized to maximize the retention of these groups of compound.

**Table 4.4.** Research findings on drying of herbs which are in the form of leave, whole plant, fruit and crude extract

Herbs	Drying method	Findings	Reference
<b>Leaves</b>			
<b>Mint leaves</b>	Closed system solar drying.	Solar dried mint contained 40% higher ethereal oil content and more intensive in terms of color as compared to fuel heated batch dried product. The operating cost was reduced in term of the heating cost as compared to fuel heated batch dryer.	<a href="#">Muller et al., 1989</a>
	Hot air tray drying.	In terms of technical and economic performance, heated air dryer shows high drying capacity, short payback periods and relatively low specific heat energy consumption values during drying at 46°C as compared to the solar green house drying of mint.	<a href="#">Soysal and Oztekin, 2001</a>
	Heat pump (HP) dryer.	The specific energy consumption (SEC) of heat pump dryer for drying of herbs was about 15% lower than the average SEC of conventional dryer.	<a href="#">Baker, 1997</a>
	Hot air drying with step up drying temperature.	Step up drying strategy was introduced for energy saving, by using low temperature (30°C) at the beginning of drying and higher temperature (50°C) at the later stage of the drying process.	Lebert et al., 1992
	Tray drying	Peleg model was found to best describe the desorption isotherms of mint whereas the drying curves were fitted with page’s empirical model, for all drying conditions.	<a href="#">Park et al., 2002</a>

	Hot air cabinet drying.	The effective moisture diffusivities were found to increase considerably with increase in drying temperature and the activation energy of the mint leaves were determined. The drying kinetic of air dried mint leaves was well described by the logarithmic model.	Ibrahim Doymaz, 2006
	Microwave drying.	The effective moisture diffusivities increased with the increase of microwave output power and decrease of material load, which the relationship could be described by Arrhenius type exponential model.	Ozbek and Dadali, 2007
	Air drying, sun drying and oven drying.	Oven drying of <i>Mentha longifolia</i> leaves at 40°C is recommended to reduce the amount of pulegone, menthone, and 1,8-cineole, which is harmful to human's health.	<a href="#">Asekun et al., 2007</a>
<b>Kaffir lime leaves</b>	Tray drying, heat pump dehumidified drying.	Heat pump dehumidified drying reduced the total the total drying time from 15.2% to 30% as compared to tray drying method. Furthermore, heat pump dehumidified dried kaffir leaves could retain up to 30% higher citronellal content as compared to tray dried kaffir leaves.	<a href="#">Phoungchandang et al., 2008</a>
<b>Pitanga cherry leaves</b>	Air drying, sun drying.	Air dried pitanga cherry leaves (room temperature) contain significantly higher total phenolic content as compared to those sun dried leaves.	<a href="#">Kade et al., 2008</a>
<b>French Tarragon leaves</b>	Hot air drying.	Hot air drying of tarragon leaves at low temperature (45°C) is recommended to maintain the quality of dried leaves in terms of color and essential oil content, espe-	<a href="#">Arabhosseini et al., 2007</a> ; <a href="#">Arabhosseini et al.</a>

		cially during storage period. The total drying time was inversely proportional to the drying temperatures and Page model was selected as best fit model to describe the drying kinetic.	<a href="#">2009</a>
<b>Rosemary leaves</b>	Sun drying, oven drying and microwave oven drying.	Microwave oven drying of rosemary leaves shortened the drying time more than 99% to reach equilibrium moisture content, as compared to sun drying and oven drying methods. It shows optimum color values in the dried product. However, the highest mineral values were determined in oven dried samples due to the convective energy and wave strength of the oven during the drying process enhanced the solubility of the elements of the mineral contents.	<a href="#">Arslan and Ozcan, 2008</a>
<b><i>Citrus aurantium leaves</i></b>	Force convection solar dryer.	The drying air temperature significantly influenced the drying kinetic of the leaves, as compared to relative humidity and the drying air flow rate in the dryer. The drying process was controlled by internal moisture diffusion of the leaves.	<a href="#">Mohamed et al., 2005</a>
<b>Parsley leaves</b>	Microwave drying	Microwave drying of Parsley leaves mainly took place in constant period following by a rapid decrease of falling rate for all drying conditions. Increasing the drying material load during microwave drying could enhance the cumulative drying efficiency and reduce the specific energy consumption of the microwave dryer, at constant microwave output power. Highest power level (900W) reduced the drying time and able to maintain the color	<a href="#">Soysal, 2004;</a> <a href="#">Soysal et al., 2006</a>

		which close to the original fresh parsley leaves.	
<b>Betel leaves</b>	Oven drying	Drying process took place mostly in the falling rate period and Logarithmic model was found to be the most suitable model to describe the drying kinetic for all the studied temperatures (40 to 80°C). Drying of betel leaves at 70°C retained the highest concentration of hydroxychavicol and eugenol as compared to other drying temperatures.	<a href="#">Pin et al., 2009</a>
<b>Basil leaves</b>	Microwave drying	Increase of microwave output power from 180W to 900W enhances the total color change and browning index. However, this could be mitigated by drying in larger amount of sample.	<a href="#">Demirhan and Ozbek, 2009</a>
Whole plant			
<b>Meadowsweet and willow</b>	Freeze drying, air drying, oven and tray drying.	Tray drying at low temperature (40°C) is preferred drying method as the drying rate of this method was twice those of the air drying and oven drying method. In addition, tray drying at low temperature could retain most of the flavonoids content of dried meadowsweet and willow.	<a href="#">Harbourne et al., 2009</a>
<b>Sage and hops</b>	Closed system solar drying.	Apart from low operating cost, solar dried sage and hops were found to contain 25% and 70% higher ethereal oil content, respectively, whereas the alpha acid content of solar dried hops was 30% more than the hops dried by fuel heated continuous conveyor dryer.	<a href="#">Muller et al., 1989</a>

<b>Oregano</b>	Freeze drying, convective drying and vacuum microwave (VM) drying.	Reducing the drying temperature in convective drying whereas increasing the microwave power in VM methods tend to gain higher amount of phenolic content and antioxidant in dried products.	<a href="#">Jaloszynski et al., 2008</a>
<b>Gentianaceae</b>	Normal air drying, sun drying, microwave drying.	Both Sun drying and normal air drying of Gentianaceae retained highest amount total phenolic content (TPC) and possessed highest antioxidant power as compared to microwave dried products.	<a href="#">Sthishkumar et al., 2009</a>
Fruits			
<b>Javanese pepper</b>	Freeze drying, oven drying.	At the constant surface temperature of the sample, higher chamber pressure and lower freezing rate tended to shorten the primary and secondary drying time. The piper content of freeze dried Javanese pepper was about 0.6% higher than the oven dried product at 35 to 40°C.	<a href="#">Tambunan et al., 2001</a>
<b>Green sweet pepper</b>	Heat pump drying, hot air drying.	Heat pump drying at 40°C with low relative humidity (19%) of drying air required shorter drying time with the highest drying rate and specific moisture extraction rate as compared to other drying conditions and hot air drying at 45°C. Due to the constraint of energy consumption and degradation of product quality at higher drying temperature, heat pump drying of green sweet pepper was suggested to be conducted at drying temperature of 35°C with relative humidity of 27%.	<a href="#">Pal et al., 2008</a>

<p><b>Red pepper</b></p>	<p>Microwave convective drying, convective hot air drying, commercial belt drying.</p>	<p>Intermittent microwave-convective drying reduced the energy consumption and retained the original colors of red peppers. The hardness was comparable with the convective air dried and commercial belt dried samples, which are are favorable based on the sensory evaluation.</p>	<p><a href="#">Soysal et al., 2009</a></p>
<p>Crude Extracts</p>			
<p><i>Bauhinia forficata Link extract</i></p>	<p>Spray drying.</p>	<p>The product loss on drying of dried extract was found to inversely proportional to the inlet gas temperature and the feed flow rate of the drying gas, but it increases with the ratio between the feed flow rate of the extract to the evaporation capacity of the dryer. The increase in the feed flow rate of drying gas stimulates the thermal degradation of the flavonoids compounds in the final products.</p>	<p><a href="#">Souza and Oliveira, 2006</a></p>
<p><i>Maytenus ilicifolia leaves extract</i></p>	<p>Jet spouted bed drying.</p>	<p>Low values of product loss on drying were obtained at high temperature of drying gas with an increment of static bed height. However, it was found that the degradation rate of flavanoid tends to increase with the static bed height increment, due to the longer time of heat treatment on the concentrated extract.</p>	<p><a href="#">Cordeiro and Oliveira 2005</a></p>



#### 4.2.5. Effective moisture diffusivity of medicinal plants

Effective moisture diffusivity of the materials during drying process is predominated by the drying methods and drying conditions. Based on the reported drying characteristics, most of the medicinal plants showed falling rate period, indicating the drying process is controlled by internal moisture diffusion. Effective moisture diffusivity values of medicinal plants are scarcely reported in the literatures. **Table 4.5** presents the effective moisture diffusivity for some species of medicinal mushrooms and herbs reported in the literature.

**Table 4.5.** Effective moisture diffusivity of several medicinal plants

Classification	Medicinal plants	Drying methods	Drying conditions	Diffusivity / $\times 10^{10} \text{ m}^2 \text{ s}^{-1}$
Medicinal mushrooms	<i>Ganoderma tsugae</i> Murrill	Oven drying	50°C – 80°C	7.20 – 139.72
	Button mushrooms ( <i>Agaricus bisporus</i> )	Dehumidified air drying	20°C – 40°C	0.26 – 1.20
		Microwave drying	60 W – 240 W	1.15 – 29.0
		Vacuum drying	50°C (0.26 mbar – 40 mbar)	1.05 – 1.60
Herbs	Kaffir lime leaf ( <i>Citrus hystrix</i> DC.)	Tray drying	40°C – 60°C	0.43 – 2.41
		Heat pump drying	40°C – 60°C	0.55 – 5.40
	Mint leaves ( <i>Mentha spicata</i> L.)	Cabinet drying	35°C – 60°C	30.67 – 194.10
		Microwave drying	180 W – 900 W	0.31 – 2.07
	Garden mint leaves ( <i>Mentha crispa</i> L.)	Tray drying	30°C – 50°C	0.005 – 0.03

#### 4.3. CLOSING REMARKS

A general overview on the drying of various medicinal plants is provided. The effect of drying on the quality of medicinal plants is covered. Generally, low temperature drying is preferred to preserve the quality of the dried medicinal plants, but the technical and economic performance of the drying process are equally important and must be considered for a viable economic venture. Hence, emerging drying techniques such as two-stage drying, step-up temperatures drying, heat pump drying, intermittent drying and superheated steam drying have attracted the attention of researchers to improve

the drying performance at the same time to enhance the quality of dried medicinal plants. It should be noted that medicinal plants have a wide range of size, shape and characteristics; hence proper selection of dryer is key to the success of drying of medicinal plants whilst maintaining high product quality.

## REFERENCES

Akpınar, E. K. Mathematical modeling of thin layer drying process under open sun of some aromatic plants. *Journal of Food Engineering* 2006, 77, 864 – 870.

Amic, D.; Davidovic- Amic, D.; Beslo, D.; Trinajstić, N. Structure radical scavenging activity relationship of flavonoids. *Croatia Chem Acta* 2003, 76, 55 – 61.

Amonkar, A. J.; Nagabhushan, M.; D'Souza, A. V.; Bhide, S. V. Hydroxychavicol: A new phenolic antimutagen from betel leaf. *Food and Chemistry Toxicology* 1986, 24, 1321 – 1324.

Arabhosseini, A.; Huisman, W.; Boxtel, A. V.; Muller, J. Long-term effects of drying conditions on the essential oil and color of tarragon leaves during storage. *Journal of Food Engineering* 2007, 79, 561 – 566.

Arabhosseini, A.; Huisman, W.; Boxtel, A. V.; Muller, J. Modeling of thin layer drying of tarragon (*Artemisia dracuncululus* L.). *Industrial crops and products* 2009, 29, 53 – 59.

Arambewala, L. S. R.; Arawwawala, L. D. A. M.; Ratnasooriya, W. D. Antidiabetic activities of aqueous and ethanolic extracts of Piper betle leaves in rats. *Journal of Ethnopharmacology* 2005, 102, 239 – 245.

Arslan, D.; Özcan, M. M. Evaluation of drying methods with respect to drying kinetics, mineral content and color characteristics of rosemary leaves. *Energy Conversion and Management* 2008, 49, 1258 – 1264.

Asami, D. K.; Hong, Y. J.; Barret, D. M.; Mitchell, A. E. Comparison of the total phenolic and ascorbic acid content of freeze-dried and air-dried marionberry, strawberry, and corn grown using conventional, organic, and sustainable agricultural practices. *Journal of Agricultural and Food Chemistry* 2003, 51, 1237 – 1241.

Asekun, O. T.; Grierson, D. S.; Afolayan, A. J. Effects of drying methods on the quality of the essential oil of *Mentha longifolia* L. subsp. *Capensis*. *Food Chemistry* 2007, 101, 995 – 998.

Baker, C. G.; *Industrial Drying of Foods*; Chapman & Hall: London, UK, 1997.

Balladin, D. A.; Headley, O.; Chang-Yen, I.; McGaw, D. R. High pressure liquid chromatographic analysis of the main pungent principles of solar dried West Indian ginger (*Zingiber officinale* Roscoe). *Renewable Energy* 1998, 13, 531 - 536.

Bano, Z.; Rajarathnam, S. *Pleurotus* mushrooms Part II. Chemical composition, nutritional value, postharvest physiology, preservation and role as human foods. *CRC Critical Review in Food Science and Nutrient* 1988, 27, 87 – 158.

Basunia, M. A.; Abe, T. Thin layer solar drying characteristics of rough rice under natural convection. *Journal of Food Engineering* 2001, 47, 295 – 301.

Bhattarai, S.; Tran, V.; Duke, C. *The Stability of Gingerol and Shagaol in Aqueous Solutions*; New South Wales; Faculty of Pharmacy University of Sydney, 2006.

Brooker, C. *Human Structure and Function*; 2nd Ed; Mosby; 1997.

Casalichio, G.; Paoletti, C.; Bernicchia, A.; Govi, G. Research on the amino acid composition of some fungi. *Micologia Italiana* 1975, 4, 29 – 41.

Cao, W.; Nishiyama, Y.; Koide, S. Simulation of intermittent drying of Maitake mushroom by a simplified model. *Biosystems Engineering* 2004, 87, 325 - 331.

Cao, W.; Nishiyama, Y.; Koide, S. Thin layer drying of Maitake mushroom analyse with a simplified model. *Biosystems Engineering* 2003, 85, 331 - 337.

Chan, E. W. C.; Lim, Y. Y.; Wong, S. K.; Lim, K. K.; Tan, S. P.; Lianto, F. S.; Yong, M. Y. Effects of different drying methods on the antioxidant properties of leaves and tea of ginger species. *Food Chemistry* 2009, 113, 166 – 172.

Chen, G. H.; Mujumdar, A. S.; *Drying of herbal medicines and tea*. In *Handbook of Industrial Drying*; Mujumdar, A. S., Eds.; CRC Press, Taylor and Francis Group: Boca Raton, 2007; 635 – 646.

Chin, S. K.; Law, C. L. Product quality and drying characteristics of intermittent heat pump drying of *Ganoderma tsugae* Murrill. *Drying Technology* 2010 (In Press).

Chin, S. K.; Law, C. L.; Supramaniam, C. V.; Cheng, P. G.; Mujumdar, A. S. Convective drying of *Ganoderma tsugae* Murrill and effect of temperature on basidiospores. *Drying Technology* 2008, 26, 1524 – 1533.

Chin, S. K.; Law, C. L.; Supramaniam, C. V.; Cheng, P. G. Thin layer characteristics and quality evaluation of air-dried *Ganoderma tsugae* Murrill. *Drying Technology* 2009, 27, 975 – 984.

Cho, J. Y.; Kim, A. R.; Yoo, E. S.; Baik, K. U.; Park, M. H. Ginsenosides from *Panax ginseng* differentially regulate lymphocyte proliferation. *Planta Med.* 2002, 68, 497 – 500.

Christensen, L. P.; Jensen, M. Biomass and content of ginsenosides and polyacetylenes in American ginseng roots can be increased without affecting the profile of bioactive compounds. *Journal of Natural Medicines* 2009, 63, 159 – 168.

Cordeiro, D. S.; Oliveira, W. P. Technical aspects of the production of dried extract of *Maytenus ilicifolia* leaves by jet spouted bed drying. *International Journal of Pharmaceutics* 2005, 299, 115 – 126.

Cui, Z. W.; Xu, S. Y.; Sun, D. W.; Chen, W. Dehydration of concentrated *Ganoderma lucidum* extracted by combined microwave – vacuum and conventional vacuum drying. *Drying Technology* 2006, 24, 595 – 599.

Davidson, V. J.; Li, X.; Brown, R. B. Forced-air drying of ginseng root: Effects of air temperature on quality. *Journal of Food Engineering* 2004, 63, 361 – 367.

Davidson, V. J.; Martynenko, A. I.; Parhar, N. K.; Sidahmed, M.; Brown, R. B. Force – air drying of Ginseng root: Pilot – scale control system for three – stage process. *Drying Technology* 2009, 27, 451 – 458.

Deans, S. G.; Svobada, K. P. Antibacterial activity of French tarragon (*A. dracunculus*) Ankara U. Ziraat. Fakulten 1988, 10, 314–318.

Demirhan, E.; Ozbeck, B. Color change kinetic of microwave dried basil. *Drying Technology* 2009, 27, 156 – 166.

Easter, R.; Riggs, B. L. Vitamin D and osteoporosis. In *Vitamin D*; Feldman, D., Glorieux, F. H., Pike, J. W., Eds.; Academic Press: San Diego, London, Boston, New York, Sydney, Tokyo, Toronto, 1997; 695 – 711.

Fatouh, M.; Metwally, M. N.; Helali, A. B.; Shedid, M. H. Herbs drying using a heat pump dryer. *Energy Conversion and Management* 2006, 47, 2629 – 2643.

Fargali, H. M.; Nafeh, A. E. A.; Fahmy, F. H.; Hassan, M. A. Medical herb drying using a photovoltaic array and solar thermal system. *Solar Energy* 2008, 82, 1154 – 1160.

Fennema, O. W. *Food Chemistry*; Marcel Dekker; New York, 1996.

Giri, S. K.; Prasad, S. Drying kinetics and rehydration characteristic of microwave-vacuum and convective hot air dried mushroom. *Journal of Food Engineering* 2007a, 78, 512-521.

Giri, S. K.; Prasad, S. Optimization of microwave-vacuum drying of button mushroom using respond surface methodology. *Drying Technology* 2007b, 25, 901 – 911.

Gothandapani, L.; Parvathi, K.; Kennedy, Z. J. Evaluation of different methods of drying on the quality of oyster mushroom (*Pleurotus* sp.). *Drying Technology* 1997, 15, 1995 – 2004.

Harbourne, N.; Marete, E.; Jacquier, J. C.; O’Riordan, D. Effect of drying methods on the phenolic constituents of meadowsweet (*Filipendula ulmaria*) and willow (*Salix alba*). *LWT-Food Science and Technology* 2009, 42, 1468 – 1473.

Hawladar, M. N. A.; Perera, C. O.; Tian, M. Comparison of the retention of 6-Gingerol in drying of ginger under modified atmosphere heat pump drying and other drying methods. *Drying Technology* 2006, 24, 51 – 56.

Jaloszynski, K.; Figiel, A.; Wojdylo, A. Drying kinetics and antioxidant activity of oregano. *Acta Agrophysica* 2008, 11, 81 – 90.

Jung, K. Y.; Kim, D. S.; Oh, S. R.; Lee, I. S.; Lee, J. J.; Park, J. D.; Kim, S. I.; Lee, H. K. Platelet activating factor antagonist activity of ginsenosides. *Biological and Pharmaceutical Bulletin*. 1998, 21, 79 – 80.

Kade, I. J.; Ibukun, E. O.; Nogueira, C. W.; Rocha, J. B. T. Sun drying diminishes the antioxidant potentials of leaves of *Eugenia uniflora* against formation of thiobarbituric acid reactive substances induced in homogenates of rat brain and liver. *Experimental and Toxicologic Pathology* 2008, 60, 365 – 371.

Khairallah, K. Fresh cut herbs for export in Jordan. In *Regional Consultation on Linking Producers to Markets*, Cairo, Egypt, January 29 – February 2, 2006, 1 – 11.

Kotwaliwale, N.; Bakane, P.; Verma, A. Changes in textural and optical of oyster mushrooms during hot air drying. *Journal of Food Engineering* 2007, 78, 1207 – 1211.

Lai, L. S.; Yang, D. H.; Rheological properties of the hot water extracted polysaccharides in Ling-Zhi (*Ganoderma lucidum*). *Food Hydrocolloids* 2007, 21, 739 – 746.

Lee, Y. J.; Jin, Y. R.; Lim, W. C.; Park, W. K.; Cho, J. Y.; Jang, S. Y.; Lee, S. K. Ginsenoside-Rb1 act as a weak phytoestrogen in MCF-7 human breast cancer cells. *Arch. Pharmacol. Res.* 2003, 26, 58 – 63.

Li, X. Improved Ginseng Drying With Three-Stage Temperature Control; M.Sc. Thesis; University of Guelph, 2002.

Li, Y. R.; Morey, V. Thin-layer drying rates and quality of cultivated American Ginseng. *Transactions of The ASAE*, 30, 842 – 847.

Lozak, A.; Soltyk, K.; Ostapczuk, P.; Fijalek, Z. Determination of selected trace elements in herbs and their functions. *Science of the Total Environment* 2002, 289, 33 – 40.

Martinez-Soto, G.; Ocana-Camacho, R.; Paredes-Lopez, O. Effect of pretreatment and drying on the quality of Oyster mushrooms (*Pleurotus Ostreatus*). *Drying Technology* 2001, 19, 661 – 672.

Mau, J. L.; Chen, P. R.; Yang, J. H. Ultraviolet irradiation increased vitamin D2 content in edible mushrooms. *Journal of Agricultural and Food Chemistry* 1998, 46, 5269 – 5272.

Mau, J.L.; Liu, H.C.; Chen, C.C. Antioxidant properties of several medicinal mushrooms. *Journal of Agricultural and Food Chemistry* 2002, 50, 6072 - 6077.

Mau, J. L.; Tsai, S. Y.; Tseng, Y. H.; Huang, S. J. Antioxidant properties of hot water extracts from *Ganoderma tsugae* Murrill. *LWT* 2005, 38, 589 – 597.

Mahmoud, A. A.; AL-Shihry, S. S.; Son, B. W. Diterpenoid quinones from rosemary (*Rosmarinus officinalis* L.). *Phytochemistry* 2005, 66, 1685 – 1690.

Meepagala, K. M.; Sturtz, G.; Wedge, D. A. Antifungal constituents of the essential oil fraction of *Artemisia dracunculus* L. Var. *dracunculus*. *Journal of Agricultural Food Chemistry* 2002, 50, 6989–6992.

Mimica, D. N.; Bozin, B. Sokovic, M. Mihailovic, B. Matavuj, M. Antimicrobial and antioxidant activities of three *Mentha* species Essentials oils. *Planta Medica* 2003, 69, 413 – 419.

Mohamed, L. A.; Kouhila, M.; Jamali, A.; Lahsasni, S.; Kechaou, N.; Mahrouz, M. Single layer solar drying behaviour of citrus aurantium leaves under force convection. *Energy conversion and Management* 2005, 46, 1473 – 1483.

Muller, J.; Reisinger, G.; Kisgeci, J.; Kotta, E.; Tesic, M.; Muhlbauer, W. Development of a greenhouse-type solar dryer for medicinal plants and herbs. *Solar and Wind Energy* 1989, 6, 523 – 530.

Muller, J.; Reisinger, G. Muhlbauer, W. Drying of medicinal and aromatic plants in a solar greenhouse dryer. *Landtechnik*, 2, 58 – 65.

Oztekin, S.; Bascetincelik, A.; Soysal, Y. Crop drying programme in Turkey. *Renewable Energy* 1999, 16, 789 – 794.

Oyedjeji, O. A.; Afolayan, A. J. Chemical composition and antibacterial activity of Essentials oil of the South Africa *Mentha longifolia*. *Journal of Ethnopharmacology* 2006, 18, 57 – 59.

Pal, U. S.; Chakraverty, A. Thin layer convective-drying of mushrooms. *Energy Convers. Mgmt* 1997, 38, 107 – 113.

Pal, U. S.; Khan, M. K.; Mohanty, S. N. Heat pump drying of green sweet pepper. *Drying Technology* 2008, 26, 1584 – 1590.

Pan, Y. K.; Zhao, L. J.; Zhang, Y.; Chen, G.; Mujumdar, A. S. Osmotic dehydration pre-treatment in drying of fruits and vegetables. *Drying Technology* 2003, 21, 1101 – 1114.

Park, K. J.; Vohnikova, Z.; Brod, F. P. R. Evaluation of drying parameters and desorption isotherms of garden mint leaves (*Mentha crispa* L.). *Journal of Food Engineering* 2002, 51, 193 – 199.

Paterson, R. R. M. *Ganoderma* – A therapeutic fungal biofactory. *Phytochemistry* 2006, 67, 1985-2001.

Peleg, S.; Molecular basis for differential action of vitamin D analogues. In *Vitamin D*; Feldman, D., Glorieux F. H., Pike, J. W., Eds.; Academic Press: New York, 1997; 1011 – 1025.

Perera, C. O.; Jasinghe, V. J.; Ng, F. L.; Mujumdar, A. S. The effect of moisture content on the conversion of ergosterol to vitamin D in Shiitake mushrooms. *Drying Technology* 2003, 21, 1091 – 1099.

Perumal, K. Indigenous technology on organic cultivation of Reishi (*Ganoderma lucidum*); Shri AMM Murugappa Chettiar Research Centre; Chennai, 2009.

Phoungchandang, S.; Nongsang, S.; Sanchai, P. The development of Ginger drying using tray drying, heat pump dehumidified drying, and mixed-mode solar drying. *Drying Technology* 2009, 27, 1123 – 1131.

Phoungchandang, S.; Srinukroh, W.; Leenanon, B. Kaffir lime leaf (*Citrus hystric* DC.) drying using tray and heat pump dehumidified drying. *Drying Technology* 2008, 26, 1602 – 1609.

Rama, V.; Jacob John, P. Effects of methods of drying and pretreatments on quality of dehydrated mushroom. *Indian Food Packer* 2000, 54, 59 – 64.

Ren, G.; Chen, F. Drying of American Ginseng (*Panax quinquefolium*) roots by microwave-hot air combination. *Journal of Food Engineering* 1998a, 35, 433 – 443.

Ren, G.; Chen, F.; Chen, H. Physical properties of *Panax ginseng* and *Panax quinquefolium* starch, *Starch* 1998b, in press.

Rodriguez, R.; Lombrana, J. I.; Kamel, M.; de Elvira, C. Kinetic and quality study of mushroom drying under microwave and vacuum. *Drying Technology* 2005, 23, 2197 – 2213.

Sagdic, O.; Ozcan, M. Antibacterial and activity of Turkish spice hydrosols. *Food Control* 2003, 14, 141 – 143.

Schmeda-Hirschmann, G.; Theoduloz, C.; Franco, L.; Ferro, E.; Rojas de Arias A. Preliminary pharmacological studies on *Eugenia uniflora* leaves: xanthine oxidase inhibitory activity. *Journal of Ethnopharmacol* 1987, 21, 183 – 186.

Seyhan, F. G.; Evranuz, O. Low temperature mushroom (*A. bisporus*) drying with desiccant dehumidifiers. *Drying Technology* 2000, 18, 433 – 445.

Shiao, M. S.; Lee, K. R.; Lin, L. J.; Cheng, T. W.; Natural products and biological activities of the Chinese medicinal fungus, *Ganoderma lucidum*. In *Proceedings of the ACS Symposium Series on Food Phytochemicals for Cancer Prevention II*. American Chemical Society: Washington DC, 1994; 342–354.

Sokhansanj S.; Bailey, W. G.; Van Daltsen, K. B. Drying of North American ginseng roots. *Drying Technology* 1999, 17, 2293 – 2308.

Souza, C. R. F.; Oliveira, W. P. Powder properties and system behavior Turing spray drying of *Bauhinia forficata* link extract. *Drying Technology* 2006, 24, 735 – 749.

Soysal, Y. Microwave drying characteristics of parsley. *Biosystems Engineering* 2004, 89, 167 – 173.

Soysal, Y.; Ayhan, Z.; Esturk, O.; Arikan, M. F. Intermittent microwave-convective drying of red pepper: Drying kinetics, physical (color and texture) and sensory quality. *Biosystems Engineering* 2009, 103, 455 – 463.

Soysal, Y.; Oztekin, S. Technical and economic performance of a tray dryer for medicinal and aromatic plants. *Journal of Engineering Research* 2001, 79, 73 – 79.

Soysal, Y.; Oztekin, S.; Eren, O. Microwave drying of Paisley: Modelling, kinetics, and energy aspects. *Biosystems Engineering* 2006, 93, 403 – 413.

Sthishkumar, R.; Lakshmi, P. T. V.; Annamalai, A. Effect of drying treatment on the content of antioxidants in *Enicostemma littorale* Blume. *Research Journal of Medicinal Plant* 2009, 3, 1 – 9.

Surh, Y. J.; Lee, J. Y.; Choi, K. J.; Ko, S. R. Effects of selected ginsenosides on phorbol ester induced expression of cyclooxygenase-2 and activation of NF-kappa B and ERK1/2 in mouse skin. *Ann. N. Y. Acad. Sci.* 2002, 973, 396 – 401.

Tambunan A. H.; Yudistira; Kisdiyani; Hernani. Freeze drying characteristics of medicinal plants. *Drying Technology* 2001, 19, 325 – 331.

Tseng, Y. H.; Lee, Y. L.; Li, R. C.; Mau, J. L. Non-volatile flavor components of *Ganoderma tsugae*. *Food Chemistry* 2005, 90, 409 – 415.

Van Daltsen, B.; Bailey, W. G.; Goo, Y. Drying north American ginseng in British Columbia, Canada. In proceedings of the International Ginseng Conference; Bailry, W. G., Whitehead, C., Proctor, J. T. A., Kyle, J. T., Eds.; Vancouver, British Columbia, Canada, 1995; 278 – 291.

Van Daltsen, B. Ginseng dryer operation; Farm Mechanization Fact Sheet; Ministry of Agriculture; Food and Fisheries; British Columbia, Canada, 1998.

Van, W. B.; Gericke, N. *People's Plants*; Pretoria; Briza Publications, 2000.

Walde, S.G.; Velu, V.; Jyothirmayi, T.; Math R.G. Effects of pretreatments and drying methods on dehydration of mushroom. *Journal of Food Engineering* 2006, 74, 108-115.

Wang, X. M.; Yang, M.; Guan, S. H.; Liu, R. X.; Xia, J. M.; Bi, K. S.; Guo, D. A. Qualitative determination of six major triterpenoids in *Ganoderma lucidum* and related species by high performance liquid chromatography. *Journal of Pharmaceutical and Biomedical Analysis* 2006, 41, 838 – 844.

Wasser, S. P.; Weis, A. L. Medicinal properties of substances occurring in higher Basidiomycetes mushrooms: current perspective (review). *International Journal of Medicinal Mushrooms* 1999, 1, 31-62.

Yahya, M.; Sopian, K.; Daud, W. R. W.; Othman, M. Y.; Yatim, B. Design of solar assisted dehumidification of air drying system for medicinal herbs: Pegaga leaf, In Proceedings of the Second Asian-Oceania Drying Conference (ADC 2001), Batu Feringhi, Pulau Pinang, Malaysia, 2001; 383 – 392.

Yogeshwer, S.; Madhulika, S. Cancer preventive properties of ginger: A brief review. *Journal of Food Science* 2007, 45, 683 - 690.

Yoshida, N.; Takagi, A.; Kitazawa, H.; Kawakami, J. Inhibition of P-glycoprotein-mediated transport by extracts of monoterpenoids contained in *Zanthoxyli fructus*. *Toxicology and Applied Pharmacology* 2005, 209, 167 – 173.



## **Chapter 5**

# **Use of Drying in Processing of Functional Foods**

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## ABSTRACT

A functional food appears similar to or is a conventional food that is consumed as part of a usual diet and has a physiological benefit or assists in the management or prevention of chronic and/or degenerative disease. Functional food products are mainly cereals, fruits and vegetable based. In the manufacture of most of the functional food products, drying is one of the most important unit operations. The main losses in bioactive substances occur due to water solubility, mass transfer, heat sensitivity, and enzymatic oxidation during drying. During the process of drying, changes in quality parameters in dried products takes place. The extent of the change depends on type of drying process and levels of the process parameters selected. This chapter presents an overview of the various drying techniques used in the development of various functional foods. The details on effect of drying technique on the retention of bioactive components in functional foods are discussed in the chapter. Also, future research needs in application of drying process in functional food manufacture are mentioned

## 5.1. INTRODUCTION

With increased life expectancy and greater media coverage of health care issues, consumers are more interested in the potential benefits of nutritional support for disease control or prevention. At the same time, advances in food/ingredient technologies, coupled with a better understanding of specific nutrient properties have stimulated an explosion of innovative nutrition products by food manufacturers <sup>[1]</sup>. There is growing recognition of the potential role for functional foods in helping to reduce health risks and improve health quality. In the global market, functional foods have become a multi-billion dollar industry. Functional foods are the fastest growing segment of today's food industry. Functional foods defined as "a food similar in appearance to conventional food, consumed as a part of the usual diet which contains biological active components with demonstrated physiological benefits and offers the potential of reducing the risk of chronic disease beyond basic nutritional functions". Foods that may have health benefits beyond the traditional nutrients that they contain are often called "functional foods". The concept of functional foods has become popular, first in Japan and later in other countries, including U.S <sup>[2]</sup>. As a working definition, a food can be said to be functional if it contains a component (whether or not a nutrient) that benefits one or a limited number of functions in the body in a targeted way that is relevant to either the state of well-being and health or the reduction of the risk of a disease <sup>[3]</sup>, or if it has physiologic or psychologic effect beyond the traditional nutritional effect<sup>[4]</sup>. A functional food component can be a macronutrient if it has specific physiological effects (e.g. Omega-3 fatty acids) or an essential micronutrient if its intake is more than the daily recommendations. Indeed, beyond its nutritional (metabolic requirements) value and function of providing pleasure, a diet provide consumers with components able to both modulate body functions and reduce the risk of some diseases <sup>[5]</sup>. Selected examples of functional foods, their functional components and health benefits are presented in **Table 5.1**. Production of functional foods is being recognized as the number one global food industry as changing trends in population demography, consumer affluence, increased education, life ex-

pectancy and improved health care give rise to rapidly emerging diet and health conscious consumer clientele [12].

**Table 5.1. Health benefits of various functional components**

Type of functional food	Functional component	Benefit to health and well being
Whole oat products	Beta - glucan	Lower cholesterol levels
Psyllium	Soluble fiber	Lower cholesterol levels
Whole soy foods and foods made with soy protein	Soy protein	Lower cholesterol levels
Special fortified margarines or salad dressings	Plant stanol or sterol esters	Lower cholesterol levels
Sugarless chewing gums and candies	xylitol	Helps prevent dental caries
Fatty fish	Omega-3 fatty acids	Reduced risk of heart disease
Cranberry juice	Proanthocyanidins, Phenolic acid, anthocyanins, flavonols, procyanidins, proanthocyanidins	Reduced urinary tract infections, Antioxidant, antibacterial, antiinflammatory
Garlic	Organo sulphur compounds	Lower cholesterol levels
Green tea	Catechins	Reduced risk of some types of cancer
Tomatoes and tomato products	Lycopene, Carotenoids, insoluble fibers, vitamin A	Reduced risk of some types of cancer, especially prostate cancer, Antioxidant, prooxidant, hypoglycemic
Dark green leafy vegetables	Lutein	Reduced risk of age related macular degeneration
Meats and dairy products	Conjugated linoleic acid	Reduced risk of breast cancer, increased muscle mass
Eggs	Omega-3 content	Reduced risk of heart disease
Cruciferous vegetables	Isothiocyanates, indoles	Reduced risk of some types of cancer
Fermented dairy products	Probiotics	Support gastrointestinal tract health, boost immunity
Blueberries	Phenolic acids, anthocyanins,	Antioxidant, antiinflammatory,

	fl avonols, fl avanols, procyanidins, proanthocyanidins, tannins	antiedemic, astringent, regeneration of rhodopsin
Reference [2,5,6, 7, 8, 9, 10,11]		

### 5.1.1. Economic Opportunities from Functional Foods

Functional foods entered the global markets with force in past decade and rapidly gained market share conservatively esteemed to exceed that for organic foods. Thus, in addition to health benefits, functional foods present new economic opportunities. Moreover, demand for functional foods within the developing countries is growing, presenting lucrative opportunity to develop domestic market. Besides the opportunity for diversified and high value production, farming for the functional foods industry can benefit primary producers and rural communities in other ways. Even though developing countries are rich source of raw materials for functional food product because of their vast biodiversity and cost advantages in crop production, developing a functional food industry in these countries faces significant barriers. The cost of bringing new product to the market can be significant, especially the upfront costs associated with high value food processing and exporting (search for markets, product research and certification, meeting regulatory demands, consumer research and public relations) [13].

### 5.1.2. Disease/ Target Functions

This section includes the concepts of functional foods by focusing on major target functions and the science base required for providing evidence that specific nutrients positively affect function. Functional foods have nutritional and physiological benefits and are applicable in disease prevention and management. The application of biotechnology techniques for the development of functional food plants with higher levels of bioactive components or increased availability of nutrients would greatly benefit most populations in developing countries and improve the health and nutritional status overall [14]. Probiotics (lactobacilli and bifidobacteria) and prebiotics (inulin and its hydrolysate oligofructose) are recent concepts in nutrition that have already and will in the future be used to support the development of functional foods targeted towards gastrointestinal functions. Different studies evidenced that plant based diets, in particular those rich in vegetables and fruits, provide a great amount of antioxidant phytochemicals such as Vitamin C and E, glutathione, phenolic compounds and vegetable pigments which give defence against cellular damage. Lifestyle factors including a diet high in saturated fat, in energy and in cholesterol have an important role in risk of cardiovascular disease. Consuming a diet rich in natural antioxidants has been associated with prevention and/or treatment of Cardio Vascular Disease [15].

## 5.2. DRYING AND FUNCTIONAL FOODS

Drying is one of the important unit operations used in formulation of a functional food product. Many food ingredients are heat labile and thus the effect of various tem-

peratures on these ingredients is the focus. Drying can be done basically by two methods, natural and artificial, sun drying is considered for natural and artificial – by means of heat from other sources in specially constructed dryers. Mainly artificial method of drying is used as it gives good quality product than sun drying method, since it gives faster processing and less exposure time to enzymatic changes which may injure the processing material like fruits, vegetables etc. Some of the major criteria for the quality of the products are; shrinkage of cells, less rehydration ratio, wettability, movement of solids, case hardening, and loss of volatile aroma components. Several functional food ingredients are subjected to various drying methods during product formulation. Most of the functional components are temperature sensitive. Therefore, to maintain the nutritional as well as the pleasing appearance of the functional food product, selection of suitable drying method with the temperature control is very important.

### 5.3. DRYING METHODS USED TO MANUFACTURE FUNCTIONAL FOODS

Literature shows several studies on drying applications in functional food manufacture.

Functional food like garlic, tomatoes, grapes, berries, oats, mushroom, fortified milk, probiotic foods etc. are dried using methods like freeze, spray, fluidized bed, spouted bed, kiln, osmotic, foam mat, hot air and microwave drying. Literature review indicates that the process variables in the drying plays major role in retention of functional components and therefore, detailed study of drying process is important during design and formulation of functional food. Summary of the different drying techniques applicable to functional food formulation is given in **Table 5.2** [13], [16], [17], [18], [19], [20], [21], [22], [23], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40] and the important methods are discussed in foregoing subsections.

**Table 5.2.** Drying methods suitable for various functional foods

Functional Food Product	Drying Method	Reference
Probiotic, Flavonoids in centella asiatica	Freeze Drying	[16]
Egg White Powder	Foam Mat Freeze Drying	[17]
Calcium Fortified Milk Probiotic Bacteria	Spray Drying	[13, 18, 19]
Carrots, Canberries, Blueberries	Fluidized Bed Drying and Encapsulation	[20, 21]
Soyabean, Blueberries	Spouted Bed Drying	[22]
Oats	Kiln Drying	[23, 24]
Blueberries, Cranberries	Osmotic Dehydration	[25]

Maitake Mushroom	Thin Layer Drying	[27]
Whole Button Mushroom, Carrot, garlic, garlic cloves	Microwave Drying	[28, 29, 30]
Mushroom, Carrot, Bitter gourd, Red Sweet Pepper	Convective Drying	[31, 32, 33]
Carrot	Microwave Vacuum Drying	[34, 35, 36]
Seaweed	Sun, oven, and freeze-drying	[37]
Passion flower	Spray and spouted bed	[38]
Echinacea	Freeze-drying, vacuum-microwave, and convective drying	[39]
Chives	Freeze-drying, vacuum-microwave, vacuum-microwave _ convection, vacuum-microwave _ vacuum, and convection drying	[40]

### 5.3.1. Freeze drying

Freeze drying (Lyophilization) works on the principle of freezing the material and reducing the surrounding pressure to allow the frozen water in the material to sublime directly from the solid phase to gas. This minimizes compositional changes during dehydration and contributes to obtain very low levels of final moisture content. Freeze drying is well known drying technique for its ability to produce excellent quality dehydrated product. Therefore, it is commonly used in functional food formulation. The functional food industry requires an improvement of probiotic strain stability during storage, especially when they are stored at room temperature. Freeze drying is one of the most common methods to dry the probiotic strain. Savini et al. [16] studied the viability of freeze-dried *Lactobacillus rhamnosus* IMC 501® and *Lactobacillus paracasei* IMC 502® using different protective agents (i.e., glycerine, mannitol, sorbitol, inulin, dextrin, Crystalean®) and compared with semi skimmed milk (SSM) control. They observed no significant differences between the tested protectants and the control (SSM) during storage at refrigerated conditions. At room temperature storage conditions, they found that only glycerine had stabilized the viability better than other tested substances. Mohd Zainol et al. [41] compared the freeze drying with hot air oven and vacuum drying in the degradation of flavonoids in *Centella asiatica* and reported that air oven method results in highest total flavonoids degradation followed by vacuum oven and freeze dried with percent degradation of 97, 87.6 and 73 % respectively. Catechin and rutin were found to be the

most stable flavonoids with percent degradation up to 35 %, 66 % and 76 % for freeze dried, vacuum oven and air oven respectively.

Retention of total and individual ginsenosides in ginseng roots was verified for freeze drying by Popovich et al. [42]. Freeze-drying system provides better retention and extraction efficiency of total ginsenosides than convective drying at 70°C [43].

### **5.3.1.1 Foam Mat Freeze Drying**

The high cost of operation associated with freeze drying can restricts its usage to functional foods. Foam-mat drying can be used for the functional products that can be foamed to increase the surface area to improve the mass transfer rate. Foam-mat freeze drying is one of the promising methods of drying of, which tries to utilize the advantages of both freeze drying and foam-mat drying to produce better quality functional food products like egg white powder. Muthukumaran [17] used foam mat drying technique to prepare egg white powder. He used different stabilizers (Methyl cellulose, Propylene glycol alginate and Xanthan gum) to optimize foam stability and determined the bubble size distribution using microscopy to understand foam structure. His results showed that Xanthan gum at 0.125% provide sufficient stability for freeze drying. Also, he conducted experiments to study foam-mat freeze drying of egg white, in an effort to determine the suitability of their method. His results indicated that the addition of Xanthan Gum during foaming had a positive impact in reducing the total drying time producing excellent quality egg white powder. The addition of stabilizer also plays an important role in improving drying.

### **5.3.2. Spray drying**

Spray drying has important application in functional food formulation. The spray drying process consists of the conversion of a spray of pumpable liquid (i.e., juices, slurries, and purees) into a dry particulate (i.e., powder, granules, or agglomerate) by exposure to a hot (150 to 200°C) medium [44]. Operating and dryer components that influence the final product include the feed rate, temperature of the inlet drying air, pressure of compressed air at the nozzle, air flow (i.e., cocurrent, counter current, or mixed flow), atomizer design, and air heating method. Spray dryers are the most widely used drying systems for the formation of powdered food additives and flavors in the dairy, beverage, and pharmaceutical industries. This drying method has been investigated for many products including milk, tomato pulp, flaxseed gum, medicinal plant extracts, and field pea protein [45].

The preparation of spray dried calcium fortified milk powders with functional salts is evident from literature. The choice of appropriate calcium salts for fortification of milk or milk powders is a challenge for the dairy industry. Depending on the form of salt used, the addition of calcium to dairy products has the potential to influence the colour, texture, stability, flavour, and processing characteristics of the final product [46]. A new technique was developed by Williams et al. [46] for the calcium fortification of liquid milk and calcium-fortified milk powders, based on results obtained in liquid milk systems. The process involved adding a combination of orthophosphates with a soluble calcium salt (calcium chloride) to milk, subjecting the milk to low-heat (72 °C/30 s) or high-heat (90 °C/10 min) treatment, concentrating the milk to approximately 450 g total solids•kg<sup>-1</sup> and spray drying the concentrate to produce powders with approximately 50 g•kg<sup>-1</sup>



moisture. They prepared calcium-fortified skim and milk powders with up to an extra 8 g of calcium per kg of powder. The calcium fortified skim and milk powders easily re-constituted in water to give skim milk solutions (100 g total solids•kg<sup>-1</sup>) with a total calcium content of between 2000 and 2300 mg Ca•L<sup>-1</sup>. They found that the total concentration of calcium in the fortified powder was dependent on the level of calcium in the base milk from which it was produced. Recovery rates of at least 97% obtained in the final powders produced using spray drying.

### **5.3.2.1. Spray Drying of Probiotic Cultures**

Probiotic cultures are described as live microbial feed supplements that improve intestinal microbial balance and are intended for maintenance of health or prevention, rather than the curing of disease. Probiotic strains and their key beneficial traits can withstand the stresses involved in the manufacture of Cheddar cheese and spray-dried powders. Spray drying is a cost effective method for producing large quantities of some probiotic cultures in a form suitable for functional food applications [18]. The potential of environmental adaptation as a survival mechanism enabling a human-derived probiotic *Lactobacillus* strain to withstand heat stress during spray drying was investigated. They reported that viability of the heat-adapted *L. paracasei* NFBC 338 in RSM (Response Surface Methodology) was enhanced 18-fold during spray drying at outlet temperatures of 95 to 105 °C, while salt-adapted cultures exhibited 16-fold greater viability than controls. They highlighted the potential of preconditioning treatments for maximizing survival of probiotic bacteria during development of probiotic functional foods. The cross protection afforded by salt against thermal stress may indicate that certain common protective mechanisms are induced by both heat and salt stress. The alternative probiotic preparation is easily scalable for commercial operations in eco- friendly and cost effective manner. Spray drying being a proven technology compared to convective current, infra red exposure and lyophilization, it can make visible impact on production, sale and use of *bacillus coagulans* as an effective probiotic preparation [19].

### **5.3.2.2 Spray Drying Encapsulation**

Another application for spray drying includes the encapsulation of functional foods and flavours. Spray drying microencapsulation includes preparation and homogenization of dispersion, atomization of the in-feed dispersion, and dehydration of the atomized particles. Shell materials are limited to gum acacia, maltodextrin, hydrophobically modified starch, and their mixtures because of solubility in water [19]. With different material preparations and operating conditions, other less water-soluble casings like polysaccharides (alginate, carboxymethylcellulose, and guar gum) and proteins (whey, soy, and sodium caseinate) can be used. According to [18], the advantages of spray drying encapsulation are: low operating cost; high quality, stability, and rapid solubility of the capsules; and small size.

### **5.3.3. Fluidized Bed Drying**

Functional foods like diced carrots, cranberries and blueberries can be dried using fluidized bed which have a perforated drying stage through which air flows at a specific velocity to fluidize the product. It is mainly used for granular solid and particulate products. A fluidized bed is induced when a fluid, liquid or gas, flows upward through a bed of suitably sized particles at a velocity high enough to suspend/disperse the particles

and impart them a turbulent motion. High heat transfer rates can be achieved in fluidized systems resulting in savings in processing time and this is the main reason why they are used in a variety of food processes like freezing and drying [47]. Now a day, with the modern technology different types of fluidized bed dryers such as pulsed fluidized, vibrated fluidized, spouted bed, and rotary dryers are available. They can be of batch type or continuous type. These dryers are designed such that heat sensitive and oxygen sensitive materials can be dried easily while maintaining their quality as the drying time are less, also drying can take place at low temperatures. The pulsed fluidized bed and the vibro-fluidized bed dryer gives better results than the normal fluidized bed dryer for those products which have stickiness [20].

The various advantages of fluidization as reported by research workers are as follows [20, 66]

- (a) Efficient gas-solid contact leads to compact units and relatively low capital cost.
- (b) The handling of the particles is quite easier compared to some other types of dryer.
- (c) The lack of moving parts, other than feed and discharge keeps reliability high and maintenance cost low.
- (d) Thorough mixing of solids leads to uniform drying.
- (e) Heat and mass transfer rates between gas and particles are high when compared with other models resulting in high rates of transport processes.
- (f) Several processes can be combined in the process.

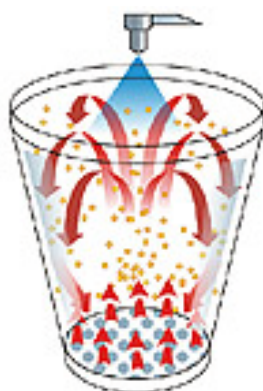
Besides these advantages there are some limitations associated with fluidized bed drying. The main limitation is that the material being dried must be fluidizable. Following are other limitations [20]:

- (a) Wide size distribution of product may lead to loss of small size particles from the bed due to high velocity.
- (b) The process demands extra expenditure of power for fluidization.
- (c) The dynamics of bed is not sufficiently well understood, so as to scale up laboratory data into commercial reality.
- (d) If material is wet, it is difficult to fluidize initially.
- (e) Minimum fluidization velocity changes with time as moisture is lost and particles become lighter.

High Temperature Fluidized Bed (HTFB) can be used in finish drying of osmotically dehydrated blueberries which is carried out at 170° C for 8 minutes and 150° C for 4 minutes with air velocity of 15 m s<sup>-1</sup>. It results in reduced dehydration time compared to conventional air dehydration and simultaneously puff the blueberries during the process. HTFB increases drying rate and prevents sticking of berries to each other thus facilitating the final drying of osmotically dehydrated blueberries [21].

### 5.3.3.1. Fluid Bed Encapsulation

Encapsulation is one of the important methods of commercializing valuable nutrients, bioactive components, additives and functional foods. Specially designed fluidized bed dryer are modified for the encapsulation of these food components. The different types of fluidized bed dryers for encapsulation are; top spraying (**Figure 5.1**) mostly used for the microencapsulation of droplets as small, bottom spray coating type used for similar particles. The rotating drum fluidized dryer also can be used which enhances gravitational forces and assists in fluidizing smaller particles. This is also used in coating process, where the core particles are fluidized, coating solution is sprayed, evaporation from the coating solution, and adherence of the coating material. Coating materials may be carbohydrates (e.g., starch, maltodextrins, and corn syrup solids), cellulose (hemicellulose), gums (e.g., gum acacia, agar, and carrageenan), lipids (e.g., wax, paraffin, and oils), and proteins (e.g., gluten, casein) [20].



**Figure 5.1.** Top spray fluidized bed processor (Courtesy: SB. Panchal and Company Mumbai, India)

### 5.3.4. Kiln drying

Oat flakes are nowadays becoming popular breakfast cereals falling in category of functional foods. Generally kiln dryers are used for pre-processing in oat flake manufacturing. The most important quality parameters of oat flakes are the absence of lipid hydrolysing enzymes, specific weight, thickness, break-age (fines), water absorption. At the mill, oats are often kilned to stabilise the product by inactivating lipid hydrolysing enzymes. Almost invariably steaming is used during flaking, to soften the groats and reduce flake breakage [23]. The falling number determination is a potential tool for estimating the adequacy of kiln drying of oats. Kaarlheto and Salovaara [24] studied the suitability of falling number method for oats using 4.5 to 8 g sample of oat groats, oat bran, oat endosperm flour and rolled oats. Their result showed that a standard 7 g sample falling number determination would be suitable for oats, the falling number of oat samples varying from 328 to 721 seconds. Oat groat samples from two separate kiln drying processes showed that kiln drying increased the falling number values by 30 – 89 %.

### 5.3.5. Osmotic Drying

Osmotic dehydration plays an important role in drying of functional foods like grapes, berries, tomato, carrots and mushrooms. It is an attractive dehydration technique due to its mild heat treatment to product which helps to minimise the losses of

functional components. Osmotic drying removes the water from the fruit with the help of osmotic solution (sugar or salt solution). This consists of two counter current flows with water diffusion from the product to the surrounding solution and migration of solutes from the solution to the product. A third transfer process, leaching of product solutes (sugars, acids, minerals, vitamins) into the medium, although recognized as affecting the organoleptic and nutritional characteristics of the product, is considered quantitatively negligible [48]. The driving force for water removal is the concentration gradient between the solution and the intracellular fluid. If the membrane is perfectly semi permeable, solute is unable to diffuse through the membrane into the cells. Selective properties of cell membranes make it possible for water and low-molecular cell sap components diffuse into the surrounding solution of higher osmotic pressure. However, it is difficult to obtain a perfect semi permeable membrane in food systems due to their complex internal structure, and there is always some solid diffusion into the food, which means that osmotic dehydration is actually combination of simultaneous water and solute diffusion process [24, 49].

Some functional foods like grapes, cherry tomatoes (Lycopene) and berries (Proanthocyanidins) have a coating of wax for its protection from external factors. This waxy layer does not allow the moisture to move from inside the fruit to its surface, thus increases the osmotic dehydration drying time. These fruits offer health benefits beyond basic nutritional requirements, and may require special pre-treatment(s) to reduce the impermeability of their skin to moisture movement. A system which minimizes exposure to light, oxidation and heat, (i.e. high heat (70°C) and shorter time duration) may help conserve critical bioactive compounds George et al. (2004). Carrot is osmotically dehydrated using sucrose (50° to 80°Brix) and salts solution (5 to 15%). The range of osmotic solution temperature, sample to solution ratio and time are 30° to 55°C, 1:4 to 1:5 and 0 to 240 min, respectively. Solution temperature does not show significant effect on mass transfer. The effective diffusivity of water range between  $1.594 \times 10^{-9}$  and  $2.078 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$  and that of solute between  $1.175 \times 10^{-9}$  and  $1.645 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$  [49, 50, 51]. Osmotically pre-treated carrot cubes (11% salt concentration, 30 °C solution temperature and 120 min process duration) dried in a cabinet dryer (65 °C air temperature) and then rehydrated in water at ambient temperature for 8–10 h results in to product with better rehydration ratio, colour and overall acceptability and minimum shrinkage. Osmotic dehydration of carrots can also be done using pulsed microwave vacuum to enhance the mass transfer with minimal sugar gain and to avoid the leaching of functional component from carrot along with soluble solids. Also, substantial decrease in osmotic dehydration time takes place. It results in to 40.46 % water loss and 11.58 % solid gain at microwave time per minute of 36 seconds during initial five minutes and osmosis time of 12.48 min. In comparison to the osmotic dehydration of carrots at atmospheric pressure, the application of combined pulsed microwave vacuum increases water loss [52].

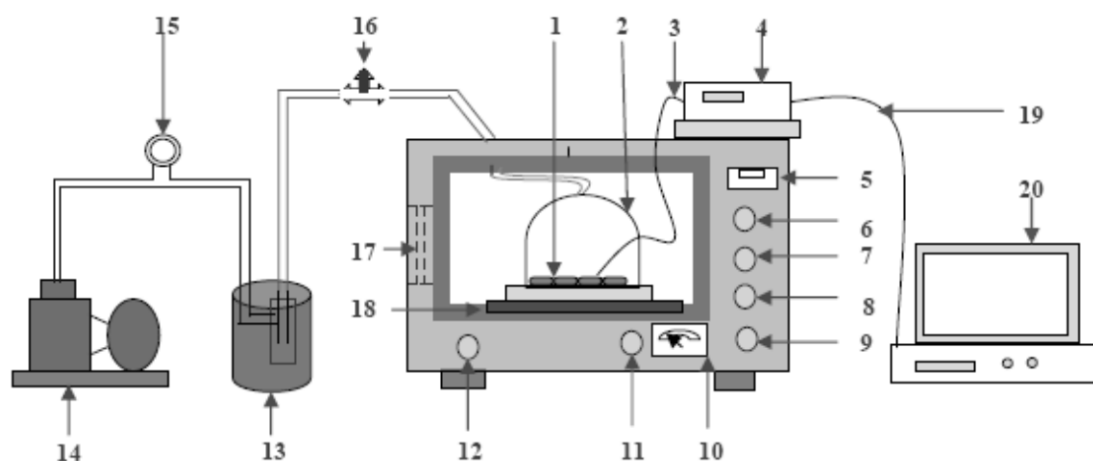
Button mushroom is osmotically dehydrated in the salt solution temperature range of 25° to and 55°C. The rates of moisture loss, salt gain and solid loss are mainly influenced by temperature and more pronounced between 25° and 40°C compared to 40° and 55°C [53].

### 5.3.6. Microwave drying

Microwaves are a form of electromagnetic radiation; that is, they are waves of electrical and magnetic energy moving together through space falling into the radio frequency band of electromagnetic radiation (300 MHz to 300 GHz). They are produced inside the oven by an electron tube called a magnetron. The microwaves bounce back and forth within the metal interior until they are absorbed by food and cause the water molecules in food to vibrate, producing heat that cooks the food. Microwave dehydration benefits include minimal change to flavour, colour and texture; more uniform temperature and moisture profiles, improved yields and enhanced product performance [54]. Microwaves are generally combined with conventional hot air or vacuum dryers. Literature shows some functional foods like mushroom, carrots and garlic have been successfully dried using microwave assisted drying techniques.

#### 5.3.6.1. Microwave vacuum drying

Microwave vacuum drying, the emerging food dehydration method is done by incorporating microwave radiation in a conventional vacuum dryer for heating and evaporation of moisture instead of heating by conduction and convection. Microwave vacuum drying combines the advantages of the rapid volumetric heating by microwaves and the low temperature evaporation of moisture with faster moisture removal by vacuum [55, 56, 57]. Typical arrangement of microwave vacuum drying is shown in **Figure 5.2** [52]. This reduces the time required for complete drying by more than 30% as compared to conventional methods [57]. Some researchers have done the microwave vacuum drying studies of functional fruit and vegetables like cranberries, carrots, mushrooms and showed that microwave vacuum drying can be used to dry the functional fruit and vegetables with better quality.



**Figure 5.2.** Experimental setup of microwave vacuum dryer [52]

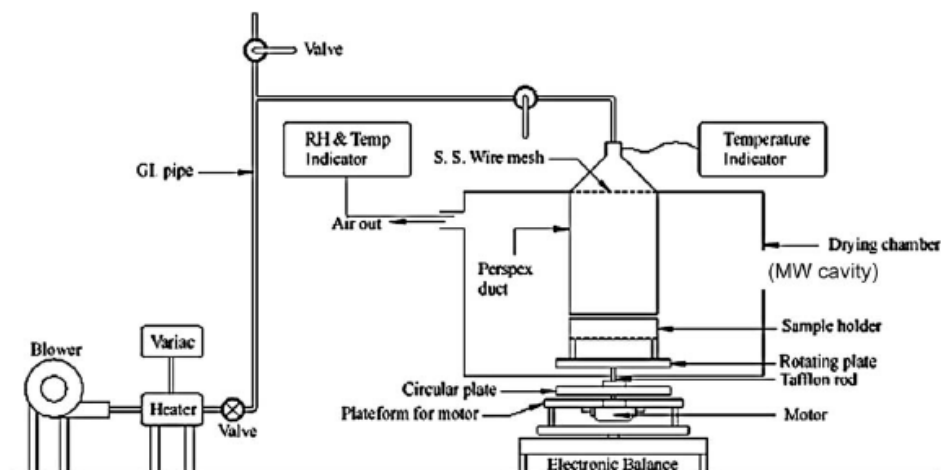
(1.Food material 2.Vacuum chamber 3.Fiber optic cables with sensors 4.Signal conditioner 5.Microwave timer 6.Microwave power on/off switch 7.Turn table controller 8.Electric power switch 9.Manual microwave power control 10.Microwave power level indicator 11.Remote power control 12.Heat extractor fan switch 13.Moisture condenser 14.Vacuum pump 15.Pressure gauge 16.Pressure control valve in moisture suction line 17.Heat extractor fan 18.Turn table 19.RS-232 cable 20.Personal computer)

Microwave vacuum drying of carrot slices at 2.45 GHz frequency and 4 kW power results in to higher rehydration potential,  $\alpha$ -carotene and vitamin C content, lower density and softer texture than other samples prepared by air (70°C air temperature) or freeze drying (1.6 mmHg, chamber temperature 20 °C and condenser temperature – 55 °C) [34]. Microwave vacuum drying helps in uniform temperature distribution in small thickness product which avoids the degradation of temperature sensitive functional components. During microwave vacuum drying carrots slices (thickness  $\leq$  8 mm) at wide range of microwave power and vacuum pressure levels the core temperature of sample attains the same as its surface temperature with uniform temperature distribution within the sample and for the thickness  $>$  8 mm, temperature gradient develops along the thickness of the sample [35]. The microwave vacuum drying of carrot slices can also be carried out with and without osmotic pretreatment. As compared to the microwave power density, the chamber pressure is less effective on the drying rates of carrot slices. The osmotic pretreatment is beneficial in retention of  $\beta$ -Carotene and ascorbic acid in microwave vacuum dried carrot slices, whereas, it reduces the rehydration ratio. The quality parameters of microwave vacuum and osmotic microwave vacuum dried carrots fall in between air and freeze dried carrots [67].

Microwave-vacuum drying of button mushroom results in 70 to 90 % reduction in the drying time as compared to hot air drying and shows 8 to 10 folds higher mean effective moisture diffusivity. Microwave power and slice thickness of mushroom shows significant effect ( $p \leq 0.05$ ) on drying efficiency whereas the system pressure strongly affect the quality of the dehydrated products such as colour, hardness, rehydration ratio and sensory scores. An optimum drying conditions of 202 W microwave power; 6.5 kPa system pressure; and 7.7 mm thickness results in to better quality dehydrated sliced mushrooms [28].

### **5.3.6.2. Microwave Hot Air drying**

Microwaves can be combined in the existing hot air dryer to increase the heating rate of the product. In addition to the heat supply from hot air, heat is generated volumetrically by microwaves. Due to the internal heat generation the moisture gets evaporated and creates additional pressure gradient for moisture removal. Therefore, microwave assisted hot air drying results in to faster drying. The schematic diagram of the microwave hot air dryer is shown in **Figure 5.3**. Due to shorter drying time, the losses due to oxidation can be minimized during drying of functional products like carrots and garlic. The quality parameters like rehydration ratio, moisture content, water activity, particle density, bulk density, porosity and colour are higher in microwave hot air dried carrots and garlic compared to infrared and hot air dried products [29]. Microwave convective drying of garlic can be done at power of 40W, air temperature of 70°C and air velocity of 1.0 m/s. It results in to superior product attributes like flavour, colour, vitamin C content and rehydration ratio than commercially dehydrated samples. Also, microwave convective drying requires very low specific energy for moisture removal [30].



**Figure 5.3.** Schematic diagram of microwave convective dryer [30]

An alternative two-stage microwave power system using varying microwave power during drying of functional food products was recommended by Wang and Xi [36]. They used a two-stage microwave power system, using a first and second stage power input for varying times during drying. They described microwave drying characteristics of carrot and discussed the effect of sample thickness, power applied during first-stage (first-stage power), power applied during the second-stage (second-stage power) and duration of first-stage on  $\beta$ -carotene content, and rehydration ratio. The study showed that dehydration rate increased and the drying energy consumption decreased, as the thickness of the sample decreased, power level increased and mass load decreased. They observed that slice thickness, first-stage power, second-stage power, and duration of the first-stage affected  $\beta$ -carotene content and rehydration ratio. The rehydration ratio of the dried products decreased with increase in duration of the first-stage and slice thickness.  $\beta$ -carotene content decreased with increase of power applied during the second-stage and duration of the first-stage.

### 5.3.7. Convective drying

Conventional air-drying is the most frequently used dehydration operation in functional food industry. They are mainly of the kind, cabinet and tunnel dryers, in which heating is done by warm air moving over or across the surface of a layer of product spread on perforated trays. Functional foods and ingredients like tomatoes, mushrooms, carrots, garlic, Eschinacea roots, and *E. angustifolia* roots are dried using these methods. It can be also used for drying of semisolid products such as tomato purees, slurries and pomace of fruit or vegetables. Due to high temperature and longer drying times convective drying may result in quality and product degradation [58]. Since convective drying is one of the most economical methods of drying. Few researchers have attempted drying of functional fruit and vegetables and showed that convective drying at low temperature can result into acceptable quality dehydrated functional foods. The Oyster Pleurotus variety of mushroom can be dried in thin layer. Drying air temperature of 50 °C and air velocity 0.9 m s<sup>-1</sup> is suitable for pre treated (steam blanching followed by sulphating and citric acid dip) mushroom dehydration process [31]. Similarly, the drying of Maitake mushroom (*Grifola frondosa*), which has high initial moisture content is dried in tem-

perature range 35° to 55°C and relative humidity 30-70% to obtain good quality dehydrate product [27].

A low cost forced convection greenhouse drier that is the Tunnel Greenhouse Drier is also used for functional food like garlic. Its main parts are: a plastic greenhouse cover containing a drying tunnel made with transparent plastic walls; a line of carts with several stacked trays containing the product and moved manually inside the tunnel and an electrical fan that moves the hot air from the greenhouse into the tunnel. The trays receive solar radiation through the transparent walls, increasing the product temperature. Heat losses from the tunnel are low since greenhouse temperatures are higher than ambient temperature [33].

Garlic slices (2-4 mm) can be dried using hot air in the temperature range 50- 90 °C, relative humidity 8- 24 % and airflow range 0.5- 1 m s<sup>-1</sup>. During drying only temperature and slice thickness affect the drying rate of garlic whereas there is no significant effect of relative humidity and airflow rate. Page model gives better prediction of drying kinetics of garlic slices [59].

Convective drying of tomato at 80 °C air temperature preserves substantial amount of the lycopene, ascorbic acid and antioxidant activity. Oxidative heat damage to tomato takes place at high temperature (> 100 °C) during hot air drying. Colour and ascorbic acid degrade severely by heat damage during drying whereas lycopene shows high stability. Lycopene content decreases to a maximum of 10 % after drying at 110 °C and did not change during drying at 80 °C [60].

The roots of Echinacea are widely accepted for their potential role in boosting of the immune system. Alkamides 1 and 2, echinacosides, and cynarin, some of the many bioactives identified in echinacea, are used as marker compounds for the evaluation of post-harvest processing effects [61]. The times achieved for moisture removal from 57 to 10% moisture content for roots dried in a convective oven at 23, 30, 40, 50, 60, and 70°C were 103.4, 55.7, 13.1, 11.2, 6.5, and 5.3 h, respectively. Echinacoside losses of 28 to 45% at temperatures of 30 to 65°C, respectively, were significant, whereas the effect on the other marker compounds was inconclusive. Shiu [62] studied the suitability of forced air thin-layer dryer for the dehydration of *E. angustifolia* roots by examining the drying characteristics of the roots and evaluating the quality of dehydrated roots with echinacoside as a reference compound. They examined drying temperatures (30° and 50°C), air velocities (0.7 and 1.1 m s<sup>-1</sup> for forced-air thin layer dryer) and root sizes (small and medium) drying experiments. Drying air temperature and root size are important parameters affecting the drying rate in thin-layer drying. Page equation appeared to fit the experimental data ( $R^2 > 0.96$ ). They found that thin-layer drying was better able to preserve the echinacoside in the roots as compared to fluidized-bed drying- They observed no significant difference in echinacoside loss between the two drying temperatures or air velocities specified in this study. Another important functional ginseng root can be dried at 38°C which is recommended by British Columbia Ministry of Agriculture, Food, and Fisheries [43], because higher temperatures are associated with degradation of ginsenosides and colour and with higher energy costs.



## 5.4. MODELLING DRYING PROCESS

Several theoretical, semi-theoretical and empirical models are available to study the drying kinetics of functional foods and their ingredients during drying. The most important models applicable to the drying of functional foods are given below:

Exponential Model <sup>[63]</sup>

$$MR = e^{-k\theta} \quad (5.1)$$

where, MR is moisture ratio,  $(M_0 - M) / (M_0 - M_e)$  in fraction,  $M_0$  is initial moisture content, (% db),  $M$  is intermediate moisture content (% db),  $M_e$  is equilibrium moisture content (% db),  $k$  is drying constant (% M/min),  $\theta$  is time period (min).

Page Model <sup>[63]</sup>,

$$MR = e^{-k\theta^n} \quad (5.2)$$

where,  $k$  and  $n$  are model constants

Henderson and Pabis Model <sup>[31]</sup>

$$MR = Ae^{-k\theta} \quad (5.3)$$

where,  $A$  and  $k$  are model constants

Food dehydration generally occurs in the falling rate period of drying during which moisture movement from the interior to the surface by diffusion is considered as the principal moisture transport mechanism. In the analysis of falling rate-drying period, a simple diffusion model based on Fick's second law of diffusion is considered for the evaluation of moisture transport, which is given by the following equation <sup>[64]</sup>.

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial M}{\partial x} \right) \quad (5.4)$$

Where,  $M$  is moisture content (kg water/kg dry matter),  $t$  is time (s),  $x$  is diffusion path or length (m),  $D$  is moisture dependent diffusivity (m<sup>2</sup>/s)

The diffusivity varies considerably with moisture content of the food and can be estimated by analyzing drying data, using the "method of slopes" technique <sup>[65]</sup>.

## CONCLUSIONS

The progress has been made recently in developing new drying technologies and pre-treatments to reduce the energy and costs associated with the process and to enhance quality aspects of dried functional foods. The literature shows that freeze and spray drying are the most important methods of drying used in development of functional foods. Also, selection of the drying method for development of the functional food should be based on the stress of the drying process parameters on the particular functional component.

## RESEARCH NEEDS

The available functional foods drying processes are specific to a particular situation requiring pilot-scale optimization/investigation in order to attain the better results. Hybrid drying technologies have good potential to cope with present trends in functional foods drying, but they still require numerous research works to practically apply their results.

## REFERENCES

1. Hardy, G. Nutraceuticals and functional foods: introduction and meaning. *Nutrition* 2000, 16, 688-689.
2. Hasler, C. M. The changing face of functional foods. *Journal of the American College of Nutrition* 2000, 19, 499.
3. Bellisle, R., Diplock, A. T. and Hornstra, G. Functional food science in Europe. *British Journal of Nutrition* 1998, 80, 191-193.
4. Clydesdale, F. M. A proposal for the establishment of scientific criteria for health claims for functional foods. *Nutrition reviews* 1997, 55, 413-422.
5. Roberfroid, M. B. Concepts and strategy of functional food science: the European perspective. *American Journal of Clinical Nutrition* 2000, 71, 1660S.
6. Vvedenskaya, I.O., Rosen, R.T., Guido, J.E., Russell, D.J., Mills, K.A., Vorsa, N., Characterization of flavonols in cranberry (*Vaccinium macrocarpon*) powder, *J. Agriculture journal of Food Chemistry* 2004; 52, 188-195.
7. Neto, C. C. Cranberry and its phytochemicals: a review of in vitro anticancer studies. *Journal of Nutrition* 2007, 137, 186S.
8. Bruneton, J., *Pharmacognosy: Phytochemistry Medicinal Plants*, 2nd ed., Lavoisier Publishing, Paris 1999.
9. Fleming, T., Ed., *Physicians Desk Reference: PDR for Herbal Medicines*, Medical Economics Company, Montvale, NJ 2000.
10. Shi, J., LeMaguer, M., and Bryan, M., Lycopene from tomatoes, in *Functional Foods: Biochemical and Processing Aspects*, CRC Press, Boca Raton, FL 2002, 2, 135-167.
11. Eskin, N. A., Tamir, S. *Dictionary of nutraceuticals and functional foods*: CRC Press, 2006.
12. Melissa, W., Eija, P and Catherine, R., *Functional foods: Opportunities and Challenges for developing countries*. Report submitted to Agriculture and Rural development, The World Bank, Washington, DC 2006, 19, 1-4.
13. Williams, M., Pehu, E., Ragasa, C. *Functional foods: opportunities and challenges for developing countries*. *Agricultural Rural Development Notes* 2006, 19.
14. Niba, L. L. The relevance of biotechnology in the development of functional foods for improved nutritional and health quality in developing countries. *African Journal of Biotechnology* 2003, 2, 12.
15. Anonymous, *Food Quality and Standard Service, Report on Functional Foods* Food and Agriculture Organization of United States, Rome, Italy; 2007.

16. Savini, M., Cecchini, C., Verdenelli, M. C., Silvi, S., Orpianesi, C., Cresci, A. Pilot-scale Production and Viability Analysis of Freeze-Dried Probiotic Bacteria Using Different Protective Agents. *Nutrients* 2, 2010.
17. Muthukumaran, A. Foam-mat freeze drying of egg white and mathematical modeling: McGill University, 2007.
18. Stanton, C., Ross, R. P., Fitzgerald, G. and Collins, K., Application of Pro biotic Bacteria to Functional Foods, Dairy Product Research Centre, Cork; 2000.
19. Yadav, A. K., Chaudhari, A. B., Kothari, R. M. Enhanced viability of *Bacillus coagulans* after spray drying with calcium lactate, storage and re-hydration, *Indian journal of Chemical Technology* 2009, 16, 519- 522.
20. Srisang, N., Prachayawarakorn, S., Soponronnarit, S., Varayanond, W. Fluidized Bed Drying of Germinated Brown Rice, 16th International Drying Symposium, Hyderabad, India; 2008.
21. Kim, M. H., Toledo, R. T. Effect of osmotic dehydration and high temperature fluidized bed drying on properties of dehydrated rabbiteye blueberries. *Journal of Food Science* 1987, 52, 980-984.
22. Rocha, S. C. S., Toranto, O. P., Advances in Spouted Bed Drying of Foods, Advances in Food Dehydration, National University, Dublin, Ireland; 2009.
23. Gates F. Role of heat treatment in the processing and quality of oat flakes, Unpublished M. Tech thesis, Department of Food Technology, University of Helsinki 2007.
24. Kaarlehto, T., Salovaara, H. Effect of kiln drying on falling number of oats. *Cereal Chemistry* 2000, 77, 177-180.
25. Shi, J., Xue, S. J., Application and Development of Osmotic Dehydration Technology in Food Processing, Advances in Food Dehydration, National University, Dublin, Ireland 2009.
26. George, S. D., Cenkowski, S., Muir, W. E. A review of drying technologies for the preservation of nutritional compounds in waxy skinned fruit. North Central ASAE/CSAE Conf, Winnipeg, Manitoba, Canada 2004, 24-25.
27. Cao, W., Nishiyama, Y., Koide, S. Thin layer drying of Maitake mushroom analysed with simplified model, *Biosystems Engineering* 2003, 85 (3), 331-337.
28. Giri, S. K., Prasad, S. Modeling shrinkage and density changes during microwave-vacuum drying of button mushroom. *International Journal of Food Properties* 2006, 9, 409-419.
29. Baysal, T., Icier, F., Ersus, S., Yildiz, H. Effects of microwave and infrared drying on the quality of carrot and garlic. *European Food Research and Technology* 2003, 218, 68-73.
30. Sharma GP, Prasad S. Drying of garlic (*Allium sativum*) cloves by microwave-hot air combination. *Journal of Food Engineering* 2001, 50, 99-105.
31. Pal, U. S., Chakraverty, A. Thin layer convection-drying of mushrooms. *Energy Conversion and Management* 1997, 38, 107-113.
32. Gornicki, K., Kaleta, A. Drying curve modelling of blanched carrot cubes under natural convection condition. *Journal of Food Engineering* 2007, 82, 160-170.
33. Condori, M., Echazu, R., Saravia, L. Solar drying of sweet pepper and garlic using the tunnel greenhouse drier. *Renewable Energy* 2001, 22, 447-460.

34. Lin, T. M. D., Durance, T., Scaman, C. H. Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International* 1998, 31, 111-117.
35. Cui, Z. W., Xu, S. Y., Sun, D. W., Chen, W. Temperature changes during microwave-vacuum drying of sliced carrots. *Drying Technology* 2005, 23, 1057-1074.
36. Wang, J., Xi, Y. S. Drying characteristics and drying quality of carrot using a two-stage microwave process. *Journal of Food Engineering* 2005, 68, 505-511.
37. Chan, J.C.-C., Cheung, P.C.-K., Ang, P.O., Jr. Comparative studies on the effect of three drying methods on the nutritional composition of seaweed *Sargassum hemiphyllum* (Turn.), *Journal of Agricultural Food Chemistry* 1997, 45, 3056-3059.
38. Oliveira, W. P., Bott, R. F. Souza, C. R. Manufacture of standardized dried extracts from medicinal Brazilian plants. *Drying Technology* 2006, 24, 523-533.
39. Kim, H. O., Durance, T. D., Scaman, C. H., Kitts, D. D. Retention of alkaloids in dried *Echinacea purpurea*. *Journal of Agricultural Food Chemistry* 2000, 48, 4187-4192.
40. Cui, Z. W., Xu, S. Y., Sun, D. W. Effect of microwave-vacuum drying on the carotenoids retention of carrot slices and chlorophyll retention of Chinese chive leaves. *Drying Technology* 2004, 22, 563-575.
41. Mohd Zainol, M. K., Abdul Hamid A., Abu Baker A., Pak Dek S., Effect of different Drying Methods on Degradation of Selected Flavonoids in *Centella Asiatica*, *International Food Research Journal* 2009, 16, 531- 537.
42. Popovich, D.G., Hu, C., Durance, T.D., and Kitts, D.D., Retention of ginsenosides in dried ginseng root: Comparison of drying methods, *Journal of Food Science* 2005, 70, 355-358.
43. Gross, M. R. One species with two biologies: Atlantic salmon (*Salmo salar*) in the wild and in aquaculture. *British Journal of Fisheries and Aquatic Sciences* 1998, 55, 131-144.
44. Sunjka, P., Raghavan, G. S. V., Orsat, V., Drying Pre treatments: A Review of Methods and their Influence on the Process, 16th International Drying Symposium, Hyderabad, India 2008.
45. Tonali, J., Park, K., Negreiros, A., Oliveira, R. A. and Murr, F., Influence of the Spray Drying Conditions on the Microstructure of Inulin Powder, 16th International Drying Symposium, Hyderabad, India 2008.
46. Williams, R. P., D'Ath, L., Augustin, M. A. Production of calcium-fortified milk powders using soluble calcium salts 2005, 85, 369-381.
47. Sheen, S., Whitney, L. F. Modelling heat transfer in fluidized beds of large particles and its applications in the freezing of large food items. *Journal of Food Engineering* 1990, 12, 249-265.
48. Lazarides, H. N., Katsanidis, E., Nikolaidis, A. Mass transfer kinetics during osmotic preconcentration aiming at minimal solid uptake. *Journal of Food Engineering* 1995, 25, 151-166.

49. Ghosh, P. K., Agrawal, Y. C., Jayas, D. S., Kumbhar, B. K. Mass Transfer Kinetics Model of Osmotic Dehydration of Carrots. *Transactions of the ASAE-American Society of Agricultural Engineers* 2004, 47, 1179-1228.
50. Rastogi, N. K., Raghavarao, K. Water and solute diffusion coefficients of carrot as a function of temperature and concentration during osmotic dehydration. *Journal of Food Engineering* 1997, 34, 429-440.
51. Singh, B, Panesar P. S, Nanda, V, Gupta, A. K, Kennedy, J. F. Application of response surface methodology for the osmotic dehydration of carrots. *Journal of Food Process Engineering* 2006, 29, 592-614.
52. Sutar, P. P., Prasad, S. Optimization of Osmotic Dehydration of Carrots under Atmospheric and Pulsed Microwave Vacuum Conditions, Article in Press 2010.
53. Kar, A., Osmo-air dehydration characteristics of button mushroom. Unpublished M.Tech. Thesis, G.B.P.U.A. & T., Pantnagar, India 1998.
54. Lombrana, J. I., Fundamentals and Tendencies in Freeze Drying of Foods, *Advances in Food Dehydration*, National University, Dublin, Ireland 2009.
55. Cui, Z. W., Xu, S. Y., Sun, D. W. Dehydration of garlic slices by combined microwave-vacuum and air drying. *Drying technology* 2003, 21, 1173-1184.
56. Drouzas, A. E., Schubert, H. Microwave application in vacuum drying of fruits. *Journal of Food Engineering* 1996, 28, 203-209.
57. Durance, T. D., Wang, J. H. Energy consumption, density, and rehydration rate of vacuum microwave-and hot-air convection-dehydrated tomatoes. *Journal of food Science* 2002, 67, 2212-2216.
58. Carrin, M. E., Crapiste, G.H., *Convective Drying of Foods*, *Advances in Food Dehydration*, National University, Dublin, Ireland 2009.
59. Madamba, P. S., Driscoll, R. H., Buckle, K. A. The thin-layer drying characteristics of garlic slices. *Journal of food engineering* 1996, 29, 75-97.
60. Giovanelli, G., Zanoni, B., Lavelli, V., Nani, R.. Water sorption, drying and antioxidant properties of dried tomato products. *Journal of food engineering* 2002, 52, 135-141.
61. Kabganian, R., Carrier, D. J., Sokhansanj, S. Physical characteristics and drying rate of Echinacea root. *Drying Technology* 2002, 20, 637-649.
62. Shiu, L., *Drying and Storage Study on Echinacea Angustifolia*, Department of Agricultural, Food and Nutritional Science, Unpublished Thesis, University of Alberta; 2001.
63. Brooker, D. B., Bakker-Arkema, F. W., Hall, C. W. *Drying cereal grains*, Connecticut. The AVI Publication Co. Inc. 1974, 265.
64. Karthanos, V.T., Kastaropoulos, A.E., Saravacos, G.D., Air dryin behaviour of osmotically dehydrated fruits. *Drying Technology* 1995, 13, (5-7): 1503.
65. Perry, R. H., Chilton, C. H. *Chemical Engineering Handbook* (6th edn.), McGraw Hill International Editions, New York 1984.
66. Lewicki, P.P., Lenart, A. Energy consumption during osmoconvection drying of fruits and vegetables. *Drying of Solids* (ed. A.S. Majumdar). Inter Sci. Publ., New York and Oxford and IBH Publ. Co., New Delhi 1992, 354.

67. Sutar, P. P. Combined osmotic and microwave vacuum dehydration of carrot, Unpublished Ph. D. thesis, Indian Institute of Technology, Kharagpur, India 2007.

## **Chapter 6**

# **An Introduction to Probiotics and Dessication Technology Used for Their Preservation**

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## 6.1. INTRODUCTION

The modern western lifestyle is characterized by significant alterations in food consumption, stress, lack of physical exercises, use of alcohol, tobacco and pharmaceuticals, and increasing exposure to environmental chemicals also seem to contribute to the burden of chronic disease in western society. Foods that are consumed refined and calorie-condensed food products contain large amounts of saturated and trans fatty acids, sugar and starch, and bioactive peptides such as gluten and are low in omega-3 PUFA, plants antioxidants, and health promoting plant fibres and bacteria. Common to most of the above mentioned food ingredients are that they affect the function of the innate immune system, the inflammatory response and the individuals' resistance to disease [1]. Apart from the modern lifestyle, infectious diseases are still the biggest problem for humans to solve in the 21st century. Intestinal infectious diseases caused by pathogenic microorganisms including Shigella, Vibrio cholera, pathogenic Escherichia coli, Campylobacter, and rotavirus are the main causes of death in developing countries. Even in a developed country, the USA, 21-37 million cases of diarrhea occur annually in a population of 16.5 million children [2], and Salmonella, Campylobacter, and enterohemorrhagic E. coli 0157 have been problematic as etiologic bacteria of food borne infection. Moreover, overuse of antibiotics has allowed the spread of nosocomial infections with antibiotic-resistant bacteria, particularly multidrug-resistant bacteria, as adverse effects. Under these circumstances, some useful bacteria contained in yogurt, lactobacillary beverages, and other fermented foods have been medically found useful and recognized as probiotics [3,4]. Probiotics have been identified mainly by experience of their ingestion as foods, but there is growing scientific evidence supported by mechanistic and clinical studies that probiotics can provide health benefits [5-9]. Probiotic therapy has been investigated for its effectiveness against a range of gastrointestinal diseases and disorders such as:

- In relief of lactose maldigestion
- To combat diarrhoea
- For the treatment of IBD (Inflammatory Bowel Disease)
- Impact on CRC (Colorectal cancer)
- Impact on immune function
- To combat pancreatitis
- Helicobacter pylori infection

With rapidly increasing knowledge of intestinal microbiota and modulating factors, interest in supplementing various types of food products with probiotic bacteria has grown significantly [10]. The term probiotic refers to a preparation of defined microorganisms or a product containing viable microorganisms, in sufficient numbers to alter the micro flora in a compartment of the host and bring beneficial health benefits [11, 12].

Lilly and Stillwell first coined the term probiotic in 1965 in reference to substances produced by protozoa, which stimulated the growth of other organisms. But the dietary use of live microorganisms has a long history. Elie Metchnikoff, the father of modern immunology, spoke highly about the possible health benefits of lactic acid bacteria (LAB) *Lactobacillus bulgaricus* and *Streptococcus thermophilus* in his writing at the consump-

tion of live bacteria, such as *S. thermophilus* and *L. bulgaricus*, in the form of yogurt was beneficial for gastro intestinal health as well as for general health and for longevity [13].

### **6.1.1. Definition and guidelines for use of the term 'probiotic'**

A number of definitions of the term 'probiotic' have been used over the years but the one derived by the Food and Agriculture Organization of the United Nations–World Health Organization (FAO–WHO) and endorsed by the International Scientific Association for Probiotics and Prebiotics best exemplifies the breadth and scope of probiotics as they are known today: "Live microorganisms, which when administered in adequate amounts, confer a health benefit on the host". This definition retains the historical elements of the use of living organisms for health purposes but does not restrict the application of the term only to oral probiotics with intestinal outcomes. This is important considering that vaginal applications of probiotics have existed for >20 years. The guidelines that stipulate what is required for a product to be called a probiotic were published by FAO–WHO in 2002. They require that strains must be designated individually, speciated appropriately and retain a viable count at the end of their shelf life in the designated product formulation that confers a proven clinical end-point. Although member nations were encouraged to use these guidelines, the fact that some products continue to be of dubious quality and claim health benefits that are not supported by appropriate, peer-reviewed human studies suggests that many regulatory authorities are not yet aligned. Although companies often genuinely try to inform consumers of the attributes of probiotics, some might consider new approaches so that evidence-based outcomes take precedence and product recommendations can be supported by well-designed human studies [14].

### **6.1.2. Mechanism of probiotic action**

The mode of action of probiotic strains is likely to be multifactorial and, from existing evidence, appears to be strain specific. Enhancement of colonization resistance and/or direct inhibitory effects against pathogens is likely to be important in situations in which probiotics have reduced the incidence and duration of gastroenteritis. The main function of the gut microbiota, from the host's point of view is to prevent colonization by potentially pathogenic microorganisms. It does so efficiently by outcompeting invading pathogens for ecological niches and metabolic substrates. Microbial metabolism also serves as an important source of energy for the gut wall, providing up to 50% of the daily energy requirements of colonocytes by fermentation of carbohydrates to organic acids, mainly butyrate. The defense mechanisms afforded by a healthy gut microbiota might be overcome when compromised by chemotherapy (especially antibiotics) or chronic disease [e.g. colon cancer and inflammatory bowel disease (IBD)]. This realization has led to the development of foods specifically designed to fortify the gut microbiota [15]. Probiotic strains have inhibited pathogenic bacteria both in vivo through several different mechanisms. These include production of directly inhibitory compounds (e.g. bacteriocins), reduction of luminal pH through short chain fatty acid production (which could themselves be directly inhibitory to certain pathogens), competition for nutrients and adhesion sites on the gut wall, modulation of the immune response and regulating colonocyte gene expression (e.g. expression of mucin genes) [16-18]. The gut microbiota acts as an important modulator of the immune system, not only educating the naïve infant immune system but also serving as an important source of non-

inflammatory immune stimulators throughout life in healthy individuals. Applying probiotics to stimulate immune function, especially in individuals with underdeveloped or dysregulated immune function, appears to be sound, considering the positive outcomes of feeding studies targeting viral infections, IBD and allergic diseases.

Probiotics influence digestive processes by the improvement of the microbial population that is beneficial for the microorganism, by enhancing its enzyme activity, by improving digestibility and feed utilization. The antitumour activity of probiotics may be realized in three ways: (a) the inhibition of tumour cells, (b) the suppression of bacteria producing  $\beta$ -glucosidase,  $\beta$ -glucuronidase, and azoreductase, which catalyze the conversion of procarcinogens to proximal carcinogens and (c) by the destruction of carcinogens such as nitrosamines, and by the decrease of nitroreductase activity which is involved in their synthesis. Probiotics influence blood cholesterol level by the inhibition of cholesterol synthesis, or decrease its level directly by assimilation [19].

## 6.2. PROBIOTIC PRODUCT DEVELOPMENT

Probiotics are commonly included in fermented milks, yoghurts and cheese, but are also available in the form of dietary supplements where the probiotic is in the form of a dried product. Probiotic-containing foods can be categorized as functional foods, and along with prebiotics represent the largest segment of functional foods market in Europe, Japan and Australia. The market for this food category continues to expand, in parallel with growing consumer awareness of the role of diet in health maintenance [20], and represents an exciting market opportunity for the food and dairy industries.

Human intestinal isolates, many of which are obligatively anaerobic grow very poorly outside their natural habitat, the human gut. Indeed, much of the human intestinal flora is uncultivable and can only be studied using culture-independent approaches. Consequently, the large-scale cultivation and subsequent storage of probiotic lactobacilli and bifidobacteria in high numbers often presents a major bottle neck to the realization of their commercial potential. For this reason, intensive research efforts have recently focused on protecting cultures both during product manufacture and storage and during gastric transit. These studies have demonstrated that cultures can be significantly protected via encapsulation in a variety of carriers, which include milk proteins and complex (prebiotic) carbohydrates. The physiological state of the probiotic cultures being added to a product can also be a major factor affecting overall culture viability. In this respect, the induction of stress responses in probiotic strains can have a dramatic effect on the ability of cultures to survive processing, such as freeze drying and spray drying and during gastric transit.

These micro-organisms share a number of common traits, such as generally regarded as safe (GRAS) status, acid and bile tolerance, and ability to adhere to intestinal cells [21]. For successful delivery in foods, probiotics must survive food processing and storage during product maturation and shelf-life.

### 6.2.1. Stabilization of probiotics by desiccation technology

Dehydration is commonly used as a means to stabilize probiotics for their ease of storage, handling, transport and subsequent use in functional food applications. Freeze-

drying is the most widespread technique for dehydration of probiotic and dairy cultures, while spray-drying has been applied to the dehydration of a limited number of probiotic cultures.

### **6.2.1.1. Freeze drying**

Freeze-drying has been used to manufacture probiotic powders for decades and is based upon sublimation, occurring in three phases; freezing, primary, and secondary drying. Typically, cells are first frozen and then dried by sublimation under high vacuum [22]. As the processing conditions associated with freeze-drying are milder than spray-drying, higher probiotic survival rates are typically achieved in freeze-dried powders [23]. Interestingly, it has been shown that cellular inactivation occurs mostly at the freezing step [24]. Indeed, To and Etzel (1997) demonstrated that 60-70% of cells that survived the freezing step can live through the dehydration step [25]. During freezing, the formation of extracellular ice causes an increase in extra-cellular osmolality, so, as soon as ice forms outside of the cell in solution, the cell begins to dehydrate. The intracellular and extra-cellular solution concentrations will increase as temperature drops until a eutectic point is reached. There are as such two kinds of freezing methods, i.e. slow freezing and fast freezing. During slow freezing, the process of gradually dehydrating the cell as ice is slowly formed outside the cell leads to extensive cellular damage, while fast freezing can avoid solute effects and excessive cellular shrinkage [26]. It has been reported that the higher the surface area of the cell, the higher the membrane damage owing to extracellular ice crystal formation during freezing [27]. Consequently, cell size has a strong influence on survival of probiotics during freeze-drying, with small spherical cells such as enterococci being more resistant to freezing and freeze-drying than larger rod shaped lactobacilli [27]. Removal of bound water from bacterial cells during drying leads to damage of surface proteins, cell wall and the cell membrane. Bound water plays an important role in stabilizing structural and functional integrity of biological macromolecules through different types of weak bonding, including those present on the cell wall and cell membrane. Consequently, water removal during desiccation can lead to destabilization of the structural integrity of these cellular components, resulting in loss or impairment of function [28]. It has been proposed that the lipid fraction of the cell membrane is the primary target area for damage during drying, where lipid peroxidation may occur [28, 29]. In addition, the secondary structures of RNA and DNA destabilize, resulting in reduced efficacy of DNA replication, transcription, and translation [30]. Therefore, in order to achieve optimum results during the desiccation of probiotics, attention must be strongly focused on approaches to minimize damage to these cellular components.

### **6.2.1.2. Spray-drying**

Commercial scale production of freeze-dried cultures is an expensive process with low yields, and as such spray drying offers an alternative inexpensive approach yielding higher production rates [31]. The spray-drying process involves the injection of the spray-drying medium at high velocity at temperatures up to 200°C, which then blasts through a nozzle leading to formation of granules. Consequently, this process results in exposure of the drying medium to high temperatures for a short time, which can be detrimental to the integrity of live bacterial cells. During spray-drying, bacterial cells encounter heat stress, in addition to the other stresses already mentioned during freeze-drying, i.e. dehydration, oxygen exposure and osmotic stress [28, 32]. The effect of spray-drying on the

cell membrane can lead to increased cell permeability which may result in the leakage of intracellular components from the cell into the surrounding environment [33]. The cytoplasmic membrane is among the most susceptible sites in bacterial cells to the stresses associated with spray-drying, while the cell wall, DNA and RNA are also known to be affected, leading to loss of metabolic activity [32, 34]. Removal of hydrogen-bonded water from the head group region of phospholipid bilayers increases the head group packing and forces the alkyl chains together. As a result, the lipid component may undergo a transition from lamellar to gel phase, which can be seen as a dehydrated lamellar phase in which the chains are stiff and fully extended. Furthermore, certain phospholipids undergo a transition from lamellar to hexagonal phase as water is removed [35, 36]. A number of studies have reported on the performance of a variety of probiotics during spray-drying, and in general, the survival rate of probiotic cultures depends on such factors as the particular probiotic strain used, outlet temperature, and drying medium among others. Using a rifampicin resistant variant of *Lactobacillus paracasei* NFBC 338, it was shown that survival rate of >80% was achievable during spray-drying in RSM (Reconstituted Skim Milk), at outlet temperatures of 85–90°C [37], while under similar conditions (outlet temperature of 80°C), Ananta and Knorr (2003) reported a survival rate of >60% for *L. rhamnosus* GG [38]. It has been shown that different bacterial species vary with respect to spray-drying tolerance, highlighting the importance of strain selection, for example *L. paracasei* NFBC 338 survived significantly better than *L. salivarius* UCC 118 at similar spray-drying conditions, which may be attributed to the greater thermal tolerance of strain *L. paracasei* NFBC 338 compared to *L. salivarius* UCC 118 [39]. When the heat and oxygen tolerance of a number of *Bifidobacterium* species, and the relative performance of selected strains during spray-drying were compared, it was found that closely related species exhibiting superior heat and oxygen tolerance performed best, notably *Bifidobacterium animalis* subsp. *lactis* which survived spray-drying at 70% or greater in RSM (20% w/v) at an outlet temperature of 85–90°C [40]. Outlet air temperature is a major processing parameter affecting the number of survivors during spray-drying. For example, Kim and Bhowmik (1990) reported that numbers of *Streptococcus salivarius* subsp. *thermophilus* and *L. debrueckii* subsp. *Bulgaricus* decreased with increasing outlet or inlet air temperatures and atomizing air pressure, while similar findings were reported by Gardiner et al., 2000 for both *L. paracasei* NFBC 338 and *L. salivarius* UCC 118 [39, 41]. Consequently, improved viability can be achieved by reducing the outlet temperature during spray-drying, but beyond probiotic viability, powder quality is also influenced by these parameters, with moisture content of 3.5% being preferred for shelf-stable products [42].

### **6.2.1.3. Fluidized bed drying**

When compared with spray drying, publications on drying bacterial starter cultures with a fluidized bed are rare. Most of the fluidized-bed work is related to yeast drying. In a fluidized-bed dryer the drying time can be much longer than in a spray dryer (e.g. 60 min vs. 30s). Because the dimensions of the drying apparatus and the required ratio air flow/moisture flow to reach a certain final water concentration are no longer coupled, the residence time in the fluidized bed can be chosen freely. This also means that the air inlet temperature can be controlled without influencing the minimal obtainable water concentration after drying.

The free choice of residence time makes it possible to use relative low air temperatures, which will help to minimize thermal inactivation. The thermal inactivation can also be minimized by controlling the product temperature, instead of the inlet temperature of the bed. The process design can help to minimize the thermal inactivation. For example, yeast can be dried with a constant air inlet temperature of 80°C at the first stage where charges of 1500 kg compressed yeast (2.3 kg kg<sup>-1</sup>) are dried in 45 min to water concentrations of 0.4 kg kg<sup>-1</sup>. At the second stage, where water concentrations of 0.1 kg kg<sup>-1</sup> are reached in 45 min, the air temperature can be controlled in such a way, that the product temperature never exceeds 38°C. In the final stage of the process the air humidity can also be controlled, thereby limiting the dehydration and thus the inactivation of the yeast cells. These control schemes can be used to minimize both thermal and dehydration inactivation. By accurate control of temperature and water concentration, in relation to particle diameter, an optimum between inactivation and drying time can be reached.

Due to the usually large distribution in residence time, a continuous fluidized-bed drying process can be disadvantageous for the drying of microorganisms. At higher drying temperatures, a distribution in residence time can cause significant thermal inactivation. In a batch-operated process there is no variation in residence time but such a process is less attractive from an economical view point. Generally, series of batch-operated fluidized beds are used.

Several additional advantages/disadvantages of the fluidized-bed drying process can be mentioned. A general problem during fluidized-bed drying can be the stickiness of the granulated material. This can influence the survival rate after fluidized-bed drying. Sticky particles agglomerate easily, which can result in a substantial increase in particle size, inhomogeneous beds, and decreasing drying rates. This problem can possibly be avoided by adjusting the initial water concentration, using the disintegration forces of a vibrating grid under the bed, a right choice of the support material, and/or the use of fluidizing agents. Another drawback is that only materials which can undergo granulation can be dried. Bacterial cells are not readily obtained in a granular form and therefore, support materials have to be used. One possibility is to mix the cells with a support material such as starch or wheat bran and to extrude the paste formed. Gel-like materials are also used, such as xanthan gum, carrageenan or alginate. Unfortunately, these materials can be considered unacceptable in the (food) substance to be inoculated. Concentration, mixing and granulation are unavoidable processes preceding the fluidized-bed drying process. In these preceding steps, it is possible that inactivation of the cells may occur. However, there is no known literature about this effect.

Another disadvantage can be the poor reconstitution properties of the fluidized bed-dried product. Usually, the product is less porous when compared to a spray or freeze-dried product and rehydration times can be relatively long. To facilitate the rehydration (and dehydration) process, the paste-like material is extruded as very small particles with diameters of 0.2 mm. After drying, particles of 0.1 mm diameter remain which are small enough for direct addition into the dough, without the need of a separate rehydration step.

An advantage of the fluidized-bed process, compared to the spray drying process, is that it can be modelled relatively easily. The insights into the influence of the parame-

ters on the drying and inactivation process, obtained with the modeling and simulation, can be readily implemented. The measurements and calculations practiced with a laboratory or pilot plant drying installation can be translated to an industrial scale process [43].

#### **6.2.1.4. Vacuum drying**

The survival ratio of *Lactobacillus acidophilus* during vacuum drying was found to be the lowest as compared to freeze drying and controlled low temperature vacuum drying. Since the culture was maintained at 40°C during vacuum dehydration, cell damage was inevitable and vacuum drying under these conditions was not a method appropriate for culture preservation. Cultures dehydrated by controlled low-temperature vacuum dehydration possessed a survival ratio close to that dehydrated by freeze-drying, and that of freeze dried culture could be higher owing to the beneficial conditions during drying. The time required for the controlled low-temperature vacuum dehydration operation was much less than that for freeze-drying. Compared to 24 hours for freeze-drying, controlled low-temperature vacuum dehydration took only four hours for drying to a final moisture content of 5% and drying cost could be greatly reduced. However, there were still several aspects of controlled low-temperature vacuum dehydration requiring improvement as compared with freeze-drying [44].

#### **6.2.1.5. Heat pump drying**

Heat pump drying is a low temperature convective drying technique which utilizes dehumidified air for dehydration. This technique is useful for drying of bacteria because the drying can be carried out at low temperatures. It is a comparatively economical and comparable drying method as compared to freeze drying. But not many references are available in the literature for drying of probiotics using heat pump drying. A lot of work has been carried out in our lab for drying of *Lactobacillus acidophilus* and *Saccharomyces boulardii*. The inactivation kinetics data proved that the HP-FBD is a superior drying technique to FBD for drying of probiotics (unpublished). It was found that with HP-FBD, there is less than one log cycle reduction in viability of bacteria and probiotic yeast which proves it to be a comparable drying technique against freeze drying. HP-FBD is also a more economic option as compared to freeze drying and hence can be used for large scale production. As HP-FBD uses dehumidified cold air, any heat sensitive biological material (biotechnological, pharmaceutical, food products) can be dried using this technique with or without additives.

### **6.2.2. Protectants used during drying**

Probiotic cultures for food applications are frequently supplied in frozen, or dried form, either as freeze-dried or spray-dried powders [43, 45]. The successful drying of lactobacilli and bifidobacteria has previously been reported for a number of different strains, including *Lactobacillus paracasei* [39, 46], *Lactobacillus curvatus* and *Lactobacillus* sp. 8Z [47], *Lactobacillus acidophilus* (Prajapati et al. (1987) [48], *Lactobacillus bulgaricus* [33], *Lactobacillus helveticus* [49], *Lactobacillus rhamnosus* GG [50] and *Bifidobacterium ruminantium* [51]. Most probiotic lactobacilli do not survive well, however, during the temperature and osmotic extremes to which they are exposed during the spray-drying and freeze drying processes [39,52,53]. When used for the preservation of potential probiotic cultures much of their activity is typically lost after a few weeks of storage at room temperature. This is associated with stress that is induced by temperature changes,

phase changes and drying, a combination of which tend to damage cell membranes and proteins.

A variety of protectants have been added to the drying media before freeze-drying or spray-drying to protect the viability of probiotics during dehydration, including skim milk powder, whey protein, trehalose, glycerol, betaine, adonitol, sucrose, glucose, lactose and polymers such as dextran and polyethylene glycol [54, 55].

### **6.2.2.1. Protectants used for spray drying**

Spray-dried powder harbouring high numbers of viable probiotics is a convenient means of storage and transport of probiotic cultures and their subsequent application in functional foods. While spray drying is an economical process for the large-scale preparation of these cultures, and is commonly used for the preparation of food ingredients, it suffers from the disadvantage of causing bacterial cell injury and death, which has been attributed primarily to the effects of heat and dehydration leading to destruction of the properties and performance characteristics of probiotic cultures [25, 33]. One approach used by a number of workers to improve probiotic performance in food systems is the addition of protectants to the media prior to drying. For example, the incorporation of thermoprotectants such as trehalose [56], non-fat milk solids and/or adonitol [50, 52], growth-promoting factors, including various probiotic/prebiotic combinations [50, 57-59] and granular starch [60] have been employed in efforts to improve culture viability during drying, storage and/or gastric transit. The incorporation of the soluble fibre, gum acacia in milk-based medium prior to spray drying the probiotic *Lactobacillus paracasei* NFBC 338, increased probiotic viability during powder storage, compared with milk powder alone [59]. However, other prebiotics investigated, including inulin and polydextrose did not enhance probiotic viability during spray drying or powder storage [50].

The use of gum acacia in the spray-drying medium resulted in enhanced probiotic survival of *L. paracasei* NFBC 338, which displayed 10-fold greater survival than control cells (20% RSM) when grown in a mixture of RSM (10% w/v) and gum acacia (10% w/v) prior to spray-drying at air outlet temperature of 100–105°C [59]. RSM appears to be a very suitable media for efficacious spray-drying of probiotic cultures [50, 59, 61] as skim milk protein can prevent cellular injury by stabilizing cell membrane constituents [62]. Furthermore, it may form a protective coating on the cell wall proteins, while calcium in milk increases survival after dehydration [63]. Corcoran et al. (2004) reported that the inclusion of the prebiotics polydextrose and inulin in the spray-drying medium (RSM) did not enhance viability during spray-drying or powder storage [50]. Compatible cryoprotectants may be added to media prior to fermentation to assist in the adaptation of probiotics to the environment [64]. As compatible cryoprotectants accumulate within the cells, the osmotic difference between the internal and external environments is reduced [65].

On the other hand, survival of *L. helveticus* during vacuum drying was improved by the addition of 1% sorbitol [22]. It is well documented that carbohydrates have protective effects for probiotic bacteria during freeze-drying, given that these cryoprotectants can raise the glass-phase transition temperature, and therefore viable cells can reach the glassy phase without nucleating intracellular ice [26]. It also has been demonstrated that trehalose is an effective cryoprotectant during freezing and freeze-drying, enabling



higher survival of *L. acidophilus* [56], due to the remarkably high glass transition temperature (T<sub>g</sub>) of trehalose, and the strong ion–dipole interactions and hydrogen bonding between trehalose and the biomolecule [66]. In a recent study, the protective effects of a series of disaccharides on *L. rhamnosus* GG survival during freeze-drying and storage were compared and it was found that trehalose, trehalose/lactose and lactose/ maltose were the most efficacious disaccharides during both freezing and freeze-drying. Compatible solutes have also proven beneficial in probiotic viability protection in acidic environments. For example, the presence of 19.4 mM glucose resulted in up to 6-log<sub>10</sub>-enhanced survival following 90 min of exposure to simulated gastric juice at pH 2.0 compared with the control [67]. In this study, it was reported that the presence of glucose resulted in the provision of ATP to F<sub>0</sub>F<sub>1</sub>-ATPase via glycolysis, thus enabling proton exclusion from the cell and thereby enhancing survival in simulated gastric environments.

#### **6.2.2.2. Protectants used for freeze drying**

The addition of cryoprotectants during freeze drying of lactobacilli has been used to help overcome inactivation during drying and stabilization during storage. In a recent study, freeze-dried *Lactobacillus bulgaricus* survived better during storage at 20°C over 10 months when cells had been grown in the presence of fructose, lactose or mannose or when glucose, fructose or sorbitol were added to the drying medium [68]. In particular, trehalose, a disaccharide of glucose, has been found to be effective at protecting proteins during freezing and drying [69].

#### **6.2.3. Encapsulation**

Encapsulation, as a means of protecting live cells from extremes of heat or moisture, such as those experienced during drying and storage is a technique that is increasingly used in the probiotic food industry [51,70,71]. This technique allows the active core ingredient, or substrate, to be separated from its environment by a protective film or coating. This separation occurs until the release of the functional ingredient is desired. For the incorporation of probiotics into food products, micro-encapsulation offers protection to fine particles such as those produced during the spray drying of probiotic concentrates. Several methods of microencapsulation of probiotic bacteria have been reported and include spray drying, extrusion, emulsion and phase separation [72,73]. In a study by Guerin et al. (2003), *Bifidobacterium bifidum* cells encapsulated in gel beads composed of alginate, pectin, and whey proteins, and surrounded by two membranes exhibited good survival at pH 2.5 for up to 2 h, while free cells did not survive under these conditions, and furthermore protection was also afforded by this system, when the cells were exposed to bile salt solutions [74]. Furthermore, it was found that encapsulating lactobacilli in calcium-alginate beads improved their heat tolerance [52], while this technology has also been shown to prolong the viability during storage of a spray-dried *Bifidobacterium ruminatum* [51]. The incorporation of gum acacia in the drying medium has also been successfully used to improve the stability of dried *Lactobacillus paracasei* NFBC 338 during powder storage at 15 and 30°C, by up to 1000-fold, and also afforded protection to bifidobacteria [75]. Furthermore, viability of probiotic lactobacilli in gum acacia-containing powders was 100-fold higher when exposed to porcine gastric juice over 120 min, compared with the control spray dried culture [59]. In addition, it has been reported that exopolysaccharide-producing strains of bifidobacteria may be naturally protected [76].

O’Riordan, Andrews, Buckle, and Conway (2001) prepared microencapsulated Bifidobacterium PL-1 with starch by spray-drying, however the starch-coated cells did not display any enhanced viability compared with free PL1 cells when exposed to acid conditions for 6 h or in two dry food preparations over 20 days storage at ambient temperature (19–24°C). Hence, the efficiency of microencapsulation of probiotics depends on the encapsulating materials and techniques of micro-encapsulation [51].

### 6.3. PREBIOTICS

Future challenges include the incorporation of one or more probiotics together or in combination with suitable prebiotic substrates to enhance the efficacy of the preparations for clinical use [77]. A prebiotic is a non-digestible food ingredient that beneficially affects the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon. In order for a food ingredient to be classified as prebiotic, it must (1) be neither hydrolyzed nor absorbed in the upper part of the gastrointestinal tract, (2) be a selective substrate for one or a limited number of beneficial bacteria commensal with the colon, which are stimulated to grow and/or are metabolically activated, (3) consequently, be able to alter the colonic flora in favour of a healthier composition, and (4) induce luminal or systemic effects that are beneficial to the hosts health. The examples of prebiotic oligosaccharides are; Fructo-oligosaccharides, Inulin, Galacto-oligosaccharides, Lactulose, Lactosucrose, Isomalto-oligosaccharides, Soybean oligosaccharides, Xylo-oligosaccharides, Gentio-oligosaccharides.

The resident gut microbiota ferments substances that cannot be digested by the host in the small gut, these include resistant starch, non-digestible carbohydrates, oligosaccharides, proteins and mucins. The two main types of fermentation that are carried out in the gut are saccharolytic and proteolytic. Saccharolytic activity is more favourable than a proteolytic fermentation due to the type of metabolic end products that are formed. The main end products of saccharolytic fermentation are the short chain fatty acids (SCFA), acetate, propionate and butyrate. All contribute towards the host’s daily energy requirements. Acetate is metabolized in systemic areas like muscle, while propionate is transported to the liver and used to generate ATP. Butyrate is an important source of energy for the colonocytes and is thought to have anti-tumour properties. The end products of proteolytic fermentation on the other hand, include nitrogenous metabolites (such as phenolic compounds, amines and ammonia) some of which are carcinogens.

### 6.4. SYNBIOTIC CONCEPT

A synbiotic can be defined as ‘a mixture of probiotics and prebiotics that beneficially affects the host by improving the survival and implantation of live microbial dietary supplements in the gastrointestinal tract, by selectively stimulating the growth and/or by activating the metabolism of one or a limited number of health-promoting bacteria, and thus improving host welfare’. Synbiotics aim to enhance the survival and activity of proven probiotics in vivo as well as stimulating indigenous bifidobacteria.

Few studies have been carried out in humans on the effectiveness of synbiotics. The effect of a synbiotic mix containing inulin and Bifidobacterium spp. in healthy volunteers

was monitored. Although an overall increase in faecal bifidobacterial numbers was observed, the authors concluded that no additional increase in the numbers of bifidobacteria was observed solely due to the prebiotic component. A fermented milk product consisting of yoghurt starter strains and *L. acidophilus* plus 2.5% FOS decreased total serum cholesterol levels, as well as decreasing low density lipoprotein (LDL)-cholesterol and the LDL/high density lipoprotein (HDL) ratio. More recently, it was shown that long-term (7 weeks) consumption of synbiotic yoghurt (*L. acidophilus* 145, *B. longum* 913 plus FOS) led to a significant improvement in LDL/HDL cholesterol ratios in 29 healthy women. Further convincing evidence for the enhanced performance of synbiotics compared with either their probiotic or prebiotic moieties taken alone has been forthcoming from animal models of CRC. Synbiotics products containing *B. longum* and lactulose or inulin reduced the incidence and size of aberrant crypt foci in rats challenged with the carcinogen azoxymethane.

Synbiotic products have the potential for enhanced health promotion over either probiotics or prebiotics alone but require further investigations in human feeding studies [77].

## **6.5. THE IMPORTANCE OF SAFETY WITHIN THE GUIDELINES**

Safety is the state of being certain that adverse effects will not be caused by an agent under defined conditions. The reciprocal of safety is risk. The issue of safety for any product is arguably paramount during pregnancy and in newborn babies. The best example of the safe use of probiotics during pregnancy is that of *Lactobacillus rhamnosus* GG, which was used in 132 women who were at high risk of their newborn babies developing atopic dermatitis [78]. Two interesting outcomes relevant to adults and children emerged from this study. There were no reports of adverse effects in the mothers, which indicated that ingestion of the probiotic was safe. This is further supported by the long-term use of this probiotic in Finland (since the late 1980s) and the low rate of cases of bacteremia potentially associated with its use [79] (<0.05 cases per 100 000 in Finland [80]). Nevertheless, cases of bacteremia have been reported following intake of this probiotic and some deaths have occurred in patients with severe underlying disease [81]. The question of how to relay a perceived risk on labels of products that contain *L. rhamnosus* GG or other strains remains unresolved, in part because it is not clear which type of person should be advised not to take a probiotic. The case for advising immunocompromised or seriously ill surgical patients against taking *L. rhamnosus* GG is countered by studies that show it can be used safely (twice a day for two weeks) in HIV/AIDS patients [82]. In addition, studies have shown the benefits of *Lactobacillus plantarum* 299 v in patients undergoing major abdominal surgery [83]. Benefits have also been seen in patients with inflammatory conditions of the intestine who received the high-dose, eight-strain probiotic VSL#3 [84], *L. rhamnosus* GG [85], *Saccharomyces boulardii* lyo [86], and even a gram-negative probiotic, *Escherichia coli* Nissle 1917 [87]. Nevertheless, invasive fungemias associated with *S. boulardii* lyo [88], and endocarditis apparently caused by *Lactobacillus paracasei* subsp. *paracasei* [89] and *L. rhamnosus* GG [81], demonstrate that a proportion of recipients of probiotics, however small, seem to be at risk of adverse effects. The reasons for susceptibility in some individuals remain unclear. Regulatory agencies might consider requiring probiotic products to include an insert, which could

state that anyone who has a serious underlying medical condition of the intestine or bloodstream should inform their physician that they are consuming a particular probiotic, and immediately report any episodes of fever, chills or vomiting that arise. Although the Finnish study resulted in a significant reduction in babies born with atopic dermatitis, a small number of newborns who were administered *L. rhamnosus* GG during the first six months of life later developed asthma [90]. In other studies of premature babies treated with probiotics to prevent necrotizing enterocolitis and death, no such asthma cases were reported; safety was assessed against risk of disease and by the lack of adverse effects on height or weight-for-heights [91, 92]. Future use of probiotics in newborns should have long-term end points (of at least five years) in an attempt to determine that no significant increased risk of conditions like diabetes, allergies or inflammatory diseases arises. Such studies would probably be expensive and logistically difficult, however, in countries like Finland and Sweden they could be feasible because probiotics are readily available and patients are often particularly well monitored in studies. Only then can the true risk-benefit analysis be assessed. The link between probiotics and safety also requires that true probiotic products are evaluated. In one case, the issue of probiotic safety was raised by authors who neither cited clinically proven products and the extent of their use, nor took into account underlying medical conditions in subjects in which adverse effects occurred [93]. This only damages the reputation of the research field and does not help to identify cause and effect [94].

## REFERENCES

1. Bengmark, S. Acute and "Chronic" phase response – a mother of disease. *Clinical nutrition* 2004, 23, 1256-66.
2. Glass, R.I.; Lew, J.F.; Gangarosa, R.E.; LeBaron, C.W.; Ho, M.S. Estimates of morbidity and mortality rates for diarrheal diseases in American children. *Journal of Pediatrics* 1991, 118, S27– S33.
3. Fuller, R. Robotics in man and animals. *Journal of Applied Bacteriology* 1989, 66, 365–378.
4. Reid, G. The importance of guidelines in the development and application of probiotics. *Current Pharmaceutical Design* 2005, 11, 11–16.
5. Reid, G.; Jass, J.; Sebulsky, M.T.; McCormick, J.K. Potential uses of probiotics in clinical practice. *Clinical Microbiology Reviews* 2003, 16, 658–672.
6. Gill, H.S. Probiotics to enhance anti-infective defences in the gastrointestinal tract. *Best Practice & Research Clinical Gastroenterology* 2003, 17, 755–773.
7. Bengmark, S. Use of some pre-, pro- and synbiotics in critically ill patients. *Best Practice & Research Clinical Gastroenterology* 2003, 17, 833– 848.
8. Alvarez-Olmos, M.I.; Oberhelman, R.A. Probiotic agents and infectious diseases: a modern perspective on a traditional therapy. *Clinical Infectious Disease* 2001, 32, 1567–1576.

9. de Roos, N.M.; Katan, M.B. Effect of probiotic bacteria on diarrhea, lipid metabolism, and carcinogenesis: a review of papers published between 1988 and 1998. *American Journal of Clinical Nutrition* 2000, 71, 405–411.
10. Lacroix, C.; Yildirim, S. Fermentation technologies for the production of probiotics with high viability and functionality. *Current Opinion in Biotechnology* 2007, 18, 176-183.
11. Schrezenmeir, J.; de Vrese, M. Probiotic, prebiotics and synbiotics- approaching a definition. *American Journal of Clinical Nutrition* 2001, 73, 361s – 364s.
12. Saxelin, M.; Tynkkynen, S.; Mattila-Sandholm, T.; de Vos, W.M. Probiotics and other functional microbes: from markets to mechanisms. *Current Opinion in Biotechnology* 2005, 16, 204 – 211.
13. Lilly, D.M.; Stillwell, R.H. Probiotics: growth-promoting factors produced by microorganisms. *Science* 1965, 147, 747-748.
14. Reid, G. Safe and efficacious probiotics: what are they? *Trends in Microbiology* 2006, 14 (8), 348-352.
15. Tuohy, K.M.; Probert, H.M.; Smejkal, C.W.; Gibson, G.R. Using probiotics and prebiotics to improve gut health, *Drug Discovery Today* 2003, 8 (15), 692-700.
16. Steer, T.; Carpenter, H.; Tuphy, K.; Gibson, G. Perspectives on the role of the human gut microbiota and its modulation by pro- and prebiotics. *Nutrition Research Reviews* 2000, 13, 229-254.
17. Fooks, L.J.; Gibson, G.R. Probiotics as modulators of the gut flora. *British Journal of Nutrition* 2002, 88, s39-s49.
18. Mack, D.R.; Michail, S., Wei, S., McDougall, L.; Hollingsworth, M.A. Probiotics inhibit enteropathogenic *E.coli* adherence in vitro by inducing intestinal mucin gene expression. *American Journal of Physiology* 1999, 276, G941-G950.
19. Zacconi, C.; Bottazzi, V.; Rebecchi, A.; Bosi, E.; Sarra, P. G.; Tagliaferi, L. Serum cholesterol levels in axenic mice colonized with *Enterococcus faecium* and *Lactobacillus acidophilus*. *Microbiologica* 1992, 15, 413–418.
20. Stanton, C.; Gardiner, G.; Meehan, H.; Collins, K.; Fitzgerald, G.; Lynch, P.B.; Ross, R.P. Market potential for probiotics. *American Journal of Clinical Nutrition* 2001, 73, 476s–483s.
21. Dunne, C.; O’Mahony, L.; Murphy, L.; Thornton, G.; Morrissey, D.; O’Halloran, S.; Feeney, M.; Flynn, S. In vitro selection criteria for probiotic bacteria of human origin: correlation with in vivo findings. *American Journal of Clinical Nutrition* 2001 73, 386S–392S.
22. Santivarangkna, C.; Kulozik, U.; Foerst, P. Alternative drying processes for the industrial preservation of lactic acid starter cultures. *Biotechnology Progress* 2007, 23, 302–315.
23. Wang, Y.C.; Yu, R.C.; Chou, C.C. Viability of lactic acid bacteria and bifidobacteria in fermented soymilk after drying, subsequent rehydration and storage. *International Journal of Food Microbiology* 2004, 93, 209–217.

24. Tsvetkov, T.; Brankova, R. Viability of micrococci and lactobacilli upon freezing and freeze-drying in the presence of different cryoprotectants. *Cryobiology* 1983, 20, 318–323.
25. To, B.C.S.; Etzel, M.R. Spray-drying, freeze-drying, freeze drying or freezing of three different lactic acid bacteria species. *Journal of Food Science* 1997, 63, 576–585.
26. Fowler, A.; Toner, M. Cryo-injury and biopreservation. *Annals of New York Academy of Sciences* 2005, 1066, 119–135.
27. Fonseca, F.; Beal, C.; Corrieu, G. Method of quantifying the loss of acidification activity of lactic acid starters during freezing and frozen storage. *Journal of Dairy Research* 2000, 67, 83–90.
28. Brennan, M.; Wanismail, B.; Johnson, M.C.; Ray, B. Cellular damage in dried *Lactobacillus acidophilus*. *Journal of Food Protection* 1986, 49, 47–53.
29. Linders, L.J.; Wolkers, W.F.; Hoekstra, F.A.; van't Riet, K. Effect of added carbohydrates on membrane phase behavior and survival of dried *Lactobacillus plantarum*. *Cryobiology* 1997, 35, 31–40.
30. van de Guchte, M.; Serror, P.; Chervaux, C.; Smokvina, T.; Ehrlich, S.D.; Maguin, E. Stress responses in lactic acid bacteria. *Antonie Van Leeuwenhoek* 2002, 82, 187–216.
31. Zamora, L.M.; Carretero, C.; Pares, D. Comparative survival rates of lactic acid bacteria isolated from blood, following spray-drying and freeze-drying. *Food Science and Technology International* 2006, 12, 77–84.
32. Teixeira, P.; Castro, H.; Mohacsi-Farkas, C.; Kirby, R. Identification of sites of injury in *Lactobacillus bulgaricus* during heat stress. *Journal of Applied Microbiology* 1997, 83, 219–226.
33. Teixeira, P.; Castro, H.; Kirby, R. Spray-drying as a method for preparing concentrated cultures of *Lactobacillus bulgaricus*. *Journal of Applied Microbiology* 1995, 78, 456–462.
34. Teixeira, P.; Castro, H.; Malcata, F.X.; Kirby, R.M. Survival of *Lactobacillus delbrueckii* spp. *bulgaricus* following spray-drying. *Journal of Dairy Science* 1995, 78, 1025–1031.
35. Crowe, J.H.; Crowe, L.M.; Carpenter, J.F.; Rudolph, A.S.; Wistrom, C.A.; Spargo, B.J. Interactions of sugars with membranes. *Biochimica et Biophysica Acta* 1988, 947, 367–384.
36. Leslie, S.B.; Israeli, E.; Lighthart, B.; Crowe, J.H.; Crowe, L.M. Trehalose and sucrose protect both membranes and proteins in intact bacteria during drying. *Applied and Environmental Microbiology* 1995, 61, 3592–3597.
37. Gardiner, G.E.; Bouchier, P.; O'Sullivan, E.; Kelly, J.; Collins, J.K.; Fitzgerald, G.F. A spray-dried culture for probiotic Cheddar cheese manufacture. *International Dairy Journal* 2002, 12, 749–756.
38. Ananta, E.; Knorr, D. Pressure-induced thermotolerance of *Lactobacillus rhamnosus* GG. *Food Research International* 2003, 36, 991–997.

39. Gardiner, G.E.; O'Sullivan, E.; Kelly, J.; Auty, M.A.; Fitzgerald, G.F.; Collins, J.K. Comparative survival rates of human derived probiotic *Lactobacillus paracasei* and *L. salivarius* strains during heat treatment and spray-drying. *Applied and Environmental Microbiology* 2000, 66, 2605–2612.
40. Simpson, P.J.; Stanton, C.; Fitzgerald, G.F.; Ross, R.P. Intrinsic tolerance of *Bifidobacterium* species to heat and oxygen and survival following spray-drying and storage. *Journal of Applied Microbiology* 2005, 99, 493–501.
41. Kim, S.S.; Bhowmik, S.R. Survival of lactic acid bacteria during spray-drying of plain yoghurt. *Journal of Food Science* 1990, 55, 1010–2008.
42. Zayed, G.; Roos, Y.H. Influence of trehalose and moisture content on survival of *Lactobacillus salivarius* subjected to freeze drying and storage. *Process Biochemistry* 2004, 39, 1081–1086.
43. Lievense, L.C.; Van't Reit, K. Convective drying of bacteria. The drying process. *Advances in Biochemical Engineering Biotechnology* 1993, 50, 46–51.
44. King, V.; Su, J. Dehydration of *Lactobacillus acidophilus*. *Process Biochemistry* 1993, 28, 47–52.
45. Holzapfel, W.H.; Haberer, P.; Geisen, R.; Bjorkroth, J.; Schillinger, U. Taxonomy and important features of probiotic microorganisms in food and nutrition. *American Journal of Clinical Nutrition* 2001, 73, 365s–373s.
46. Desmond, C.; Stanton, C.; Fitzgerald, G.F.; Collins, K.; Ross, R.P. Environmental adaptation of probiotic lactobacilli towards improved performance during spray drying. *International Dairy Journal* 2001, 11, 801– 808.
47. Mauriello, G.; Aponte, M.; Andolfi, R.; Moschetti, G.; Villani, F. Spray-drying of bacteriocin-producing lactic acid bacteria. *Journal of Food Protection* 1999, 62, 773–777.
48. Prajapati, J.B.; Shah, R.K.; Dave, J.M. Survival of *Lactobacillus acidophilus* in blended-spray dried acidophilus preparations. *Australian Journal of Dairy Technology* 1987, 42, 17–21.
49. Johnson, J.A.C.; Etzel, M.R. Properties of *Lactobacillus helveticus* CNRZ-32 attenuated by spray-drying, freeze-drying, or freezing. *Journal of Dairy Science* 1995, 78, 761–765.
50. Corcoran, B.M.; Ross, R.P.; Fitzgerald, G.F.; Stanton, C. Comparative survival of probiotic lactobacilli spray-dried in the presence of prebiotic substances. *Journal of Applied Microbiology* 2004, 96, 1024–1039.
51. O'Riordan, K.O.; Andrews, D.; Buckle, K.; Conway, P. Evaluation of microencapsulation of a *Bifidobacterium* strain with starch as an approach to prolonging viability during storage. *Journal of Applied Microbiology* 2001, 91, 1059–1066.
52. Selmer-Olsen, E.; Sorhaug, T.; Birkeland, S.E.; Pehrson, R. Survival of *Lactobacillus helveticus* entrapped in Ca-alginate in relation to water content, storage and rehydration. *Journal of Industrial Microbiology and Biotechnology* 1999, 23, 79–85.
53. Silva, J.; Carvahlo, A.S.; Teixeira, P.; Gibbs, P.A. Bacteriocin production by spray dried lactic acid bacteria. *Letters in Applied Microbiology* 2002, 34, 77–81.

54. Hubalek, Z. Protectants used in the cryopreservation of microorganisms. *Cryobiology* 2003, 46, 205–229.
55. Morgan, C.A.; Herman, N.; White, P.A.; Vesey, G. Preservation of micro-organisms by drying: A review. *Journal of Microbiological Methods* 2006, 66, 183–193.
56. Conrad, P.B.; Miller, D.P.; Cielenski, P.R.; de Pablo, J.J. Stabilization and preservation of *Lactobacillus acidophilus* in saccharide matrices. *Cryobiology* 2000, 41, 17–24.
57. Mituoka, T. The human gastrointestinal tract. In *The Lactic Acid Bacteria. The Lactic Acid Bacteria in Health and Disease Vol. 1* eds. Wood, B.J.B. 1992, pp. 69–114. London: Elsevier.
58. Modler, H.W.; Mckeller, R.C.; Goff, H.D.; Mackie, D.A. Using ice cream as a mechanism to incorporate bifidobacterium and fructo-oligosaccharides into the human diet. *Cultured Dairy Products Journal* 1990, 25, 4–29.
59. Desmond, C.; Ross, R.P.; O'Callaghan, E.; Fitzgerald, G.; Stanton, C. Improved survival of *Lactobacillus paracasei* NFBC 338 in spray-dried powders containing gum acacia. *Journal of Applied Microbiology* 2002, 93, 1003–1011.
60. Crittenden, R.; Laitila, A.; Forsell, P.; Matto, J.; Saarela, M.; Matilla-Sandholm, T.; Myllarinen, P. Adhesion of bifidobacteria to granular starch and its implications in probiotic technologies. *Applied Environmental Microbiology* 2001, 67, 3469–3475.
61. Ananta, E.; Volkert, M.; Knorr, D. Cellular injuries and storage stability of spray-dried *Lactobacillus rhamnosus* GG. *International Dairy Journal* 2005, 15, 399–409.
62. Castro, H.; Teixeira, P.; Kirby, R. Storage of lyophilized cultures of *Lactobacillus bulgaricus* under different relative humidities and atmospheres. *Applied Microbiology and Biotechnology* 1995, 44, 172–176.
63. King, V.; Su, J. Dehydration of *Lactobacillus acidophilus*. *Process Biochemistry* 1993, 28, 47–52.
64. Capela, P.; Hay, T.K.C.; Shah, N.P. Effect of cryoprotectants, prebiotics and micro-encapsulation on survival of probiotic organisms in yoghurt and freeze-dried yoghurt. *Food Research International* 2006, 39, 203–211.
65. Kets, E.; Teunissen, P.; de Bont, J. Effect of compatible solutes on survival of lactic acid bacteria subjected to drying. *Applied and Environmental Microbiology* 1996, 62, 259–261.
66. Patist, A.; Zoerb, H. Preservation mechanisms of trehalose in food and biosystems. *Colloids and Surfaces B: Biointerfaces* 2005, 40, 107–113.
67. Corcoran, B.M.; Stanton, C.; Fitzgerald, G.F.; Ross, R.P. Survival of probiotic lactobacilli in acidic environments is enhanced in the presence of metabolizable sugars. *Applied and Environmental Microbiology* 2005, 71, 3060–3067.
68. Carvalho, A.S.; Silva, J.; Ho, P.; Teixeira, P.; Malcata, F.X.; Gibbs, P. Effects of various sugars added to growth and drying media upon thermotolerance and survival throughout storage of freeze dried *Lactobacillus delbrueckii* ssp. *bulgaricus*. *Biotechnology Progress* 2004, 20, 248–254.



69. Garcia De Castro, A.; Bredholt, H.; Strom, A.R.; Tunnacliffe, A. Anhydrobiotic engineering of gram-negative bacteria. *Applied and Environmental Microbiology* 2000, 66, 4142–4144.

70. Sheu, T.Y.; Marshall, R.T. Microentrapment of lactobacilli in calcium alginate gels. *Journal of Food Science* 1993, 54, 557–561.

71. Millqvist-Fureby, A.; Malmsten, M.; Bergenstahl, B. Surface composition of spray dried milk protein-stabilised emulsions in relation to pre-heat treatment of proteins. *Colloides Surf B Biointerfaces* 2000, 21, 47–48.

72. Siuta-Cruce, P.; Goulet, J. Improving probiotic survival rates: microencapsulation preserves the potency of probiotic microorganisms in food systems. *Food Technology* 2001, 55, 37–39.

73. Kailasapathy, K. Microencapsulation of probiotic bacteria: technology and potential applications. *Current Issues Intestinal Microbiology* 2002, 3, 39–48.

74. Guerin, D.; Vuilleumard, J.C.; Subirade, M. Protection of bifidobacteria encapsulated in polysaccharide-protein gel beads against gastric juice and bile. *Journal of Food Protection* 2003, 66, 2076–2084.

75. Lian, W.C.; Hsiao, H.C.; Chou, C.C. Survival of bifidobacteria after spray-drying. *International Journal of Food Microbiology* 2002, 74, 79–86.

76. Roberts, C.M.; Fett, W.F.; Osman, S.F.; Wijey, C.; O'Connor, J.V.; Hoover, D.G. Exopolysaccharide production by *Bifidobacterium longum* BB-79. *Journal of Applied Bacteriology* 1995, 78, 463–468.

77. Salminen, S.; Bouley, C.; Boutron-Ruault, M.C.; Cummings, J.H.; Franck, A.; Gibson, G.R.; Isolauri, E.; Moreau, M.C.; Roberfroid, M.; Rowland, I. Functional food science and gastrointestinal physiology and function. *British Journal of Nutrition* 1998, 80(Suppl. 1), 147–171.

78. Kalliomäki, M.; Salminen, S.; Arvilommi, H.; Kero, P.; Koskinen, P.; Isolauri, E. Probiotics in primary prevention of atopic disease: a randomised placebo-controlled trial. *Lancet* 2001, 357, 1076–1079.

79. Salminen, M.K.; Rautelin, H.; Tynkkynen, S.; Poussa, T.; Saxelin, M.; Valtonen, V.; Järvinen, A. Lactobacillus bacteremia, species identification, and antimicrobial susceptibility of 85 blood isolates. *Clinical Infectious Diseases* 2006, 42, 35–44.

80. Salminen, M.K.; Tynkkynen, S.; Rautelin, H.; Saxelin, M.; Vaara, M.; Ruutu, M.; Sarna, S.; Valtonen, V.; Järvinen, A. Lactobacillus bacteremia during a rapid increase in probiotic use of *Lactobacillus rhamnosus* GG in Finland. *Clinical Infectious Diseases* 2002, 35, 1155–1160.

81. Salminen, M.K.; Rautelin, H.; Tynkkynen, S.; Poussa, T.; Saxelin, M.; Valtonen, V.; Järvinen, A. Lactobacillus bacteremia, clinical significance, and patient outcome, with special focus on probiotic *L. rhamnosus* GG. *Clinical Infectious Diseases* 2004, 38, 62–69.

82. Salminen, M.K.; Tynkkynen, S.; Rautelin, H.; Poussa, T.; Saxelin, M.; Ristola, M.; Valtonen, V.; Järvinen, A. The efficacy and safety of probiotic *Lactobacillus rhamnosus*

GG on prolonged, noninfectious diarrhea in HIV patients on antiretroviral therapy: a randomized, placebo controlled, crossover study. *HIV Clinical. Trials* 2004, 5, 183–191.

83. Rayes, N.; Hansen, S.; Seehofer, D.; Muller, A.R.; Serke, S.; Bengmark S.; Neuhaus, P. Early enteral supply of fiber and lactobacilli versus conventional nutrition: a controlled trial in patients with major abdominal surgery. *Nutrition* 2002, 18, 609–615.

84. Bibiloni, R.; Fedorak, R.N.; Tannock, G.W.; Madsen, K.L.; Gionchetti, P.; Campieri, M.; De Simone, C.; Sartor, R.B. VSL#3 probiotic-mixture induces remission in patients with active ulcerative colitis. *American Journal of Gastroenterology* 2005, 100, 1539–1546.

85. Bousvaros, A.; Guandalini, S.; Baldassano, R.N.; Botelho, C.; Evans, J.; Ferry, G.D.; Goldin, B.; Hartigan, L.; Kugathasan, S.; Levy, J.; Murray, K.F.; Oliva-Hemker, M.; Rosh, J.R.; Tolia, V.; Zholudev, A.; Vanderhoof, J.A.; Hibberd, P.L. A randomized, double-blind trial of *Lactobacillus GG* versus placebo in addition to standard maintenance therapy for children with Crohn's disease. *Inflammatory Bowel Disease* 2005, 11, 833–839.

86. Guslandi, M.; Giollo, P.; Testoni, P. A pilot trial of *Saccharomyces boulardii* in ulcerative colitis. *European Journal of Gastroenterology and Hepatology* 2003, 15, 697–698.

87. Kruis, W.; Kiudelis, G.; Rácz, I.; Gorelov, I.A.; Pokrotnieks, J.; Horynski, M.; Batovsky, M.; Kykal, J.; Boehm, S.; Greinwald, R.; Mueller, R. Maintaining remission of ulcerative colitis with the probiotic *Escherichia coli* Nissle 1917 is as effective as with standard mesalazine. *Gut* 2004, 53, 1617–1623.

88. Enache-Angoulvant, A.; Hennequin, C. Invasive *Saccharomyces* infection: a comprehensive review. *Clinical Infectious Diseases* 2005, 41, 1559–1568.

89. Soleman N.; Laferl H.; Kneifel W.; Tucek G.; Budschedl E.; Weber H.; Pichler H.; Mayer H.K. How safe is safe? A case of *Lactobacillus paracasei* ssp. *paracasei* endocarditis and discussion of the safety of lactic acid bacteria *Scandinavian Journal of Infectious Diseases* 2003, 35, 759–762.

90. Kalliomäki, M.; Salminen, S.; Poussa, T.; Arvilommi, H.; Isolauri, E. Probiotics and prevention of atopic disease: 4-year follow-up of a randomised placebo-controlled trial. *Lancet* 2003, 361, 1869–1871.

91. Hoyos, A.B. Reduced incidence of necrotizing enterocolitis associated with enteral administration of *Lactobacillus acidophilus* and *Bifidobacterium infantis* to neonates in an intensive care unit. *International Journal of Infectious Diseases* 1999, 3, 197–202.

92. Lin, H.C.; Su, B.H.; Chen, A.C.; Lin, T.W.; Tsai, C.H.; Yeh, T.F.; Oh, W. Oral probiotics reduce the incidence and severity of necrotizing enterocolitis in very low birth weight infants. *Pediatrics* 2005, 115, 1–4.

93. Sipsas, N.V.; Zonios, D.I.; Kordossis, T. Safety of *Lactobacillus* strains used as probiotic agents. *Clinical Infectious Diseases* 2002, 34, 1283–1284.

94. Reid, G. Safety of *Lactobacillus* strains as probiotic agents. *Clinical Infectious Diseases* 2002, 35, 349–350.

## **Chapter 7**

# **Drying of Fish and Marine Products**

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## 7.1. INTRODUCTION

### 7.1.1. Fish Statistics

Fish is a very important foodstuff due to its high protein content and nutritional value. The spoilage of freshly caught fish proceeds at very rapid rate. The storage temperature and the humidity are the two important factors accelerating the process of fish spoilage. Fresh fish contains up to 80% water and have a short storage life ([Kakatkar et al., 2003](#)). According to the FAO statistics in 2006 (**Table 7.1**) the global production from fishing and aquaculture combined reached approximately 144 million tons, of which 110 million tons were used for human consumption. More than three-quarters of the world's fish production is consumed by humans and the remaining portion is fed to animals, particularly in the form of fishmeal. Fish consumption has undergone major changes in the past four decades. Overall, consumption per person per year has been increasing steadily, from an average 9.9 kg in the 1960s to 16.4 kg in 2005. In the last years, China has accounted for most of the global growth in fish consumption, and the Chinese per capita fish supply was about 26.1 kg in 2005. Out of three quarters fish production half of the fish is consumed fresh by humans while the other half undergoes some processing. When fish is processed, it is often frozen, but it can also be canned, cured, dried, salted, or smoked.

Since ages, the drying of fish and agricultural products has been practiced as a means of preservation. Drying in earlier times was done in the open sun but over the last 50 years or so, considerable efforts have been made to understand physical, chemical and biochemical changes occur during drying for preventing undesirable nutritional losses and the methods of food preservation has changed with the introduction of new techniques and technologies ([Rehman et al., 1999](#)). Conventional use of sun drying is being replaced these days with solar dryer to assure the quality aspects of the dried food products. Although, the changeover of the technology for food dehydration has been slow over the period, it is however necessary to hasten this process with cost effective and modern drying technologies.

Fish muscular tissue consists mainly of muscle fibers or cells (86-88%, v/v) and some extracellular space (interstitial space, 9-12% and capillary space, 2-3 %). The muscle cell consist of mainly fibrils (working unit of cell, 65%), Sarcoplasma (transport and regulatory space filled with liquid and functional units, 20-3-%), and finally connective tissue (6%). The muscle cells or fibers, each has a diameter 0.1 to 0.2 mm ([Walde 2003](#)).

**Table 7.1. World fisheries and aquaculture production and utilization) Source FAO STAT**

YEAR	2002	2003	2004	2005	2006
	<b>PRODUCTION (MILLION TONNES)</b>				
<b>INLAND</b>					
Capture	8.7	9.0	8.9	9.7	10.1
Aquaculture	24.0	25.5	27.8	29.6	31.6
Total inland	32.7	34.4	36.7	39.3	41.7
<b>MARINE</b>					
Capture	84.5	81.5	85.7	84.5	81.9
Aquaculture	16.4	17.2	18.1	18.9	20.1
Total marine	100.9	98.7	103.8	103.4	102.0
<b>TOTAL CAPTURE</b>	93.2	90.5	94.6	94.2	92.0
<b>TOTAL AQUACUL-TURE</b>	40.4	42.7	45.9	48.5	51.7
<b>TOTAL WORLD FISHERIES</b>	133.6	133.2	140.5	142.7	143.6
	<b>UTILIZATION</b>				
Human consumption	100.7	103.4	104.5	107.1	110.4
Non-food uses	32.9	29.8	36.0	35.6	33.3
Population (bil-lions)	6.3	6.4	6.4	6.5	6.6
Per capita food fish supply (kg)	16.0	16.3	16.2	16.4	16.7

## 7.2. Salting

Salting, alternatively termed as Curing, is one of the oldest processes for preservation of fish. Salting is either used as pretreatment for drying or can be used as single step in fish preservation. Both lean and fatty fishes can be salted, though methods of salting vary for lean and fatty fishes. As a pretreatment, salting is the most common process and is used for pretreating fish for drying as well as smoking process. Depending on type of fish, final product characteristics and desired form, regional variations and technological

advancements, number of salting methods are evolved over the period of time, though principle of preservation by salting remains the same.

### **7.2.1. Principle of Preservation by Salting**

During salting, fish is kept in contact with dry salt or salt solution. Over the period of time, salt penetrates into fish tissues, moisture comes out and tissue cells shrink. Depending on process chosen, at the end of salting, certain salt concentration is built in fish and moisture content is reduced. Both these conditions create adverse conditions for microbial growth. In short, salting acts as preservative method as well as it provides sensory and flavor characteristics ([Rahman, 2007](#)).

### **7.2.2. Methods of Salting**

Before salting, fish is cleaned. Depending on desired form of final salted fish and species to be salted, fish can be salted entirely or it can be beheaded, skinned, split, deboned or filleted. Number of variations does exist for preparation of fish for salting. Fish may be cleaned and washed before further processing.

Number of variations exists in salting procedure as well, but broadly salting can be classified in two ways:

#### ***Drying salting***

In dry salting, fish is led down between few centimeter thicknesses of 7%-8% salt ([Ronsivalli and Learson, 1973](#)). As time progresses, moisture come out and forms brine. Depending upon whether self brine of fish is drained out or not, dry salting can be further classified. In case of lean fishes, self brine is allowed to drain out, while in case of fatty fishes, fish is immersed in self brine as self brine is not drained out. This is particularly important because in case of fatty fishes, fats undergo oxidation due to atmospheric oxygen producing rancidity. To avoid rancidity, in case of fatty fishes, care should be taken that contact of fish with air is avoided. Some form of weight can be used for keeping fish immersed in brine. After predefined period that may vary from few hours to days salted fish are taken out, laid in stacks to press out water and processed further. In case of dry slating, though moisture content decreases considerably, salt absorption is not uniform throughout the fish.

#### ***Brine Salting***

It is a wet salting method, in which fish are soaked in salt solution. This treatment is preferred for fatty fishes and care should be taken that fish remains immersed in brine without having contact with air. When fish are kept in stack, rearrangement of fish is needed so that every layer experiences pressure created at bottom equally.

Depending on salt percentage in final dried fish, salting can be classified as Light Curing and Hard Curing. Light curing produces lower salt content fish and they are more popular due to better organoleptic properties. Hard curing produces salted fish with salt content up to 30% ([Ronsivalli and Learson, 1973](#)).

### **7.2.3. Process Parameters**

#### ***Temperature***

Increase in salting temperature raises salting rate. But it should be noted that during salting, microbes are still present and rise in temperature may enhance their growth leading to spoilage. Hence to avoid possibility of spoilage, temperature should not be raised to take advantage of higher salting rate. Though temperature selection is arbitrary, low temperatures and even brine made from ice are preferred for salting with temperature range of 0°C to 38°C ([Rahman, 2007](#)).

### ***Salt Concentration***

Initially depending on light curing or hard curing, one can decide desired salt concentration, which in turn decides final salt content in salted fish. Salt concentration decides osmotic pressure created by brine and decides salt uptake rate and moisture removal rate. Higher the salt concentration, higher is the salting rate. But this higher rate may lead to non-uniform salt distribution in salted fish. Appropriate salt concentration should be chosen looking at final salt content, desired organoleptic properties, preservation, uniform salting and salting time.

### ***Fat Content***

Fats in fish get oxidized by atmospheric oxygen producing rancidity. Hence type of salting should be chosen by considering type of fish either lean or fatty. As fat content increases in species, salting rate decreases. But total salt content intake in final dried fish is higher in lean fish and more in fatty fish. Hence, for fatty fishes though salting rate is low, it may happen that salting times are low as total salt intake in them is lower.

### ***Salting Time***

Typically, salting is carried out till equilibrium is established. But when salting is used as pretreatment, one doesn't rely on salting alone for preservation. In those cases, salting time may be reduced. Temperature, thickness of fish, fish species, salt concentration and rest of the parameters together determines salting time.

### ***Final Moisture Content***

In salting, salt content and moisture content in final product decides preservation. For longer shelf life, higher salt content is desired. Again, final moisture content to be achieved at the end of salting depends on whether salting is the only preservation step or it is a pretreatment for further processing.

### ***Thickness of Fish***

Salting is inversely proportional to thickness of fish. For fatty fishes, fillets or cuts are required to enhance salting rate. But in real sense, it is the desired form of final product that decides the shape, size and thickness of salted fish. Uniformity of salting throughout the fish is important aspect in preservation perspective, but it is complex phenomenon as it not only depends on thickness but also on species, various body parts of same fish and variation of thickness with respect to length.

### ***Salt types***

Sodium chloride, sodium and potassium nitrite and nitrate are the commonly used salt for salting. Sodium chloride is the most common salt used in salting. Purity of salt is another concern. Calcium and magnesium are impurities in sodium chloride. These im-



purities create desired effects like better color and texture characteristics while undesired effects like reduction in salt uptake, bitter flavor and may lead to spoilage. Copper, which is the minor contaminant, leads to enhancement in rancidity and discoloration. As these impurities create both desired and undesired effects, it is the desired parameter that decides purity level of salt. Still, pure salt is preferred in general. Source of salt decides impurities present and microbial contamination. Certain microbes are observed only in sea salt and not in rock salt and inland salt; hence they can be used as alternative salt sources to sea salt ([Ronsivalli and Learson, 1973](#)).

#### **7.2.4. Variations in Salting Method**

Long salting times, quality variations and regional variations do exist in salting method. Some of these variations are summarized below:

##### ***Salting and Pressing***

In this method, fish is either dry salted or wet salted. After required salting time, fish is pressed to decrease the moisture content. These types of salted and pressed fish products can be stored at ambient conditions in sealed packs with storage life of few weeks.

##### ***Sealed Salted Fishes***

In this method, fish is sealed with salt and water in air free plastic bag. The bag is sealed and kept in that position for certain time, after which characteristic flavor is created (Mendelsohn, 1974).

##### ***Cooked Salted Fish***

A combination of cooking, grinding and salting yields cooked salted fish. They are processed by alternatively arranging salt and fish layer in boiling water ([Iljas and Ronsivalli, 1969](#); [Nitibhaskara and Dollar, 1967](#)).

##### ***Del Velle and Nickerson Method***

In this method, fish flesh is ground with addition of salt. Due to ground flesh, salting period is considerably reduced. The mix is then pressed to remove water and pressed cakes are formed. These cakes are then dried under open sun or in mechanical dryers. Proper salt concentration should be maintained to avoid disintegration of dried cake ([Del and Nickerson, 1968](#)).

### **7.3. Smoking**

Smoking is a fish preservation technique as old as drying and salting. The smoke from wood is used to partially dehydrate and preserve fish in smoking process. The peculiar smell and odor distinguish smoked products and creates a special market. Depending on temperature of smoking, it is classified as hot and cold smoking. Lot of variations does exist in terms of forms of fish to be smoked, smokehouse development and pretreatment for smoking. Though smoked products have a special market, the microbiological quality aspect of smoked products has been a controversial subject. A better control and standardization of smoking procedure is desired to obtain safe products from health perspective.

### 7.3.1. Principle of Preservation by Smoking

Wood smoke is a complex mixture of volatiles. Fish products exposed to the smoke get preserved mainly by following principles:

a) Dehydration: During smoking, partial dehydration of fish occurs. The reduction in moisture content acts as one of the preservation method.

b) Smoking: Smoke contains various volatiles. These volatiles contain bactericidal and antioxidants compounds, which act as preservative. Apart from microbiological aspect, smoke imparts flavor and color to smoked product. Additionally, smoke deposition on surface avoids surface spoilage.

c) Pretreatment: Sometimes salting is used as pretreatment for smoking. The salt equilibrium is achieved during smoking process and salting acts as additional preservative step.

d) Cooking: In hot smoking, fish product is cooked at about 63°C, this leads to considerable reduction in microbial count ([Rahman, 2007](#)).

### 7.3.2. Methods of Smoking

For smoking, on broader basis, steps those are followed are enlisted ([Ronsivalli and Learson, 1973](#)):

a) Preparation: Depending on fish species and desired product form, viscera is removed, fish is scaled, beheaded, split, cut or filleted and finally washed.

b) Fish Form: For smoking, entire fish or beheaded and split or filleted fish can be used.

c) Pretreatment: Fish can be lightly salted before smoking.

d) Prior Drying: After salting, fish is washed and dried either under open sun or mechanical dryer.

e) Smoking: In smoke house, smoking is carried out mainly by two types:

- Hot smoking: In this method, fish is smoked and partially dehydrated along with cooking at 63°C for at least 30 minutes. The cooking results in decrease in microbial count ([Rahman, 2007](#)).
- Cold Smoking: Cold smoking is carried out at temperatures below 32°C, where smoking and partial dehydration is carried out. Due to lower temperatures, cooking doesn't take place ([Rahman, 2007](#)).

f) Storage: Smoked products are rapidly cooled at refrigeration temperature and stored in that condition. Dehydrated and hard smoked products can be stored at room temperatures.

### 7.3.3. Process Parameters

#### ***Fish Arrangement***

Fish as a whole, viscera removed, split or filleted can be used for smoking. Depending on form of fish, it is arranged in smoke house. S-hooks, threads or nails can be used

for whole fish. For filleted fish, wire mesh trays can be used. Sometimes coatings are given to avoid sticking and breakage of fish flesh during processing.

### ***Wood for Smoking***

Smoke is the complex mixture and its components vary with respect to raw wood used for smoking. Wood giving slow burning and large smoke is desired for smoking purpose. Though in general hard wood is preferred, for short time smoking processes, soft wood can be used. The desired color and flavor characteristics decide final choice of wood.

### ***Temperature and Time of Smoking***

Depending on method of hot or cold smoking, temperatures below 32°C and above 63°C are used ([Rahman, 2007](#)). Smoking time varies from few hours to week but most of processes are completed within 24 hours. Cold smoking requires comparatively lower time than hot smoking.

### ***Smoke House Conditions***

Typical conditions desired in smoke house are high smoke density, lower humidity and desired temperature. For good smoking, high smoke density is desired while lower humidity is desired for higher drying rate. One of the main constraints demand retention of air while other demands rejection of air. Optimum value of air rejection has to be chosen for good smoking and higher drying rate. Inside smoke house, proper air distribution should be provided so that uniform exposure is provided to all fish. For maximum smoke deposition, 60% relative humidity and 71.1°C temperature is suggested ([Chan et al., 1975](#)). Traditional and new smoke houses are available for meeting needs of smoking conditions.

Smoke generated from wood contains tar. To remove tar electrostatic precipitation or passage of smoke over water is suggested. To provide color and flavor, colorants and spices can be added.

### ***Liquid Smoke***

Health aspect and lack of control over smoking process are serious concerns in smoking. Liquid smokes are seen as a solution to these problems. Either condensed and treated smoke or artificial liquid smoke is considered to be possible alternatives to smoke. Liquid smoke is easy to use and its properties and composition can be easily controlled. In case of liquid smoke, fish samples are dipped in smoke for desired time and temperature and then further processing is carried out.

## **7.4. Drying**

Drying alone or in combination with salting is one of the most practiced, low cost fish preservation techniques. With technological development and improvement in life style, dried products demand is falling in developed world. But, in developing world due to its low processing and storage cost, dried fish are preferred. To trap developed world's market, newer technologies giving better quality are under focus, though they are costlier than air drying.

Fish are generally dried under open sun at atmospheric conditions. Mechanical dryers are developed for processing fish under controlled and hygienic conditions. These dryers also include solar dryers. Freeze, vacuum and heat pump dryers are being used with specific applications giving better quality dried fish.

#### **7.4.1. Principle of Preservation by Drying**

Main reason for degradation of fish is microbial growth. The environment for growth of microbes is indicated by moisture content and a better parameter that does so is water activity. To inhibit the growth of microbes water activity should be lower than 0.7. Water activity of 0.6 is truly desired but 0.7 values are sufficient for preservation.

Water activity of flesh fish is 0.99 and that of salted fish is generally greater than 0.7. In both of these cases, drying is carried out to reduce moisture content and water activity of fish flesh. It is also important to decrease water activity to 0.7 with respect to storage temperature and not with respect to processing temperature ([Sen, 2005](#)). Reduced water activity of 0.7 suppresses growth of microbes and hence increases shelf life of product. Proper care should be taken during packaging to create moisture entry barrier to increase shelf life of dried product.

Salting is the most common pretreatment for drying of fish, as salting alone is incapable of providing long storage life.

#### **7.4.2. Methods of Drying**

##### ***Pretreatment***

After catching, fish can be directly dried or beheaded, eviscerated, cleaned and either cut into halves or filleted. Salting is generally used as pretreatment but sometimes drying is carried out without salting as well.

##### ***Open sun drying***

It is the most common process of drying of fish but offer little control over process. Fish are either led on ground or sand or they are simply hanged in blowing air using S-hooks or threads. Open sun drying depends on atmospheric conditions and fish may degrade before drying completes. Contamination by insects, birds is another challenge. But being the cheapest drying method, it is commonly practiced in developing world. Fish containing fat less than 2% are suitable for open sun drying ([Ronsivalli and Learson, 1973](#)).

##### ***Solar drying***

This category of driers includes dryers operated on solar energy. They offer increased rate of drying, hygienic conditions of operation, control over temperature, humidity and flow rate of air. They are capital cost intensive, require high collector area. Both natural convection and forced convection based dryers operating with or without electricity are available. They provide higher temperature and lesser dependency on environmental conditions than open sun drying. Apart from increase in drying rate, these are used preferably because of hygienic and almost zero contamination they offer.

##### ***Enhanced open sun drying***

Blackened surfaces either black painted terrace or black plastic sheets are tried to increase drying rate. Black surfaces being better absorber increase the surface temperature up to 17°C-25°C above ambient conditions, increasing drying rate. But they don't offer solution to contamination ([Garg et al.,1984](#)).

### ***Mechanical dryers***

Traditional mechanical dryers used in food industry are now being used for fish drying. Unlike solar dryers, they can be operated throughout the year and shows much less effect of environmental conditions. They offer control over air temperature, humidity and flow rate inside dryer. These parameters help to increase drying rate in initial conditions but in later part of drying temperature is the key parameters which is again determined by quality parameters.

### ***Accelerated mechanical dryers***

It is suggested that as drying progresses, moisture content drops, drying temperatures can be increased to increase rate of drying. Temperatures above 100°C can be used in final stage ([Jason, 1959](#); [Jason, 1965\(a\)](#); [Jason, 1965\(b\)](#)).

### ***Other techniques***

Heat pump dryer, vacuum dryer and freeze dryers are also tried for fish drying. But its high cost is the determining factor for their commercialization.

It is the cost, fish species, value of final product, environmental suitability that decides choice of particular dryer for given application. There is no best dryer as such in general.

### ***Heat Pump Dryer***

Because drying is energy intensive operations, new drying methods those are more energy efficient are being tried. Heat pump dryer is one of the technologies in this domain. Drying being heat and mass transfer operation both, rate of drying can be improved by either raising temperature or increasing mass transfer driving force. In heat pump dryer, air is dehumidified, thus increasing mass transfer driving force. It allows drying to be carried out at lower temperature giving better quality product. Additionally, they are less affected by ambient conditions, providing better process control. Heat pump dryers are tried for fish and marine products as well.

Shi et al. (2008) carried out heat pump drying using R134a as working fluid and suggested that it is a good drying method for intermediate moisture content products. For mackerel, authors found that heat pump drying delivers quality products. Optimum conditions found to be surface load of 6kg/m<sup>2</sup>, temperature range of 20°C-30°C and air velocity to be 2-3m/s.

### ***Solar assisted heat pump dryers***

Solar drying and heat pump drying both possess their own advantages and disadvantages. Solar energy is free but dependency on atmospheric conditions and high collector area required are associated challenges. Heat pump dryers are popular for low and medium temperature applications. Solar assisted heat pump dryer (SAHPD) provides a system that can take benefit of both solar and heat pump dryer. In SAHPD, vapor

compression cycle unit is coupled with solar collector. This system operates with high coefficient of performance ([Chaturvedi and Shen, 1984](#)). Results and observation from the studies of solar assisted heat pump dryer systems indicated that for heat sensitive materials; improved quality control, reduced energy consumption, high coefficient of performance and high thermal efficiency of the dryer were achieved ([Daghigh et al., 2010](#)). [Strommen and Kramer \(1994\)](#) carried out drying of marine products (fish) in SAHPD. They found that high quality product is the remarkable advantage of SAHPD.

### **7.4.3. Process Parameters**

#### ***Air humidity and quality***

Relative humidity of air and fish flesh decides driving force for moisture transfer. With increase in temperature, relative humidity decreases and drying rate increases. Air with lower relative humidity is preferred for drying. To maintain lower relative humidity in drying chamber air rejection should be adjusted. Relative humidity of around 40% is generally used, though 10%-40% has shown only marginal difference ([Rahman, 2007](#)).

Air quality is also important for drying of marine products. The ambient air if directly used for solar drying carried considerable amount of spores and microbes along with it. These microorganisms may stay as it is on the dried products and damage the product quality mainly by microorganism growth. Air cleaning, hence is very important for marine products as these are more susceptible for microbial growth.

#### ***Air flow***

Air flow is required to provide heat and remove moisture. Typical values of local air velocity are 0.5 m/s to 1.5 m/s. The higher air airflow increases heat transfer and drying rate in constant drying rate period. In falling rate period, where resistance to mass transfer lies inside fish flesh, air velocity shows little effect. To maintain humidity at desired level, air rejection plays role. However, use of excess air can sometime result in increased pumping cost and heater load which reduces the performance of dryer unnecessarily. It is necessary to select or control the air flow depending on the drying kinetics. The drying of most of the food products fall in falling rate period and hence the air-flow has little effect on drying rate.

#### ***Drying temperature***

Drying temperature increases drying rate. Temperatures ranging from 30°C to 90°C are suggested. Some researchers have suggested that progressive temperature rise as drying progresses ([Jason, 1959](#); [Jason, 1965\(a\)](#); [Jason, 1965\(b\)](#)) while some researchers have suggested initial high temperatures ([Rahman, 2007](#)). Finally, it is the only quality that decides drying temperature. Marine products are also sensitive to the drying temperature, hence very high temperature are not preferred. The product quality, in terms of color and texture can be highly affected by use of high temperature for enhancing drying rates. In this situation, use of heat pump dryers with controlled temperature and humidity (to enhance the drying rate) could be a better choice provided the availability of market to compensate the increased drying cost as a result of using refrigeration system.

#### ***Fish arrangement***

The arrangement of marine products is very important to get uniformly dried product. The whole fish can be hanged using S hooks or threads with bamboo support. However, the Fish fillet can be dried on perforated trays. Air flow can be channeled horizontally or vertically providing equal exposure to all drying surface. Frequent change of fish orientation may be required for uniform drying. Arrangement should be such that maximum surface area is exposed to the drying area.

### ***Drying time***

Drying is carried out till moisture content drops corresponding to water activity of 0.6 or less. Dried product should be removed at conditions when relative humidity is low as final moisture content depends on surrounding air humidity. Generally the drying time for certain drying conditions is decided by laboratory scale experiments for similar arrangement of product in a drying chamber. In conventional tray dryer the product may not have uniform drying conditions at all locations of the dryer if the air distribution is not proper. This can sometime result in unacceptable product which is more susceptible to microbial growth. Hence the proper distribution of drying air is crucial with the dryers used for marine products.

### ***Fish characteristics***

Fish flesh thickness, texture, fat percentage, salt content for salted fish decides drying time. Higher the salt content, higher is the final moisture content. Increase in fat content reduces the drying rate.

Though increased temperatures, increases drying rate, fast heating may result into case hardening due to crust of dried soluble protein. Case hardening should be avoided as it decreases drying rate considerably.

## **7.5. Drying of Selected Fish products**

### **7.5.1. Drying of Bombay Duck (*Harpadon nehereus*)**

*Bombay duck* is native to the waters between Mumbai and Kutch in the Arabian Sea, and a small number are also found in the Bay of Bengal. Traditionally this fish is dried in the open ground hanging on bamboo sticks. [Nooralabettu, \(2008\)](#) carried out drying of *Harpadon nehereus* by salting and unsalting in open sun and artificial drying and found that salted fish in artificial dryer at 45°C has better quality compared to unsalted and open sun dried. [Visavale, \(2009\)](#) developed the solar cabinet dryer for drying of fish products. In this system drying is carried out hygienically in completely closed chamber with *Bombay duck* in hanging position. It takes around 8 to 10 hours for drying of *Bombay duck*. Compared to other dryers like hot air dryer, heat pump dryer and freeze dryer solar cabinet drying found low energy intensive process with acceptable quality dehydrated fish. The quality is far superior compared to traditional open sun drying.

In a typical experimental run by [Bala and Janjai, \(2005\)](#) *Bombay duck* was dried in a solar tunnel dryer from initial moisture content of 89.8% to 15% in 9 hours as compared to 20 hours of drying in the traditional method and concluded that the use of solar tunnel dryer leads to considerable reduction of drying time in comparison to sun drying with better quality *Bombay duck*.





Picture 1 shows traditional drying of Bombay duck in open sun drying in India and Picture 2 shows drying of Bombay duck in solar cabinet dryer developed by Visavale.

### 7.5.2. Drying of Sardines

Sardines (*Sardinella aurita*, *Sardina pilchardus*, *Sardinella gibbosa*, *Sardinella longiceps*) are rich in omega-3 fatty acids, which reduce the occurrence of cardiovascular disease. Sardines are found in coastal parts of France, Norway, Portugal, India, Spain and Turkey. Sardines are canned, but fresh sardines are often grilled, pickled or smoked. For drying of sardines dry salting and wet salting methods followed by hot air drying are preferred. [Belleghe et al., \(2007\)](#) carried out brine salting (21% w/w NaCl) at ambient temperature (20°C approximately) and dry salting was run by inserting a salt layer with a fish layer. After 24 hours salting these salted fish are dried in a convective dryer at 40°C with air velocity at 1.5 m/s and relative humidity varied from 13% to 17%. Both the salting methods give low aw (0.6-0.7) but 21% brined sardines shows higher acceptability than dry salted. [Goddard and Al-Yahyai, \(2001\)](#) prepared the acid sardine silage and co-silage (prepared by adding wheat bran in 3:1 ratio with silage) and dried in a solar cabinet dryer (34 to 56°C) and in open air (28 to 36°C). The solar cabinet drying of co-silaged sardines was found more effective with soft textured product compared to silaged in open air drying.

### 7.5.3. Drying of Mackerel

Mackerels are found in all tropical and temperate seas. Most live offshore in the oceanic environment but a few, like the Spanish mackerel. Mackerel is well known for its high fat content, especially unsaturated fatty acid. However, due to high content of protein and dark muscle, it is susceptible to deterioration during processing and storage. Qi-Long Shi et al., (2008) carried out drying of mackerel by osmotic dehydration followed by heat pump drying. The mass ratio of fish to osmotic solution was 1:3 which contains 10% NaCl (w/w), 15% sugar (w/w), 1% pure ginger juice (w/w), 2% yellow wine (w/w), 0.1% sodium glutamate (w/w), Osmotic drying was carried out for 1 hour followed by heat pump drying at different temperatures, different air velocities and different relative humidity. [Chavan et al., \(2008\)](#) carried out drying of Indian mackerel in solar biomass hybrid cabinet dryer and compared with open sun drying. In solar biomass hybrid dryer the temperature of air was 32.39-57.69°C, relative humidity 23.9-85.8%, and air flow rate of 0.20-0.60 m/s. To reduce initial moisture content of 72.50±0.44% (w.b.) to 16.67±0.52% (w.b.) in S-BHCD it takes 24 hours whereas to remove same amount of moisture in OSD it takes more than 44 hours. At nighttime, in S-BHCD drying was carried out by combusting biomass



#### 7.5.4. Drying of Shrimps

Shrimps are mainly found in East Asia and in Southeast Asia. Dried shrimp are used quite frequently for their sweet and unique flavor that is very different from fresh shrimp. Traditionally these shrimps are dried by sun drying or roasting in open air. [Prachayawarakorn et al., \(2002\)](#) carried out shrimp drying in two stages, initially boiling the raw shrimps in 2% NaCl for 30 minutes at room temperature followed by drying using superheated steam with steam velocity of  $1.6 \pm 0.2$  m/s and varying the steam temperature from 120 to 180°C. The drying is also carried out by using hot air instead of steam with the same velocity with temperatures in the range from 70 to 140°C. The quality of shrimps dried with superheated steam found better compared to air drying in terms of shrinkage and color. [Namsanguana et al., \(2004\)](#) also performed two-stage drying of shrimps. Initially drying of shrimps carried out with superheated steam dryer followed by heat pump dryer or hot air dryer. The quality of shrimps dried in two stage superheated steam followed by heat pump is better and more efficient than alone superheated steam drying. Also drying with superheat steam followed by hot air gives better red color than superheat steam followed by heat pump but shrinkage and rehydration properties are retained better in the heat pump dryer.

#### 7.5.5. Drying of Prawns

For drying of prawns a comparative study was carried out by [Visavale \(2009\)](#). Prawns are dried in various dryers like hot air dryer, solar cabinet dryer, freeze dryer and open sun drying. Moisture diffusivity values for prawns dried in hot air dryer showed highest moisture diffusivity followed by solar cabinet dryer and freeze dryer whereas, open sun drying showed lowest diffusivity values. In case of quality parameters, prawns dried in freeze dryer exhibited highest color retention, lowest shrinkage and soft textured compared to other processes but it is high energy intensive process. So solar cabinet drying was found low energy process compared to other processes with acceptable quality prawns

## REFERENCES

- Bala B. K. and Janjai S., Solar, Drying of Fish (Bombay duck) Using Solar Tunnel Drier. *International Energy Journal* **2005**, 6(2).
- Bellagha S., Sahli A., Farhat A., Kechaou N. and Glenza. A., Studies on salting and drying of sardine (*Sardinella aurita*): Experimental kinetics and modeling. *Journal of Food Engineering* **2007**, 78, 947-952.
- Chan, W. S., Toledo, R., Deng J., Effect of Smokehouse temperature, humidity and air-flow on smoke penetration into fish muscle, *Journal of Food Science* **1975**, 40(2), 240-242.
- Chaturvedi, S.K., Shen JY. Thermal performance of a direct expansion solar assisted heat pump. *Solar Energy* **1984**, 33(2), 155-162.
- Chavan, B. R., Yakupitiyage, A.; Kumar, S. Mathematical Modeling of Drying Characteristics of Indian Mackerel (*Rastrilliger kangurta*) in Solar-Biomass Hybrid Cabinet Dryer Drying Technology **2008**, 26(12), 1552-1562.

Daghigh R., Ruslan M.H., Sulaiman M.Y., Sopian K., Review of solar assisted heat pump drying systems for agricultural and marine products, *Renewable and Sustainable Energy Reviews* **2010**, 14, 2564–2579.

Del, V. F. R., and Nickerson, J. T. R., A quick salting process for fish I: Evolution of the process, *Food Technology* 1968, 22(8), 104-106.

FAO STAT, (2006), Food and Agriculture Organization of United Nations. FAOSTAT database <http://faostat.fao.org>,

Garg, D. K., Damle, S. P., Nambiar, V. N., Valsan A.P., Rapid and hygienic method of drying non-penaeid prawns using solar energy, In Balachandran, K. K.(Ed), *Recent trends in processing low cost fish*, Society of Fisheries Technologists(India), Kochi, 1984, 184.

Goddarda J. S. and Al-Yahyaia D. S. S. Chemical and Nutritional Characteristics of Dried Sardine Silage. *Journal of Aquatic Food Product Technology* **2001**, 10(4), 39-50.

Iljas, S. and Ronsivalli, L. J., Improved method for producing pindang, *Fishery Ind. Res.* **1969**, 5(1), 11-16.

Jason, A.C., , Drying and dehydration, In Borgstrom G., *Fish as food Vol.3-Processing Part I*, Academic Press, New York (USA), 1965(a), 1.

Jason, A.C., , Effects of fat content on diffusion of water in fish muscle, *Journal of Science of Food and Agriculture*, **1965(b)**, 16(5), 281-288.

Jason, A.C., A study of evaporation and diffusion processes in drying of fish muscle, In *Fundamental aspects of the drying of food stuffs*, Society of Chemical Industry, London(UK) **1959**, 103.

Kakatkar, A., Sharma, A., Venugopal, V., Hydration of muscle proteins of Bombay duck (*Herpodon nehereus*) during acetic acid-induced gelation and characteristics of the gel dispersion. *Food Chemistry* **2003**, 83, 99-106.

Mendelsohn, J. M., Rapid technique for salt-curing fish: A review, *Journal of Food Science* **1974**, 29, 125-127.

Namsanguana, Y. Tiaa, W., Devahastinb S., Soponronnarita, S. Drying Kinetics and Quality of Shrimp Undergoing Different Two-Stage Drying Processes. *Drying Technology* **2004**, 22(4), 759-778.

Nitibhaskara, R. and Dollar, A. M., Quality changes during storage of boiled fish products prepared from Pacific herring by improved method, *Bull. Japan. Soc. Sci. Fisheries* **1967**, 33(11), 1028-1034.

Nooralabettu K. P. Effect of Sun Drying and Artificial Drying of Fresh, Salted Bombay Duck (*Harpodon neherius*) on the Physical Characteristics of the Product. *Journal of Aquatic Food Product Technology* **2008**, 17(2), 2008, 99-116.

Prachayawarakorn, S., Soponronnarit, S., Wetchacama, S., Jaisut, D. Desorption isotherm and drying characteristics of shrimps in superheated steam and hot air. *Drying Technology* **2002**, 20(3), 669- 684

Qi-Long Shi, Chang-Hu Xue, Ya Zhao, Zhao-Jie Li, Xiang-You Wang. Drying characteristics of horse mackerel (*Trachurus japonicus*) dried in a heat pump dehumidifier. *Journal of Food Engineering* **2008**, 84, 12-20

Rahman, M. S., Drying of Fish and Seafood, pp.547-561, In Mujumdar, A. S. (Ed.), *Handbook of Industrial Drying*, Third Edition, CRC Press. 2007.

Rehman, M. S., Perera, C. O., In Rehman, A. S. (Ed.), *Handbook of Food Preservation*. New York: Marcel Dekker, 1999, 173-216.

Ronsivalli, L. J. and Learson, R. J., Dehydration of Fishery Products, pp.266-289, In Van, A., Copley, M.J., Morgan, A.I. (Ed.), *Food Dehydration: Practices and Applications*, Vol.2, Second Edition, The Avi Publishing Company, 1973.

Sen, D.P., *Advances in Fish Processing*, Allied Publishers Private Limited 2005.

Strommen, I, Kramer, K. New applications of heat pumps in drying process. *Drying Technology* **1994**, 12(4), 889-901.

Visavale, G. L., *Design and Characteristics of Industrial Drying Systems*, A thesis submitted to University of Mumbai. 2009, 19.

Walde, P. M. Transport phenomena in Dehydration of Fish Muscle. Ph.D. thesis, Norwegian University of Science and Technology, Alesund, Norway, 2003.



## **Publications of Professor Arun Mujumdar in Drying (Period: 2005 – Present)**

1. Suvarnakuta, P., Chaweerungrat, C., Devahastin, S. (2011). Effects of drying methods on assay and antioxidant activity of xanthenes in mangosteen rind. *Food Chemistry*, 125(1), 240-247.
2. Huang, L.-L., Zhang, M., Mujumdar, A.S., Lim, R.-X. (2011). Comparison of four drying methods for re-structured mixed potato with apple chips. *Journal of Food Engineering*, 103(3), 279-284.
3. Saencom, S., Chiewchan, N., Devahastin, S. (2010). Production of dried ivy gourd sheet as a health snack. *Food and Bioproducts Processing*, Article in Press.
4. Tanongkankit, Y., Chiewchan, N., Devahastin, S. (2010). Effect of processing on antioxidants and their activity in dietary fiber powder from cabbage outer leaves. *Drying Technology*, 28(9), 1063-1071.
5. Sansiribhan, S., Devahastin, S., Soponronnarit, S. (2010). Quantitative Evaluation of Microstructural Changes and their Relations with Some Physical Characteristics of Food during Drying. *Journal of Food Science*, 75(7), E453-E461.
6. Devahastin, S., Niamnuy, C. (2010). Modelling quality changes of fruits and vegetables during drying: A review. *International Journal of Food Science and Technology*, 45(9), 1755-1767.
7. Chiewchan, N., Praphraiphetch, C., Devahastin, S. (2010). Effect of pretreatment on surface topographical features of vegetables during drying. *Journal of Food Engineering*, 101(1), 41-48.
8. Thakhiew, W., Devahastin, S., Soponronnarit, S. (2010). Effects of drying methods and plasticizer concentration on some physical and mechanical properties of edible chitosan films. *Journal of Food Engineering*, 99(2), 216-224.
9. Chindapan, N., Devahastin, S., Chiewchan, N. (2010). Effect of electro dialysis pretreatment on physicochemical properties and morphology of spray-dried-fish sauce powder. *Journal of Food Engineering*, 99(1), 31-39.
10. Nimmol, C., Devahastin, S. (2010). Evaluation of performance and energy consumption of an impinging stream dryer for paddy. *Applied Thermal Engineering*, 30(14-15), 2204-2212
11. Jiang, H., Zhang, M., Mujumdar, A.S. (2010). Microwave freeze-drying characteristics of banana crisps. *Drying Technology*, 28(12), 1377-1384.
12. Duan, X., Zhang, M., Mujumdar, A.S., Huang, L.L., Wang, H. (2010). A novel dielectric drying method of sea cucumber. *International Journal of Food Science and Technology*, 45(12), 2538-2545.
13. Jangam, S.V., Thorat, B.N. (2010). Optimization of spray drying of ginger extract. *Drying Technology*, 28(12), 1426-1434.

14. Telang, A.M., Thorat, B.N. (2010). Optimization of process parameters for spray drying of fermented soy milk. *Drying Technology*, 28(12), 1445-1456.
15. Jadhav, D.B., Visavale, G.L., Sutar, P.P., Annapure, U.S., Thorat, B.N. (2010). Solar cabinet drying of bitter melon: Optimization of pretreatments and quality evaluation. *International Journal of Food Engineering*, 6(4), art. no. 5.
16. Jadhav, D.B., Visavale, G.L., Sutar, N., Annapure, U.S., Thorat, B.N. (2010). Studies on Solar cabinet drying of green peas (*Pisum sativum*). *Drying Technology*, 28(5), 600-607.
17. Patil, V.V., Dandekar, P.P., Patravale, V.B., Thorat, B.N. (2010). Freeze drying: Potential for powdered nanoparticulate product. *Drying Technology*, 28(5), 624-635.
18. Gaware, T.J., Sutar, N., Thorat, B.N. (2010). Drying of tomato using different methods: Comparison of dehydration and rehydration kinetics. *Drying Technology*, 28(5), 651-658.
19. Shyamkuwar, A.L., Chokashi, K.P., Waje, S.S., Thorat, B.N. (2010). Synthesis, characterization, and drying of absorbable gelatin foam. *Drying Technology*, 28(5), 659-668.
20. Yan, W.-Q., Zhang, M., Huang, L.-L., Tang, J., Mujumdar, A.S., Sun, J.-C. (2010). Studies on different combined microwave drying of carrot pieces. *International Journal of Food Science and Technology*, 45(10), 2141-2148.
21. Jiang, H., Zhang, M., Mujumdar, A.S. (2010). Physico-chemical changes during different stages of MFD/FD banana chips. *Journal of Food Engineering*, 101(2), 140-145.
22. Wang, R., Zhang, M., & Mujumdar, A. S. (2010). Effects of vacuum and microwave freeze drying on microstructure and quality of potato slices. *Journal of Food Engineering*, In Press.
23. Wu, Z. H., Hu, Y. J., Lee, D. J., Mujumdar, A. S., & Li, Z. Y. (2010). Dewatering and drying in mineral processing industry: Potential for innovation. *Drying Technology*, 28(7), 834-842.
24. Hsu, J., Tao, T., Su, A., Mujumdar, A. S., & Lee, D. (2010). Model for sludge cake drying accounting for developing cracks. *Drying Technology*, 28(7), 922-926.
25. Hsu, J., Su, A., Mujumdar, A. S., & Lee, D. (2010). Unified analysis of dewatering and drying of sludge cake. *Drying Technology*, 28(7), 877-880.
26. Wang, R., Zhang, M., & Mujumdar, A. S. (2010). Effect of osmotic dehydration on microwave freeze-drying characteristics and quality of potato chips. *Drying Technology*, 28(6), 798-806.
27. Yan, W., Zhang, M., Huang, L. Tang, J., Mujumdar, A. S., & Sun, J. (2010). Study of the optimisation of puffing characteristics of potato cubes by spouted bed drying enhanced with microwave. *Journal of the Science of Food and Agriculture*, 90(8), 1300-1307.

28. Pang, S., & Mujumdar, A. S. (2010). Drying of woody biomass for bioenergy: Drying technologies and optimization for an integrated bioenergy plant. *Drying Technology*, 28(5), 690-701.
29. Mujumdar, A. S., & Law, C. L. (2010). Drying technology: Trends and applications in postharvest processing. *Food and Bioprocess Technology*, Article in Press.
30. Wang, R., Zhang, M., & Mujumdar, A. S. (2010). Effect of food ingredient on microwave freeze drying of instant vegetable soup. *LWT - Food Science and Technology*,
31. Wu, G., Zhang, M., Mujumdar, A. S., & Wang, R. (2010). Effect of calcium ion and microwave power on structural and quality changes in drying of apple slices. *Drying Technology*, 28(4), 517-522.
32. Woo, M. W., & Mujumdar, A. S. (2010). Effects of electric and magnetic field on freezing and possible relevance in freeze drying. *Drying Technology*, 28(4), 433-443.
33. Woo, M. W., Daud, W. R. W., Mujumdar, A. S., Tasirin, S. M., & Talib, M. Z. M. (2010). Role of rheological characteristics in amorphous food particle-wall collisions in spray drying. *Powder Technology*, 198(2), 251-257.
34. Fernandes, F. A. N., Rodrigues, S., Law, C. L., & Mujumdar, A. S. (2010). Drying of exotic tropical fruits: A comprehensive review. *Food and Bioprocess Technology*, Article in Press.
35. Zhang, C. H., Huang, L. X., Wang, C. P., & Mujumdar, A. S. (2010). Experimental and numerical investigation of spray-drying parameters on the dried powder properties of ginkgo biloba seeds. *Drying Technology*, 28(3), 380-388.
36. Mujumdar, A. S., Huang, L. X., & Dong Chen, X. (2010). An overview of the recent advances in spray-drying. *Dairy Science and Technology*, 90(2-3), 211-224.
37. Duan, X., Zhang, M., Mujumdar, A. S., & Wang, S. (2010). Microwave freeze drying of sea cucumber (*stichopus japonicus*). *Journal of Food Engineering*, 96(4), 491-497.
38. Gong, Z. -, & Mujumdar, A. S. (2010). Simulation of drying nonaqueous systems-an application of simprosys software. *Drying Technology*, 28(1), 111-115.
39. Gong, Z., Gao, L., An, J., Zhang, M., Mujumdar, A. S., & Sun, J. (2010). Effects of predrying and vacuum impregnation with nano-calcium carbonate solution on strawberries, carrots, corn, and blueberries. *Drying Technology*, 28(1), 36-41.
40. Mujumdar, A. S., & Law, C. L. (2009). Drying technology: Trends and applications in postharvest processing. Paper presented at the 4-13.
41. Wang, R., Zhang, M., Mujumdar, A. S., & Sun, J. (2009). Microwave freeze-drying characteristics and sensory quality of instant vegetable soup. *Drying Technology*, 27(9), 962-968.
42. Song, X., Zhang, M., Mujumdar, A. S., & Fan, L. (2009). Drying characteristics and kinetics of vacuum microwave-dried potato slices. *Drying Technology*, 27(9), 969-974.

43. Huang, L., Zhang, M., Mujumdar, A. S., Sun, D., Tan, G., & Tang, S. (2009). Studies on decreasing energy consumption for a freeze-drying process of apple slices. *Drying Technology*, 27(9), 938-946.
44. Xu, P., Mujumdar, A. S., & Yu, B. (2009). Drying-induced cracks in thin film fabricated from colloidal dispersions. *Drying Technology*, 27(5), 636-652.
45. Piacentini, R., & Mujumdar, A. (2009). Climate change and drying of agricultural products. *Drying Technology*, 27(5), 629-635.
46. Huang, L., Zhang, M., Yan, W., Mujumdar, A. S., & Sun, D. (2009). Effect of coating on post-drying of freeze-dried strawberry pieces. *Journal of Food Engineering*, 92(1), 107-111.
47. Karthikeyan, M., Zhonghua, W., & Mujumdar, A. S. (2009). Low-rank coal drying technologies - current status and new developments. *Drying Technology*, 27(3), 403-415.
48. Xu, H. S., Zhang, M., Duan, X., Mujumdar, A., & Sun, J. (2009). Effect of power ultrasound pretreatment on edamame prior to freeze drying. *Drying Technology*, 27(2), 186-193.
49. Woo, M. W., Daud, W. R. W., Mujumdar, A. S., Wu, Z., Talib, M. Z. M., & Tasirin, S. M. (2009). Non-swirling steady and transient flow simulations in short-form spray dryers. *Chemical Product and Process Modeling*, 4(1)
50. Chin, S. K., Law, C. L., Supramaniam, C. V., Cheng, P. G., & Mujumdar, A. (2008). Convective drying of ganoderma tsugae murrill and effect of temperature on basidiospores. *Drying Technology*, 26(12), 1524-1533.
51. Rahman, S. M. A., & Mujumdar, A. S. (2008). A novel atmospheric freeze-drying system using a vortex tube and multimode heat supply. *International Journal of Postharvest Technology and Innovation*, 1(3), 249-266.
52. Huang, L. X., & Mujumdar, A. S. (2008). The effect of rotary disk atomizer RPM on particle size distribution in a semi-industrial spray dryer. *Drying Technology*, 26(11), 1319-1325.
53. Woo, M. W., Daud, W. R. W., Mujumdar, A. S., Wu, Z., Talib, M. Z. M., & Tasirin, S. M. (2008). CFD evaluation of droplet drying models in a spray dryer fitted with a rotary atomizer. *Drying Technology*, 26(10), 1180-1198.
54. Woo, M. W., Daud, W. R. W., Mujumdar, A. S., Talib, M. Z. M., Hua, W. Z., & Tasirin, S. M. (2008). Comparative study of droplet drying models for CFD modelling. *Chemical Engineering Research and Design*, 86(9), 1038-1048.
55. Białobrzewski, I., Zielińska, M., Mujumdar, A. S., & Markowski, M. (2008). Heat and mass transfer during drying of a bed of shrinking particles - simulation for carrot cubes dried in a spout-fluidized-bed drier. *International Journal of Heat and Mass Transfer*, 51(19-20), 4704-4716.
56. Chen, H., Huang, T., Tsai, C., & Mujumdar, A. (2008). Development and performance analysis of a new solar energy-assisted photocatalytic dryer. *Drying Technology*, 26(3), 503-507.



57. Rahman, S. M. A., & Mujumdar, A. S. (2008). A novel atmospheric freeze-drying system using a vibro-fluidized bed with adsorbent. *Drying Technology*, 26(3), 393-403.
58. Pawar, S. B., Kumar, P. S. R., Mujumdar, A. S., & Thorat, B. N. (2008). Infrared-convective drying of organic pigments. *Drying Technology*, 26(3), 315-322.
59. Jangam, S. V., Joshi, V. S., Mujumdar, A. S., & Thorat, B. N. (2008). Studies on dehydration of sapota (achras zapota). *Drying Technology*, 26(3), 369-377.
60. Duan, X., Zhang, M., Li, X., & Mujumdar, A. S. (2008). Microwave freeze drying of sea cucumber coated with nanoscale silver. *Drying Technology*, 26(3), 413-419.
61. Duan, X., Zhang, M., Li, X., & Mujumdar, A. (2008). Ultrasonically enhanced osmotic pretreatment of sea cucumber prior to microwave freeze drying. *Drying Technology*, 26(3), 420-426.
62. Wu, D., Peng, X., Su, A., Mujumdar, A., Hsu, C., & Lee, D. (2008). Heat and mass transfer in unsaturated porous cake with heated walls. *Drying Technology*, 26(8), 1079-1085.
63. Patel, A. K., Waje, S. S., Thorat, B. N., & Mujumdar, A. S. (2008). Tomographic diagnosis of gas maldistribution in gas-solid fluidized beds. *Powder Technology*, 185(3), 239-250.
64. Rahman, S. M. A., & Mujumdar, A. S. (2008). A novel atmospheric freeze-dryer using vortex tube and multimode heat input: Simulation and experiments. *Asia-Pacific Journal of Chemical Engineering*, 3(4), 408-416.
65. Gong, Z., & Mujumdar, A. S. (2008). Software for design and analysis of drying systems. *Drying Technology*, 26(7), 884-894.
66. Huang, L., Zhang, M., Mujumdar, A., Zhang, C., Lu, D., & Sun, J. (2008). Studies on controlling surface accumulation of glucose on dehydrated cabbage. *Drying Technology*, 26(7), 931-935.
67. Xu, P., Mujumdar, A. S., & Yu, B. (2008). Fractal theory on drying: A review. *Drying Technology*, 26(6), 640-650.
68. Tao, T., Peng, X., Su, A., Lee, D., & Mujumdar, A. S. (2008). Modeling convective drying of wet cake. *Journal of the Chinese Institute of Chemical Engineers*, 39(3), 287-290.
69. Chung, L. L., Waje, S. S., Thorat, B. N., & Mujumdar, A. S. (2008). Advances and recent developments in thermal drying for bio-origin and agricultural products. *Stewart Postharvest Review*, 4(1)
70. Mujumdar, A., & Zhonghua, W. (2008). Thermal drying technologies - cost-effective innovation aided by mathematical modeling approach. *Drying Technology*, 26(1), 146-154.
71. Gong, Z., Zhang, M., Mujumdar, A., & Sun, J. (2008). Spray drying and agglomeration of instant bayberry powder. *Drying Technology*, 26(1), 116-121.
72. Duan, X., Zhang, M., & Mujumdar, A. S. (2007). Study on a combination drying technique of sea cucumber. *Drying Technology*, 25(12), 2011-2019.

73. Gong, Z., & Mujumdar, A. S. (2007). Review of R&D in drying of refractories. *Drying Technology*, 25(12), 1917-1925.
74. Song, X., Zhang, M., & Mujumdar, A. S. (2007). Effect of vacuum-microwave predrying on quality of vacuum-fried potato chips. *Drying Technology*, 25(12), 2021-2026.
75. Song, X., Zhang, M., & Mujumdar, A. S. (2007). Optimization of vacuum microwave predrying and vacuum frying conditions to produce fried potato chips. *Drying Technology*, 25(12), 2027-2034.
76. Duan, X., Zhang, M., & Mujumdar, A. S. (2007). Studies on the microwave freeze drying technique and sterilization characteristics of cabbage. *Drying Technology*, 25(10), 1725-1731.
77. Rahman, S. M. A., Islam, M. R., & Mujumdar, A. S. (2007). A study of coupled heat and mass transfer in composite food products during convective drying. *Drying Technology*, 25(7-8), 1359-1368.
78. Suvarnakuta, P., Devahastin, S., & Mujumdar, A. S. (2007). A mathematical model for low-pressure superheated steam drying of a biomaterial. *Chemical Engineering and Processing: Process Intensification*, 46(7), 675-683.
79. Islam, M. R., Thaker, K. S., & Mujumdar, A. S. (2007). A diffusion model for a drum dryer subjected to conduction, convection, and radiant heat input. *Drying Technology*, 25(6), 1033-1043.
80. Konstantopoulos, D. K., Maroulis, V. Z., Karoglou, M., Moropoulou, A., & Mujumdar, A. S. (2007). Hygroscope: A moisture transfer simulator for buildings. *Drying Technology*, 25(6), 1119-1125.
81. Huang, L., & Mujumdar, A. S. (2007). Simulation of an industrial spray dryer and prediction of off-design performance. *Drying Technology*, 25(4), 703-714.
82. Wang, W., Chen, G., & Mujumdar, A. S. (2007). Physical interpretation of solids drying: An overview on mathematical modeling research. *Drying Technology*, 25(4), 659-668.
83. Waje, S. S., Thorat, B. N., & Mujumdar, A. S. (2007). Hydrodynamic characteristics of a pilot-scale screw conveyor dryer. *Drying Technology*, 25(4), 609-616.
84. Mujumdar, A. S., & Huang, L. X. (2007). Global R&D needs in drying. *Drying Technology*, 25(4), 647-658.
85. Hu, Q., Zhang, M., Mujumdar, A. S., Xiao, G., & Sun, J. (2007). Performance evaluation of vacuum microwave drying of edamame in deep-bed drying. *Drying Technology*, 25(4), 731-736.
86. Xian, H., Liu, D., Shang, F., Yang, Y., Du, X., Mujumdar, A. S. (2007). Study on heat transfer enhancement of oscillating-flow heat pipe for drying. *Drying Technology*, 25(4), 723-729.
87. Yang, G. Y., Shi, Y. C., Liu, X. D., & Mujumdar, A. S. (2007). TG-DTG analysis of chemically bound moisture removal of  $AlF_3 \cdot 3H_2O$ . *Drying Technology*, 25(4), 675-680.

88. Qgura, H., Yasuda, S., Otsubo, A., & Mujumdar, A. S. (2007). Continuous operation of a chemical heat pump. *Asia-Pacific Journal of Chemical Engineering*, 2(2), 118-123.
89. Waje, S. S., Patel, A. K., Thorat, B. N., & Mujumdar, A. S. (2007). Study of residence time distribution in a pilot-scale screw conveyor dryer. *Drying Technology*, 25(1), 249-259.
90. Zhonghua, W., & Mujumdar, A. S. (2007). Simulation of the hydrodynamics and drying in a spouted bed dryer. *Drying Technology*, 25(1), 59-74.
91. Waje, S. S., Thorat, B. N., & Mujumdar, A. S. (2007). Screw conveyor dryer: Process and equipment design. *Drying Technology*, 25(1), 241-247.
92. Mujumdar, A. S. (2007). An overview of innovation in industrial drying: Current status and R&D needs. *Transport in Porous Media*, 66(1-2), 3-18.
93. Huang, L. X., & Mujumdar, A. S. (2007). A computational fluid dynamic study of a low-humidity co-current spray dryer. *Asia-Pacific Journal of Chemical Engineering*, 2(1), 12-19.
94. Basu, S., Shivhare, U. S., & Mujumdar, A. S. (2006). Erratum: Models for sorption isotherms for foods: A review (drying technology (2006) vol. 24 (917-930)). *Drying Technology*, 24(12), 1705.
95. Hu, Q., Zhang, M., Mujumdar, A. S., Xiao, G., & Jin-cai, S. (2006). Drying of edamames by hot air and vacuum microwave combination. *Journal of Food Engineering*, 77(4), 977-982.
96. Zhonghua, W., & Mujumdar, A. S. (2006). R&D needs and opportunities in pulse combustion and pulse combustion drying. *Drying Technology*, 24(11), 1521-1523.
97. Fan, L., Zhang, M., & Mujumdar, A. S. (2006). Effect of various pretreatments on the quality of vacuum-fried carrot chips. *Drying Technology*, 24(11), 1481-1486.
98. Zhang, M., Tang, J., Mujumdar, A. S., & Wang, S. (2006). Trends in microwave-related drying of fruits and vegetables. *Trends in Food Science and Technology*, 17(10), 524-534.
99. Lee, D. J., Lai, J. Y., & Mujumdar, A. S. (2006). Moisture distribution and dewatering efficiency for wet materials. *Drying Technology*, 24(10), 1201-1208.
100. Qing-guo, H., Min, Z., Mujumdar, A., Wei-hua, D., & Jin-cai, S. (2006). Effects of different drying methods on the quality changes of granular edamame. *Drying Technology*, 24(8), 1025-1032.
101. Xu, Y., Zhang, M., Mujumdar, A., Duan, X., & Jin-cai, S. (2006). A two-stage vacuum freeze and convective air drying method for strawberries. *Drying Technology*, 24(8), 1019-1023.
102. Basu, S., Shivhare, U. S., & Mujumdar, A. S. (2006). Models for sorption isotherms for foods: A review. *Drying Technology*, 24(8), 917-930.
103. Huang, L., & Mujumdar, A. S. (2006). Numerical study of two-stage horizontal spray dryers using computational fluid dynamics. *Drying Technology*, 24(6), 727-733.

104. Wu, Z., & Mujumdar, A. S. (2006). A parametric study of spray drying of a solution in a pulsating high-temperature turbulent flow. *Drying Technology*, 24(6), 751-761.
105. Huang, L. X., Kumar, K., & Mujumdar, A. S. (2006). A comparative study of a spray dryer with rotary disc atomizer and pressure nozzle using computational fluid dynamic simulations. *Chemical Engineering and Processing: Process Intensification*, 45(6), 461-470.
106. Birchal, V. S., Huang, L., Mujumdar, A. S., & Passos, M. L. (2006). Spray dryers: Modeling and simulation. *Drying Technology*, 24(3), 359-371.
107. Waje, S. S., Thorat, B. N., & Mujumdar, A. S. (2006). An experimental study of the thermal performance of a screw conveyor dryer. *Drying Technology*, 24(3), 293-301.
108. Wanjari, A. N., Thorat, B. N., Baker, C. G. J., & Mujumdar, A. S. (2006). Design and modeling of plug flow fluid bed dryers. *Drying Technology*, 24(2), 147-157.
109. Devahastin, S., Suvarnakuta, P., & Mujumdar, A. S. (2006). *Recent advances in drying technologies for carrot and sweetpotato*
110. Lou, Z. Q., Mujumdar, A. S., & Yap, C. (2005). Effects of geometric parameters on confined impinging jet heat transfer. *Applied Thermal Engineering*, 25(17-18), 2687-2697.
111. Huang, L. X., Passos, M. L., Kumar, K., & Mujumdar, A. S. (2005). A three-dimensional simulation of a spray dryer fitted with a rotary atomizer. *Drying Technology*, 23(9-11), 1859-1873.
112. Zhao, L., Li, J., Pan, Y., Chen, G., & Mujumdar, A. S. (2005). Thermal dehydration methods for fruits and vegetables. *Drying Technology*, 23(9-11), 2249-2260.
113. Suvarnakuta, P., Devahastin, S., & Mujumdar, A. S. (2005). Drying kinetics and  $\beta$ -carotene degradation in carrot undergoing different drying processes. *Journal of Food Science*, 70(8), S520-S526.
114. Sun, L., Islam, M. R., Ho, J. C., & Mujumdar, A. S. (2005). A diffusion model for drying of a heat sensitive solid under multiple heat input modes. *Bioresource Technology*, 96(14), 1551-1560.
115. Huang, L., & Mujumdar, A. S. (2005). Development of a new innovative conceptual design for horizontal spray dryer via mathematical modeling. *Drying Technology*, 23(6), 1169-1187.
116. Ogura, H., Yamamoto, T., Otsubo, Y., Ishida, H., Kage, H., & Mujumdar, A. S. (2005). A control strategy for a chemical heat pump dryer. *Drying Technology*, 23(6), 1189-1203.
117. Jumah, R., & Mujumdar, A. S. (2005). Modeling intermittent drying using an adaptive neuro-fuzzy inference system. *Drying Technology*, 23(5), 1075-1092.
118. Xu, Y., Zhang, M., Tu, D., Sun, J., Zhou, L., & Mujumdar, A. S. (2005). A two-stage convective air and vacuum freeze-drying technique for bamboo shoots. *International Journal of Food Science and Technology*, 40(6), 589-595.

119. Birchal, V. S., Passos, M. L., Wildhagen, G. R. S., & Mujumdar, A. S. (2005). Effect of spray-dryer operating variables on the whole milk powder quality. *Drying Technology*, 23(3), 611-636.
120. Chen, X. D. (2005). A discussion on a generalized correlation for drying rate modeling. *Drying Technology*, 23(3), 415-426.
121. Fan, L., Zhang, M., & Mujumdar, A. S. (2005). Vacuum frying of carrot chips. *Drying Technology*, 23(3), 645-656.
122. Wang, B., Zhang, W., Zhang, W., Mujumdar, A. S., & Huang, L. (2005). Progress in drying technology for nanomaterials. *Drying Technology*, 23(1-2 SPEC. ISS.), 7-32.
123. Suvarnakuta, P., Devahastin, S., Soponronnarit, S., & Mujumdar, A. S. (2005). Drying kinetics and inversion temperature in a low-pressure superheated steam-drying system. *Industrial and Engineering Chemistry Research*, 44(6), 1934-1941.
124. Wang, S. J., & Mujumdar, A. S. (2005). A comparative study of five low Reynolds number  $k-\epsilon$  models for impingement heat transfer. *Applied Thermal Engineering*, 25(1), 31-44.







# Drying of Foods, Vegetables and Fruits (FVF)

## *Volume 2*

Drying is a highly energy-intensive unit operation and is of great importance in almost all industrial sectors. Drying is an essential step in food preservation to improve shelf life by reducing potential of microbial attack. There has been remarkable development in the innovative drying techniques for food products. However, related archival literature remains largely inaccessible in the developing countries. This e-book is an exploratory preliminary effort to make relevant knowledge on drying and related processing of various food products to make it freely available for readers all over the world. This book is also useful for self-study by engineers and scientists trained in any discipline and so as for the readers who have some technical background. It should also be helpful to industrial users of dryers, dryer manufacturers as well as entrepreneurs. This volume will be followed by additional e-books which can also be freely downloaded globally

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