Processing and Drying of Tropical Fruits

Editors
Law, C.L., Hii, C.L., Jangam, S.V., Mujumdar, A.S.
Processing and Drying of Tropical Fruits
Preface

Tropical fruits are abundant source of nutrients and bio-active compounds that provide numerous health benefits and have been proven in many scientific studies. In today’s fast moving society and ever changing food habit of consumers have led to the development of natural food products to fulfill not only the nutritional needs but also product specifications demanded by consumers. This e-book aims to present the latest research works carried out by researchers worldwide for drying and preservation of tropical fruits ranging from the very common (e.g. mango, pineapple) to the more exotic selections (e.g. ciku, durian, dragon fruit). By converting fresh tropical fruits into dried products via advanced drying/dehydration techniques, this helps to provide an alternative choice of healthy fruit snacks especially to consumers residing outside tropical climate regions.

This e-book and also several others can be freely downloaded from Prof. Mujumdar’s website (http://www.arunmujumdar.com/e-books.htm) for topics ranging from drying & dehydration, mathematical modelling to advanced food processing. To date, 19 e-books have been published by contributing authors from academia and industry. The readers are therefore encouraged to share the reading materials from this website to academics, students, industrial practitioners and libraries at no cost. On behalf of the editorial board, we would like to extend our appreciation to the contributing authors for their time and effort in preparing the respective e-book chapters.

Chung Lim Law, University of Nottingham, Malaysia Campus  
Chung-Lim.Law@nottingham.edu.my

Ching Lik Hii, University of Nottingham, Malaysia Campus  
Ching-Lik.Hii@nottingham.edu.my

Sachin Vinayak Jangam, NUS, Singapore  
sachinjangam1@gmail.com

Arun S. Mujumdar, McGill University, Canada  
arunmujumdar123@gmail.com
## Contributors

### List of Contributors

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Contact Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noranizan Mohd Adzahan</td>
<td>Faculty of Food Science and Technology, Universiti Putra Malaysia</td>
<td>Tel: +60389468392, Email: <a href="mailto:noraadzahan@upm.edu.my">noraadzahan@upm.edu.my</a></td>
</tr>
<tr>
<td>Shitapan Bai-Ngew</td>
<td>PD-FIP, Department of Product Development, Faculty of Agro-Industry, Kasetsart University, Bangkok</td>
<td>Tel: +66 562-5010, E-mail: <a href="mailto:swittra@yahoo.com">swittra@yahoo.com</a></td>
</tr>
<tr>
<td>Chaleeda Borompichaichartkul</td>
<td>Department of Food Technology, Faculty of Science, Chulalongkorn University, Bangkok, 10330, Thailand</td>
<td>Tel: +662-218-5518, Email: <a href="mailto:Chaleeda.b@chula.ac.th">Chaleeda.b@chula.ac.th</a></td>
</tr>
<tr>
<td>Javier Mauricio Castellanos-Olarte</td>
<td>Facultad de Ingeniería Mecánica, Universidad Pontificia Bolivarariana Seccional Bucaramanga</td>
<td>Tel: +57 7 679 6220, E-mail: <a href="mailto:javier.castellanos@upb.edu.co">javier.castellanos@upb.edu.co</a></td>
</tr>
<tr>
<td>Eric Wei Chiang Chan</td>
<td>Faculty of Applied Sciences, UCSI University, No. 1, Jalan Menara Gading, UCSI Heights, 56000 Cheras</td>
<td>Tel: +603-91018880, E-mail: <a href="mailto:ChanWC@UCSIUniversity.edu.my">ChanWC@UCSIUniversity.edu.my</a></td>
</tr>
<tr>
<td>Siew Lian Chia</td>
<td>Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM</td>
<td>Tel: +6038946 6000, Email: <a href="mailto:cslian89@gmail.com">cslian89@gmail.com</a></td>
</tr>
<tr>
<td>Chien Hwa Chong</td>
<td>School of Engineering, Taylor’s University, Malaysia</td>
<td>Tel: +60169320389, Email: <a href="mailto:ChienHwa.Chong@taylors.edu.my">ChienHwa.Chong@taylors.edu.my</a></td>
</tr>
<tr>
<td>Gun Hean Chong</td>
<td>Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM</td>
<td>Tel: +60389468414, Email: <a href="mailto:gunhean@upm.edu.my">gunhean@upm.edu.my</a></td>
</tr>
<tr>
<td>Carlos Julio Cortés-Rodriguez</td>
<td>Facultad de Ingeniería, Departamento de Ingeniería Mecánica y Mecatrónica, Universidad Nacional de Colombia- Sede Bogotá</td>
<td>Tel: (57-1) 316 5000 Ext. 11211, Email: <a href="mailto:cjortesr@unal.edu.co">cjortesr@unal.edu.co</a></td>
</tr>
<tr>
<td>Name</td>
<td>Affiliation</td>
<td>Contact Information</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------------------------------------------------</td>
<td>---------------------------------------------------</td>
</tr>
<tr>
<td>Sandra Patricia Cuervo-Andrade</td>
<td>Facultad de Ingeniería Mecánica, Grupo de Investigación en Desarrollo Tecnológico, Mecatrónica y Agroindustria (GIDETECHMA), Universidad Pontificia Bolivarariana Seccional Bucaramanga Autopista Piedecuesta Kilometro 7 Campus UPB, 681007 Bucaramanga, Colombia</td>
<td>Tel: +57 7 679 6220, E-mail: <a href="mailto:javier.castellanos@upb.edu.co">javier.castellanos@upb.edu.co</a></td>
</tr>
<tr>
<td>Adam Figiel</td>
<td>Faculty of Life Sciences and Technology, Wrocław University of Environmental and Life Sciences, Poland</td>
<td>Tel: +48 71 320 57 30, Email: <a href="mailto:adam.figiel@up.wroc.pl">adam.figiel@up.wroc.pl</a></td>
</tr>
<tr>
<td>Rarisara Impaprasert</td>
<td>Department of Microbiology, Faculty of Science, King Mongkut's University of Technology Thonburi, 126 Pracha-Uthis Rd., Thung-Khrri, Bangkok 10140, Thailand</td>
<td>Tel: +662-470-8915, Email: <a href="mailto:rarisara.imp@mail.kmutt.ac.th">rarisara.imp@mail.kmutt.ac.th</a></td>
</tr>
<tr>
<td>Chung Lim Law</td>
<td>Faculty of Engineering, The University of Nottingham, Malaysia Campus</td>
<td>Tel: +60389248169, Email: <a href="mailto:chung-lim.law@nottingham.edu.my">chung-lim.law@nottingham.edu.my</a></td>
</tr>
<tr>
<td>Sin Yee Lee</td>
<td>Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 UPM, Serdang Selangor, Malaysia</td>
<td>Tel: +603-8946 6000, Email: <a href="mailto:charmainedee912@hotmail.com">charmainedee912@hotmail.com</a></td>
</tr>
<tr>
<td>Diana Cristina Sinuco León</td>
<td>Facultad de Ciencias, Departamento de Química, Grupo de Investigación Bioprocesamiento de Compuestos Volátiles, Universidad Nacional de Colombia-Sede Bogotá Ciudad Universitaria, 111321 Bogotá, Colombia</td>
<td>Tel: 57-1-3165000 ext 14443, Email:<a href="mailto:dcsinuco@unal.edu.co">dcsinuco@unal.edu.co</a></td>
</tr>
<tr>
<td>Prabhat K Nema</td>
<td>Department of Food Engineering, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonepat – 131028, Haryana, India</td>
<td>Tel: +91-1302281100, Email: <a href="mailto:pknema2015@gmail.com">pknema2015@gmail.com</a></td>
</tr>
<tr>
<td>Rachna Sehrawat</td>
<td>Department of Food Engineering, National Institute of Food Technology Entrepreneurship and Management, Kundli, Sonepat – 131028, Haryana, India</td>
<td>Tel: +918222827173, Email: <a href="mailto:sehrawatrachna@gmail.com">sehrawatrachna@gmail.com</a></td>
</tr>
<tr>
<td>Choon Hui Tan</td>
<td>Faculty of Applied Sciences, UCSI University, No. 1, Jalan Menara Gading, UCSI Heights, 56000 Cheras, Kuala Lumpur, Malaysia</td>
<td>Tel: +603-91018880, E-mail: <a href="mailto:tanch@ucsiuniversity.edu.my">tanch@ucsiuniversity.edu.my</a></td>
</tr>
<tr>
<td>Name</td>
<td>Department</td>
<td>University</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Nantawan Therdthai</td>
<td>PD-FIP, Department of Product Development</td>
<td>Kasetsart University, Bangkok</td>
</tr>
<tr>
<td>Aneta Wojdylo</td>
<td>Department of Fruit and Vegetable Processing</td>
<td>Wroclaw University of Environmental and Life Sciences</td>
</tr>
<tr>
<td>Chen Wai Wong</td>
<td>Faculty of Applied Sciences</td>
<td>UCSI University</td>
</tr>
</tbody>
</table>
# Table of Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title/Authors</th>
<th>Page</th>
</tr>
</thead>
</table>
| 1       | The Effects of Drying Methods on the Antioxidant and Other Bioactive Properties of Fruits  
         *E.W.C. Chan, C.H. Tan and C.W. Wong* | 1    |
| 2       | Drying methods as means of increasing the availability of tropical fruits  
         *C. W. Wong, C. H. Tan and E. W. C. Chan* | 25   |
| 3       | Alternative approaches in drying to improve nutritional and textural property of mango and jackfruit based snacks.  
         *C. Borompichaichartkul and R. Impaprasert* | 39   |
| 4       | Drying of Durian Flour and Product Quality  
         *N. Therdthai and S. Bai-Ngew* | 59   |
| 5       | Drying and Dehydration of Pitaya Fruits (*Hylocereus* spp.)  
         *S. Y. Lee, S. L. Chia, Noranizan, M. and G. H. Chong* | 75   |
| 6       | Drying of Ciku (*Manilkara zapota*) Using Advanced Hybrid Dryers  
         *C. H. Chong, A. Figiel, A. Wojdyla and C.L. Law* | 103  |
| 7       | Drying of Mango Products  
         *R. Sehrawat and P. K. Nema* | 123  |
Chapter 1

The Effects of Drying Methods on the Antioxidant and Other Bioactive Properties of Fruits

E.W.C. Chan, C.H. Tan and C.W. Wong

Contents

1.1 Introduction 3
1.2 Phytochemicals and Bioactivities 4
1.3 Effects of Thermal Drying 10
1.4 Effects of Low-Temperature Drying 12
1.5 Effects of Drying Through Sublimation 12
1.6 Future Studies 14
1.7 Conclusion 15
References 16
1.1 INTRODUCTION

Fruits are an important dietary component for promoting good health. Studies have shown that a daily intake of 3 to 5 servings of fruits can prevent non-communicable or chronic diseases such as cardiovascular and respiratory diseases, cancer and diabetes, that are not passed from person to person (He et al. 2007; Lichtenstein et al. 2006; Slavin and Lloyd 2012).

Traditionally, fruits are highly recommended in dietary guides because of their high vitamin content, especially vitamin A and vitamin C. Indeed, much of the early research on the antioxidant properties of fruits was focused on vitamins. However, since 1990s, attention has shifted to other phytochemicals, most notably, the flavonoids, phenolic acids and other phenolic compounds (Miller and Rice-Evans 1997). These phenolic compounds have shown to be a greater contributor of antioxidants in fruits compared to vitamins.

A study of 10,000 men and women conducted over a 20-year period in Finland showed that the decreased risk of lung cancer was attributed to the intake of flavonoids and not vitamins (Knekt et al. 1997). Overall, fruits possess significantly higher quantity of phenolic compounds than vegetables (Vinson et al. 2001). Dried fruits with more nutrient density and fibre content, and longer shelf life, have significantly higher content of phenolic antioxidants compared to fresh fruits (Vinson et al. 2005). Total phenols in dried apricots, grapes and plums are 1.5, 2.8 and 3.5 times higher than the corresponding fresh fruits, respectively. The quality of antioxidants in the dried product is comparable to that in fresh fruits.

Fresh fruits are seasonally available and drying enables them to be sold all year round (Chang et al. 2016). Dried fruits are concentrated forms of fresh fruits, retaining much of their nutritional value. Early research on dried fruits has focused on their physiochemical properties, sensory characteristics and storage stability. By the turn of the century, the antioxidant properties of fruits started gaining attention but most studies then were confined to fresh fruits with comparisons made between tropical and temperate fruits (Leong and Shui 2002; Lim et al. 2007). Among 38 types of fresh fruits commonly consumed in Singapore, tropical fruits of *Manilkara zapota* (or known as ciku in Malaysia/Singapore) had the highest ORAC and TPC while *Psidium guajava* (guava) had the highest AA per gram fresh weight (Isabelle et al. 2010).

Recently, the phytochemistry and bioactivities of dried fruit products are receiving greater interest. It is becoming increasingly apparent that drying methods can alter the phytochemical composition and bioactive properties of fruits, even in mild drying techniques such as freeze-drying. This has been observed in several well-known fruits, vegetables and herbs (Dewanto et al. 2002; Asami et al. 2003; Chan et al. 2009, 2014).

This chapter describes how the physical process of drying affects the phytochemicals and bioactivities in fruits. Sections include phytochemicals
and bioactivities of popular and lesser-utilised tropical fruits; the effects of thermal, low-temperature and non-thermal drying; and future studies.

1.2 PHYTOCHEMICALS AND BIOACTIVITIES

Fruits are often prescribed as sources of dietary vitamin C, vitamin E and β-carotene but these comprise only a small portion of the antioxidants (Miller and Rice-Evans 1997; Kalt et al. 1999). These antioxidants have been shown to prevent coronary heart disease and certain cancers but phenolic antioxidants may play a more significant role.

Recent studies have drawn attention to polyphenols, i.e. phytochemicals with more than one phenolic group, as being the major contributors to antioxidants in fruits (Chang et al. 2016). The total phenolic content of plants is a good indicator of primary antioxidant activity scavenging of free radicals but not indicative of secondary antioxidant activity i.e. preventing the generation of free radicals (Chan et al. 2010). As potent antioxidants, polyphenols are able to protect molecules such as vitamin C from degradation. Kalt et al. (1999) studied the stability of vitamin C in strawberries, raspberries and blueberries stored at 30°C for 8 days. Among the berries, only raspberries with the lowest phenolic content showed a significant decrease in vitamin C content.

Resveratrol (Figure 1.1) is a phytoalexin found in grapes (Vitis vinifera) and raisins, their dried counterpart (Mnari et al. 2016). The chemopreventive properties of resveratrol were first reported by Jang et al. (1997). Since then, the compound has garnered worldwide attention. The antioxidant properties of resveratrol have been shown to inhibit LDL oxidation, suppress platelet aggregation and reduce myocardial damage during ischemia-reperfusion (Bradamante et al. 2004).

![Image of grapes and raisins]

Figure 1.1: Resveratrol from grapes and raisins is a phytoalexin that protects against cardiovascular disease.
Other well-studied phytochemicals in fruits are flavonoids (flavonols, flavones, flavanones, flavanols, anthocyanins and isoflavones), and phenolic acids (hydroxycinnamic acids and hydroxybenzoic acids) (Chang et al. 2016). They are well-known antioxidants that possess bioactive properties. Flavonols such as quercetin and myricetin have been shown to induce apoptosis in A-549 and HepG2 cancer cell lines, respectively (Zhang et al. 2010; Zheng et al. 2012). Chlorogenic acid, a hydroxycinnamic acid derivative, maintains glucose homeostasis by modulating the expression of SGLT-1, GLUT-2 and PLG (Peng et al. 2015).

There is considerable research on the phytochemistry and bioactive properties of tropical fruits. The phytochemicals and bioactivities of selected popular and lesser-utilised tropical fruits are summarised in Table 1.1 and Table 1.2, respectively. Several of these fruits such as dates (Phoenix dactylifera), figs (Ficus carica) and asam gelugur (Garcinia atroviridis) are consumed primarily as dried fruits (Figure 1.2).

Table 1.1: Phytochemicals and bioactivities of selected popular tropical fruits.

<table>
<thead>
<tr>
<th>Tropical fruit</th>
<th>Phytochemical</th>
<th>Bioactivity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banana (Musa spp.)</td>
<td>Carotenoids, Biogenic amines, Flavonoids, Phenolic acids</td>
<td>Antioxidant, Treatment of Parkinson’s Wound healing</td>
<td>Pereira and Maraschin (2015), Truchado et al. (2015)</td>
</tr>
<tr>
<td>Ciku (Manilkara zapota)</td>
<td>Flavonoids, Phenolic acids</td>
<td>Antioxidant, Anti-tumour, Cytotoxic, Quorum-sensing inhibition</td>
<td>Ma et al. (2003), Srivastava et al. (2014), Truchado et al. (2015)</td>
</tr>
<tr>
<td>Durian (Durio zibethinus)</td>
<td>Flavonoids, Tannins</td>
<td>Antioxidant, Anti-proliferative, Hypolipidemic</td>
<td>Gorinstein et al. (2011), Haruenkit et al. (2010)</td>
</tr>
<tr>
<td>Guava (Psidium guajava)</td>
<td>Flavonoids, Terpenoids</td>
<td>Anti-inflammatory, Antioxidant</td>
<td>Flores et al. (2015), Gutierrez et al. (2008)</td>
</tr>
<tr>
<td>Jackfruit (Artocarpus heterophyllus)</td>
<td>Carotenoids, Fatty acids, Flavonoids</td>
<td>Antibacterial, Anti-inflammatory</td>
<td>Fang et al. (2008), Jagtap and Bapat (2010), Khan et al. (2003)</td>
</tr>
<tr>
<td>Tropical Fruit</td>
<td>Phytochemicals</td>
<td>Bioactivities</td>
<td>Reference</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------</td>
<td>--------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Mango (Mangifera indica)</td>
<td>Flavonoids, Phenolic acids, Tannins, Xanthones</td>
<td>Antioxidant, Chemopreventive, Hypolipidemic</td>
<td>Gorinstein et al. (2011), Lucas et al. (2011), Oliveira et al. (2016)</td>
</tr>
<tr>
<td>Mangosteen (Garcinia mangostana)</td>
<td>Flavonoids, Phenolic acids, Tannins, Xanthones</td>
<td>Antioxidant, Hypolipidemic</td>
<td>Gorinstein et al. (2011), Zadernowski et al. (2009)</td>
</tr>
<tr>
<td>Pomegranate (Punica granatum)</td>
<td>Fatty acids, Flavonoids, Tannins</td>
<td>Antioxidant, Anti-inflammatory, Cardioprotective, Anti- oncogenic</td>
<td>Goertz and Ahmad (2015), Tezcan et al. (2009)</td>
</tr>
<tr>
<td>Star fruit (Averrhoa carambola)</td>
<td>Carotenoids, Flavonoids, Tocopherols</td>
<td>Antioxidant, Food preservative, Hypoglycaemic</td>
<td>Thomas et al. (2016), Zainudin et al. (2014)</td>
</tr>
<tr>
<td>Asam gelugur (Garcinia atroviridis)</td>
<td>Flavonoids, Hydroquinones, Xanthones</td>
<td>Antioxidant, Anti-plasmodial, Cholinesterase inhibition, Hypolipidemic</td>
<td>Abdillah et al. (2015), Al- Mansoub et al. (2014), Tan et al. (2014)</td>
</tr>
<tr>
<td>Common fig (Ficus carica)</td>
<td>Anthocyanins, Flavonoids, Phenolic acids</td>
<td>Antioxidant, Antiplatelet, Antispasmodic</td>
<td>Chang et al. (2016), Gilani et al. (2008), Vallejo et al. (2012)</td>
</tr>
<tr>
<td>Kirala (Sonneratia caseolaris)</td>
<td>Flavonoids, Norflignans</td>
<td>Antioxidant, Cytotoxic</td>
<td>Wu et al. (2009), Rahmatullah et al.</td>
</tr>
</tbody>
</table>
Phenolic acids
Flavonoids
Iridoids
Lignans
Polysaccharides

Hypoglycaemic
Analgesic
Anti-inflammatory
Antioxidant
Cytotoxic
Hepatoprotective
Hypoglycaemic

Chan-Blanco et al. (2006)
Basar et al. (2010)
Nayak et al. (2010)
Raja and Sreenivasulu (2015)
Wang et al. (2008)

Noni
(Morinda citrifolia)

Flavonoids
Phenolic acids
Sterols

Antioxidant

Prasad et al. (2013)
Nan et al. (2008)

Nipa
(Nypa fruticans)

Flavonoids
Phenolic acids

Anti-diabetic

Liu et al. (2013)
Rahman et al. (2014)
Wu et al. (2014)
Zhang et al. (2013)

Beach pandan
(Pandanus tectorius)

Flavonoids
Phenolic acids

Anti-diarrheal
Antioxidant
Hypoglycaemic
Hypolipidemic

Gorinstein et al. (2011)
Haruenkit et al. (2007)

Snake fruit
(Salacca edulis)

Flavonoids
Tannins

Antioxidant
Hypolipidemic

Among the popular tropical fruits, freeze-dried Mangifera indica (mango) pulp has been reported to modulate body fat and plasma glucose and lipids in mice fed with high-fat diet (Lucas et al. 2011). Mango juice inhibits neoplastic transformation of BALB/3T3 cells and cell cycle of HL-60 cells (Percival et al. 2006). Methyl gallate, ellagic acid and mangiferin (Figure 1.3) are among the phytochemicals found in mango (Oliveira et al. 2016). Methyl gallate has been reported to inhibit quorum sensing in Chromobacterium violaceum (Tan et al. 2015). Ellagic acid has anti-inflammatory, gastroprotective and cardioprotective effects while mangiferin can protect human neurons, organs and prevent or delay the onset of diseases (Oliveira et al. 2016).
Figure 1.3: Molecular structures of methyl gallate (top left), gallic acid (top right) and mangiferin (bottom) found in mango.

Figure 1.4: Fruits of Artocarpus heterophyllus (left) and Punica granatum (right).

Phenolic antioxidants such as methyl 4-O-galloylchlorogenate and 4-O-galloylchlorogenic acid isolated from M. zapota (ciku) fruits can induce cytotoxicity in colon cancer cells (Ma et al. 2003). Earlier, shade-dried ciku has been reported to induce apoptosis in breast cancer cell lines and inhibits
tumour progression in mice (Srivastava et al. 2014). Other popular tropical fruits with promising medicinal properties are *Artocarpus heterophyllus* (nangka) and *Punica granatum* (pomegranate) (Figure 1.4). Prenylated flavones of artocarpesin, norartocarpin and oxyresveratrol isolated from nangka fruits exhibit potent anti-inflammatory activity (Fang et al. 2008). Fruits of pomegranate display antioxidant, anti-inflammatory, cardioprotective, anticancer and anti-diabetic properties (Goertz and Ahmad 2015).

Among the lesser-utilised tropical fruits, the fruit and juice of *Morinda citrifolia* (or known as noni) display a wide array of bioactivities which include analgesic, antimicrobial, anti-inflammatory, antioxidant, anti-tumour, cardiovascular, cytotoxic, hepatoprotective, hypoglycaemic and immunological properties (Chan-Blanco et al. 2006; Raja and Sreenivasulu 2015).

The fruit kernel of *Mangifera pajang* (brown mango) exhibits cytotoxicity, cell cycle arrest and apoptosis in MCF-7 and MDA-MB-231 breast cancer cell lines (Abu Bakar et al. 2010), and the fruit extract possesses cytoprotective properties against HepG2 hepatocellular cancer cell line (Abu Bakar et al. 2013). Geranyl flavonoid derivatives from the fruit of *Artocarpus altilis* (breadfruit) (Figure 1.5) possess anti-inflammatory properties (Lin et al. 2011) and are cytotoxic to human hepatocellular carcinoma cell line (Hsu et al. 2011).

*Figure 1.5:* Young fruits of *Artocarpus altilis* (left) and mature fruit of *Pandanus tectorius* (right).
Fruits of *Pandanus tectorius* (beach pandan) (Figure 1.5) have been reported to possess hypolipidemic and anti-diabetic properties. Rich in caffeoylquinic acid, the fruit extract inhibits lipid accumulation and reduces the intracellular content of total cholesterol and triglyceride in animal models and in HepG2 hepatoma cells (Liu et al. 2013; Zhang et al. 2013; Wu et al. 2015).

In the mangroves, the edible fruits of *Nypa fruticans* (nipa) and *Sonneratia caseolaris* (kirala) (Figure 1.6) are known for their antioxidants. The fruit and juice of kirala have also been reported to have moderate cytotoxic activity against C-6 rat glioma cell line (Wu et al. 2009) and anti-hyperglycaemic properties (Rahmatullah et al. 2012).

Because phytochemicals of fruits have potent bioactive properties, the effects of different drying methods are becoming increasingly important. For instance, the resveratrol content of raisins is an important quality parameter to ensure that the bioactive properties are retained after dehydration (Mnari et al. 2016).

When reviewing current literatures on drying, caution should be taken when interpreting the results. In some studies of bioactive properties of fruits dried using different methods, results of dried fruits in dry weight are compared with results of fresh fruits in fresh weight. Hence, reported data of dried fruits are often several times higher than those of fresh fruits. These data need to be re-examined by using fresh weight equivalent which can be calculated as $(100 – \text{percent moisture loss})/100 \times \text{value in dry weight}$.

### 1.3 EFFECTS OF THERMAL DRYING

Heat decreases the stability of phytochemicals but may not affect the overall bioactive properties of fruits. Phytochemicals are often found in a matrix and can be protected from thermal degradation (Biesaga 2011). Phytochemicals vary in stability depending on their substituent groups even when they are from the same group e.g. flavonoids. Antioxidants from fruits are widely studied for their ability to prevent chronic diseases and to protect phytochemicals from oxidation.
Flavonoids, one of the most ubiquitous antioxidants in fruits have been shown to have varying thermal stabilities. Factors such as glycosidic or methoxyl substitutions can increase their stability, while hydroxyl substitution can reduce their stability (Biesaga 2011). Likewise, the presence of transition metal ions such as copper and iron, which catalyse auto-oxidation, can have adverse effects on the antioxidant properties of flavonoids (Cao et al. 1997; Lim et al. 2005).

Earlier, Nicoli et al. (1999) noted that processing methods (including drying) have variable effects on total phenolic content and antioxidant properties of fruits and vegetables. The effects include little or no change, significant loss or enhancement in antioxidant properties. Food processing can improve the properties of naturally occurring antioxidants or induce the formation of new compounds with antioxidant properties, so that the overall antioxidant activities increase or remain unchanged (Tomaino et al. 2005).

Although the presence of hydroxyl groups decreases the thermal stability of flavonoids, these functional groups are also responsible for the radical scavenging and metal ion chelating properties of flavonoids (Croft 1999). Myricetin with a large number of hydroxyl groups has been reported to exhibit the highest thermal degradation is a potent antioxidant (Biesaga 2011; Cao et al. 1997). It has a 2,3 double bond in conjugation with a 4-keto function that allows electron delocalization between the A and B rings (Croft 1999). Delocalization stabilizes free radicals and prevents their propagation and thus myricetin could have a protective effect on other phytochemicals within the same matrix.

Heat may release additional phytochemicals and inactivate polyphenol oxidase (PPO) and most of the degradation that occurs in low temperature drying is catalysed by PPO (Devic et al. 2010). The enzyme is ubiquitous in many plants and its inactivation by heat is often an important criterion in preventing browning and loss of antioxidants. Coupled with the protective effects of endogenous antioxidants, heating and drying may actually increase the amount of phytochemicals in fruits.

Temperatures greater than 70°C have been shown to inactivate PPO where heat transfer plays an important role. Ng and Wong (2015) reported that the in vitro activity of PPO extracted from eggplant (Solanum melongena) dropped drastically at temperature beyond 70°C. Previous findings on PPO inactivation in vitro have also been reported in apples, avocados, grapes, pears and plums (Weemaes et al. 1998). However, within the fruit matrix, PPO inactivation is highly dependent on heat transfer. Bai et al. (2013) studied the inactivation of PPO in Fuji apples using high humidity air impingement blanching. High humidity increases the heat transfer properties of air but at 90°C, complete inactivation of PPO still requires 7 min and this would be much longer in conventional hot-air dryers.

Dewanto et al. (2002) reported increased phenolic content of tomatoes following heat treatment. This was one of the earliest studies that changed the thermal degradation paradigm of food processing and other similar findings
have since been reported. Krüger et al. (2015) analysed the anthocyanin content of fresh elderberries (*Sambucus nigra*) and those dried in the oven at 60°C using HPTLC. It was found that dried elderberry had higher anthocyanin content. They also tested the antioxidant capacity of compounds separated on the TLC plate using the DPPH radical scavenging assay and results revealed the release of new radical scavengers that were not present in the fresh berries.

### 1.4 EFFECTS OF LOW-TEMPERATURE DRYING

Low-temperature drying methods may release more phytochemicals if PPO is properly inactivated. Many studies use freeze drying or oven drying at 50°C to preserve fruits for further research (Das et al. 2014; Ikram et al. 2009). This is based on the assumption that these drying methods do not alter the phytochemical composition of fruits. While it is true that low temperatures prevent thermal degradation but phytochemicals may still be degraded by PPO (Devic et al. 2010).

Oven drying at low temperature can cause fruits to shrink which may also rupture cells and release additional phytochemicals. Nunes et al. (2016) reported that oven drying of guava at 55°C increased the amount of quercetin and naringenin extracted. Higher temperatures such as those applied with microwave would cause rapid expansion of moisture and directly disrupt the fruit tissue but this would unlikely to be the case at mild temperature of 55°C. Similarly, da Silva et al. (2013) reported that drying of pineapple at 46°C increased its phenolic and flavonoid content but its ascorbic acid content was reduced.

Sun drying entails long exposure to UV-radiation that may degrade phytochemicals. In the Portuguese pear (*Pyrus communis*), drying in the sun caused a 64% decrease in phenolic content (Ferreira et al. 2002). Most recently, Toontom et al. (2016) reported that sun drying destroyed flavour compounds in Thai chillies with oxidation products of 2-methylpropionic and 2-methylbutyric acid formed as a result of Strecker degradation.

### 1.5 EFFECTS OF DRYING THROUGH SUBLIMATION

Freeze drying has been shown to increase the phytochemical content and antioxidant capacity of some fruits. Freeze-dried tomatoes have higher flavonoid content (Chang et al. 2006) and stronger cupric ion reducing antioxidant capacity (Gümüşay et al. 2015) compared to those of fresh fruits. Similarly, highest amounts of total polyphenols, flavonoids and anthocyanins were detected in freeze-dried black chokeberry (*Aronia melanocarpa*) compared to sun-dried and oven-dried fruits (Thi and Hwang 2016).

A study on the effects of three drying methods on the bioactive properties of persimmon (*Diospyrus kaki*) was conducted by Karaman et al. (2014). The results showed that the total contents of phenolics, flavonoids, condensed tannins and hydrolysable tannins, and DPPH radical scavenging activity of freeze-dried, vacuum oven-dried and oven-dried fruits were significantly
higher than those of fresh fruits. Among the three drying methods, freeze drying yielded the highest values. The antidiabetic activity of freeze-dried persimmon was comparable to fresh fruits.

Freeze drying causes the release of additional phytochemicals because ice crystals formed within the plant matrix can rupture cell structure, which allows better exit of cellular components and better access of solvent (Chan et al. 2009). Freeze-dried samples may also be subjected to oxidation by PPO upon rehydration as the enzyme would not be permanently inactivated.

However, a study on the effects of freeze drying on antioxidant compounds and antioxidant activities of five tropical fruits, namely, star fruit, mango, papaya, muskmelon, and watermelon showed variable results (Shofian et al. 2011). Significant declines in total phenolic content were observed in all fruits except for muskmelon. There was no significant change in ascorbic acid and β-carotene concentration. DPPH radical scavenging remained unchanged, fresh starfruit and mango had relatively higher ferric reducing power, and freeze-dried papaya, muskmelon and watermelon displayed stronger linoleic acid peroxidation inhibition.

Supported by scientific evidence that dried fruits contain higher concentrations of antioxidants and nutrients, comparable to those of fresh fruits, in terms of quantity and quality (Vinson et al. 2005), the consumption of dried fruits is gaining popularity. Freeze-dried tropical fruits are now sold as health snacks in sealed packets in most major supermarkets (Figure 1.7). Freeze-dried jackfruit and mango show less shrinkage compared to dehydrated guava.
1.6 FUTURE STUDIES

Dried fruits retain much of their bioactive properties but there have been only few studies showing how the drying process affects bioactivity. In their recent review, Chang et al. (2016) described the phytochemistry and bioactivities of eight traditional dried fruits. Through the additive and synergistic combinations of essential nutrients and phytochemicals such as flavonoids, phenolic acids, phytoestrogens and carotenoids, they concluded that a regular intake of dried fruits can provide beneficial health effects, but this remains to be studied.

Given that phytochemicals and associated bioactive properties can be influenced by a variety of factors including PPO inactivation, thermal decomposition and the release of additional phytochemicals, it is not possible to predict which drying method would be ideal. There may be variations between species of fruits, and between different cultivars and varieties of a given species. Elderberries dried in the oven at 60°C have been reported to possess stronger DPPH radical scavenging ability (Krüger et al. 2015). The increased DPPH radical scavenging is associated with higher anthocyanin content and release of other phenolic compounds. However, out of the 10 varieties of elderberries studied, oven drying resulted in a 15% loss of anthocyanin in one of the varieties.

Most of the phytochemicals extracted with polar solvents have decent radical scavenging properties and this is a common trend not only in fruits but also in other plant parts (Chan et al. 2010). These phytochemicals may also have other bioactive properties. Some of the DPPH radical scavengers released in oven-dried elderberries have shown to be good acetylcholinesterase and tyrosinase inhibitors (Krüger et al. 2015).

Studies have compared the bioactive properties of fruits dried using different methods but not with those of fresh fruits. Wu (2015) reported that freeze-dried finger citron has higher antioxidant properties than vacuum- and hot air-dried fruits. Freeze-dried citrus fruits retained more of their phenolic compounds compared to sun-dried and hot air-dried fruits (Sun et al. 2015). Similarly, bitter gourd fruits dried with thermal oven drying and microwave drying had lower phenolic content and antioxidant activity than those dried with non-thermal freeze drying (Tan et al. 2013). However, none of these studies compared the phenolic contents and antioxidant activities with those
of the undried fruits. Therefore, it is impossible to tell if freeze drying merely retain or increase the phytochemical content.

It should be noted that fruits are rich in ascorbic acid and sugars, when measuring the total phenolic content of fresh and dried fruits, these substances can interfere with the results of the Folin-Ciocalteu (FC) assay. They contribute to the formation of the blue molybdenum-tungsten complex of the FC reagent resulting in an inaccurate estimation of the total phenolic content. The use of the new Fast Blue BB method which does not react with interfering substances (Lester et al. 2012) is definitely worth testing to determine the phenolic contents of fruits.

Recently, there is a growing interest in the effects of pre-treatment of fruits prior to drying. Osmotic pre-treatment, which is widely used to remove part of the water content of fruits, has been shown to reduce the duration of thermal drying and improve the sensory and functional properties of papaya and pineapples (Lombard at al. 2008; Germer et al. 2014). Abrasive pre-treatment was used by Adiletta et al. (2015) to remove the wax layer so as to reduce the drying time of Goji berries. The shortened drying time resulted in dried Goji berries with improved antioxidant properties. Microwave pre-treatment has been shown to inactive polyphenol oxidase and reduce the loss of antioxidants during oven drying at 50°C (Chan et al. 2012). This has been demonstrated in several culinary herbs but its applicability to fruits remains to be tested.

1.7 CONCLUSION

It is only in recent years that there are more studies showing how drying processes change the phytochemistry and bioactive properties of fruits. Depending on the drying technique used, the phytochemical content and consequently the bioactive properties can increase, decrease or remain unchanged. The effects of the same drying methods do vary from fruit to fruit, and between cultivars and varieties of a given species. There is much to be studied and the prospects for new and innovative research findings are promising.

ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>ascorbic acid</td>
</tr>
<tr>
<td>DPPH</td>
<td>2,2-diphenyl-1-picrylhydrazyl</td>
</tr>
<tr>
<td>GLUT</td>
<td>glucose transporter</td>
</tr>
<tr>
<td>HPTLC</td>
<td>high performance thin layer chromatography</td>
</tr>
<tr>
<td>LDL</td>
<td>low-density lipoprotein</td>
</tr>
<tr>
<td>ORAC</td>
<td>oxygen radical absorbance capacity</td>
</tr>
<tr>
<td>PLG</td>
<td>plasminogen</td>
</tr>
<tr>
<td>PPO</td>
<td>polyphenol oxidase</td>
</tr>
<tr>
<td>SGLT</td>
<td>sodium/glucose transporter</td>
</tr>
<tr>
<td>TLC</td>
<td>thin layer chromatography</td>
</tr>
<tr>
<td>TPC</td>
<td>total phenolic content</td>
</tr>
<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
</tbody>
</table>
REFERENCES


Abu Bakar, M.F.; Mohamed, M.; Rahmat, A.; Fry, J.R. Phytochemicals and antioxidant activity of different parts of bambangan (Mangifera pajang) and tarap (Artocarpus odoratissimus). Food Chemistry 2009, 113(2), 479-483.

Abu Bakar, M.F.; Mohamed, M.; Rahmat, A.; Burr, S.A.; Fry, J.R. Cytotoxicity, cell cycle arrest, and apoptosis in breast cancer cell lines exposed to an extract of the seed kernel of Mangifera pajang (bambangan). Food and Chemical Toxicology 2010, 48, 1688-1697.


Ferreira, D., Guyot, S., Marnet, N., Delgadillo, I., Renard, C.M., Coimbra, M.A. Composition of phenolic compounds in a Portuguese pear (Pyrus communis L.) and changes after sun-drying. Journal of Agricultural and Food Chemistry 2002, 50(16), 4537-4544.


Goertz, A.; Ahmad, K.A. Biological activity of phytochemical compounds in pomegranate – A review. EC Nutrition 2015, 1, 115-127.


Miller, N.J.; Rice-Evans, C.A. The relative contributions of ascorbic acid and phenolic antioxidants to the total antioxidant activity of orange and apple fruit juices and blackcurrant drink. Food Chemistry 1997, 60(3), 331-337.


Ng, A.W.R.; Wong, C.W. Partial purification and characterization of polyphenol oxidase from round brinjal (*S. melongena* var. *depressum*). International Food Research Journal 2015, 22(2), 826-831.


Peng, B.J.; Zhu, Q.; Zhong, Y.L.; Xu, S.H.; Wang, Z. Chlorogenic acid maintains glucose homeostasis through modulating the expression of SGLT-1, GLUT-2, and PLG in different intestinal segments of Sprague-Dawley rats.
fed a high-fat diet. Biomedical and Environmental Sciences 2015, 28(12), 894-903.


Sun, Y.; Shen, Y.; Liu, D.; Ye, X. Effects of drying methods on phytochemical compounds and antioxidant activity of physiologically dropped un-matured citrus fruits. LWT – Food Science and Technology 2015, 60(2), 1269-1275.

Tan, E.S.; Abdullah, A.; Maskat, M.Y. Effect of drying methods on total antioxidant capacity of bitter gourd (Momordica charantia) fruit. AIP Conference Proceedings of Universiti Kebangsaan Malaysia, Faculty of Science and Technology Postgraduate Colloquium 2013, 710-716.


Truchado, P.; Larrosa, M.; Castro-Ibáñez, I.; Allende, A. Plant food extracts and phytochemicals: their role as quorum sensing inhibitors. Trends in Food Science & Technology 2015, 43(2), 189-204.


Weemaes, C.A.; Ludikhuyze, L.R.; Van den Broeck, I.; Hendrickx, M.E.; Tobbback, P.P. Activity, electrophoretic characteristics and heat inactivation of polyphenol oxidases from apples, avocados, grapes, pears and plums. LWT – Food Science and Technology 1998, 31(1), 44-49.

Wu, C.; Zhang, X.; Zhang, X.; Luan, H.; Sun, G.; Sun, X.; Wang, X.; Guo, P.; Xu, X. The caffeoylquinic acid-rich *Pandanus tectorius* fruit extract increases

Wu, S.B.; Wen, Y.; Li, X.W.; Zhao, Y.; Zhao, Z.; Hu, J.F. Chemical constituents from the fruits of *Sonneratia caseolaris* and *Sonneratia ovata* (Sonneratiaceae). Biochemical Systematics and Ecology 2009, 37, 1-5.


Chapter 2

Drying methods as means of increasing the availability of tropical fruits


Contents

2.1 Introduction 27
2.2 Microwave vacuum drying 28
2.3 Microwave and convective multi-flash drying 29
2.4 Spray drying 30
2.5 Freeze drying 30
2.6 Solar drying 31
2.7 Conclusion 34
References 34
2.1 INTRODUCTION

Tropical fruits are widely cultivated in developing countries as a source of nutrients and revenue. In 2013, the export value (in current USD) of "fruits, preserved, and fruit preparations (excluding fruit juices)" increased by 6.3 percent (compared to 10.4 percent average growth rate from 2009-2013) to reach USD 20.8 billion, while imports increased by 6.4 percent to reach USD 20.2 billion (UN, 2013). According to the Food and Agriculture Organization of the United Nations (FAO), major tropical fruits include mango, pineapple, papaya and avocado; whilst guava, lychee, longan, durian, rambutan and passion fruit are categorized as minor tropical fruits. Most of these fruits are high in moisture content (>80%), therefore they are prone to deterioration and have short shelf life. Various methods can be used to preserve these fruits including drying, canning, chilling, freezing, pickling and modified atmosphere packaging.

Among these methods, drying is one of the widely used postharvest technologies. Sun drying is one of the traditional methods utilized in most developing countries. Despite the low cost, there are several inherent limitations such as potential losses due to rodents, birds, insects and growth of microorganisms. Sun drying is also dependent on weather conditions and may cause over or insufficient drying as well as discolouration by UV-radiation (Esper and Muhlbauer, 1998). Hot air or convective drying is an alternative to sun drying as it is not affected by climate change and drying rate can be monitored. Nonetheless, product thermal conductivity may increase due to shrinkage of solid matrix, thus it will lead to a higher heating rate within the product. This causes significant change to the nutritional and sensory properties of the dried fruits (Lewicki, 2006; Louka et al., 2004).

Dried fruits are often made into fruit chips and fruit powder that are incorporated into various food products. Fruit chips (Figure 2.1) and leathers can be eaten as snacks or added into cereals and dessert. Fruit powder can be used as natural flavouring and colouring agent in juice manufacturing and bakery products. The drying methods reviewed in this paper are cost effective and able to improve substantially product quality and storage stability, thereby increasing their availability. Figure 2.2 shows the general overview of techniques that can be used to dry tropical fruits.

![Figure 2.1](image1.png)  
Figure 2.1: Freeze dried mango chips (left) and jackfruit chips (right).
2.2 MICROWAVE VACUUM DRYING

Microwave-vacuum drying (MVD), has recently received great attention for water removal at low temperature for various fruits and vegetables (Pu and Sun, 2015). Microwave heating has been applied to increase the efficiency of dehydration processes by using lower pressure in a vacuum condition that could increase pressure gradient between inner and outer layers of the materials (Bai-Ngew et al., 2014). MVD can be used to create a desirable, crispy texture for dried foods that can be consumed without the need for rehydration, such as snack foods. The crispy texture was due to tissue consisting of air cavities that were surrounded by a brittle structural phase (Scaman and Durance, 2005). Sham et al. (2001) found that a decrease in chamber pressure during drying increased the puffing and crispness of apple chips.

The usage of MVD could increase the drying rate of durian drying. Bai-Ngew et al. (2015) reported that microwave power levels set at 1200, 1600 and 2200 W with a drying rate of 0.34-0.58 kg water kg dry solid$^{-1}$ min$^{-1}$ decreased the degree of crystallinity of durian flour from 7.72% to 4.05%. This agreed with previous studies conducted on crispy banana (Monteiro et al., 2016) and durian chips (Bai-Ngew et al., 2011). The drying rate of banana chips produced using microwave power intensity of 400-1000W ranged from 0.119 – 0.266 g g$^{-1}$ min$^{-1}$ (Monteiro et al., 2016). Findings showed that MVD successfully reduced the water activity ($a_w$) of banana chips to less than 0.3.
Therefore, it can be regarded as stable \((a_w < 0.6)\) against microbial, browning, hydrolytic reactions, lipid oxidation, auto-oxidation and enzymatic activity (Caliskan and Dirim, 2013). Bai-Ngew et al. (2014) reported that the moisture content of durian flour produced by MVD ranged from 4.44 – 5.27%. Moisture content below 10% is adequate to ensure the food powder produced is microbiologically safe (Ng et al., 2012).

Microwave vacuum drying at different levels of microwave power \((3.88 \text{ W g}^{-1}, 5.49 \text{ W g}^{-1} \text{ and } 7.23 \text{ W g}^{-1})\) at 13.33 kPa were used to produce durian chips (Bai-Ngew et al., 2011). Results showed that an increase in microwave power intensity did not affect appearance of the durian chips \((p > 0.05)\) but increased the drying rate. The structure and texture of the dried durian chips were similar to conventionally fried durian chips. Besides, the usage of MVD as a potential process to produce fat free durian chips had been proven.

### 2.3 MICROWAVE AND CONVECTIVE MULTI-FLASH DRYING

Monteiro et al. (2016) reported hybrid drying method known as microwave multi-flash drying (MMFD). Banana samples were first warmed up in the microwave field until approximately 60 °C under atmospheric pressure, then, the microwave generator was turned off and a sudden chamber decompression (vacuum pulse) was applied until approximately 8 kPa. This process resulted in flash evaporation and then cooling of samples at approximately 40 °C. This heating-vacuum pulse cycle was repeated, followed by keeping the samples under vacuum \((4 \text{ kPa–8 kPa})\) and microwave field until the desired time. The reported drying rate of sliced banana dried by MMFD ranged from 0.102 – 0.202 g g\(^{-1}\) min\(^{-1}\). Fruits dried by MMFD caused the formation of larger pores and porosity due to the air cavities that were surrounded by brittle structures (Scaman et al., 2014). Therefore, the texture of products dried with MMFD were crispier than those dried by MVD and freeze-dried products (Monteiro et al., 2016).

On the other hand, convective multi-flash drying (CMFD), as reported by Zotarelli et al. (2012) and Porciuncula et al. (2016), is based on the application of successive cycles of heating and vacuum pulses. The product is heated at atmospheric pressure using hot air or heated plates, until reaching a desired temperature \((\text{e.g. } 60 ^\circ \text{C})\), when a sudden pressure reduction (vacuum pulse) is applied, resulting in a fast water evaporation (flash drying) and product cooling, causing dehydration and product texturization. According to Zotarelli et al. (2012), CMFD can be used to produce very low water activity food, whereby the water activities of banana and mango were 0.276 and 0.374, respectively. Meanwhile, the moisture contents of banana and mango were 0.293 and 0.09 g/g (dry basis), respectively. In addition, CMFD produced higher drying rate as compared to conventional convective or vacuum drying due to better efficiency.
2.4 SPRAY DRYING

Spray drying is one of the most common methods to change liquids into solids for increasing shelf-life and stability of the product (Santhalakshmy et al., 2015). The resulting spray-dried powder is of good quality, low water activity, easier to transport and store (Tonon et al., 2009). Previous studies investigated the effects of inlet temperatures and maltodextrin concentrations on the physicochemical properties of spray dried fruit powders. Patil et al. (2014) optimized the spray drying process for developing guava powder with inlet air temperature ranged from 170°C to 185°C and maltodextrin concentration level varied from 7% to 12%. The optimum conditions obtained were 185°C inlet air temperature and 7% maltodextrin concentration to produce free flowing powder with the highest amount of vitamin C.

Chong and Wong (2015) determined the physicochemical properties of spray dried sapodilla (Manilkara zapota) powder with different inlet air temperatures (140°C – 220°C) and maltodextrin concentrations (10 – 50% w/v). The results indicated that the shelf life of the product was prolonged due to low moisture content (0.16-3.14%) and water activities (0.2-0.25). The spray dried powder obtained showed good solubility and low hygroscopicity.

Oberoi and Sogi (2015) successfully produced microencapsulated lycopene via spray drying from watermelon juice. Maltodextrin was incorporated into watermelon juice and this yielded free flowable spray dried powder. Lycopene of spray dried watermelon powder increased up to 56.4 mg/100g on wet basis compared to the initial watermelon juice (4.58-6.53 mg/100g). However, visual colour analysis showed that watermelon powder decreased in redness with increase in maltodextrin above 5% in spray drying.

According to Chin et al. (2010), different types of carriers and inlet drying temperatures had significant effects on the volatiles retention of spray dried durian powder. Maltodextrin blended with gum Arabic at a ratio of 3:1 showed greater retention of volatiles in the durian powder as compared to maltodextrin and N-loc starches. The retention of key volatiles (propanethiol, diethyl sulphide, ethyl propanoate and ethyl 2-methylbutanoate) for spray dried durian powder detected was in the range of 22-77%.

2.5 FREEZE DRYING

Freeze drying or lyophilization is increasingly being utilized in the food industry, which involves the removal of water via sublimation from the frozen state (ice). Freeze drying is able to preserve flavour, colour and appearance because it is carried out at low temperatures (Berk, 2009). Watermelon juice powder obtained by freeze drying retained more lycopene content compared to spray dried powder (Oberoi and Sogi, 2015). Nunes et al. (2016) reported that a total of 31 volatile compounds were identified in fresh and freeze dried guava. Freeze dried guava showed higher relative contents of volatiles such as (Z)-3-hexenyl acetate, hexanal and (E)-2-hexenal. It was concluded that freeze drying could maintain the flavour of fresh guava and freeze dried guava powder could be added into other products to reinforce fresh guava flavour.
Saxena et al. (2015) conducted a comparative study of different drying modes (freeze drying, combination drying and hot air drying) to produce jackfruit bulb crisps. The physical properties and sensory evaluation of the dried crisps were evaluated. Results showed that the degree of shrinkage was the lowest and the rehydration ratio was the highest for freeze dried crisps. The degree of browning for freeze dried crisps was lesser as compared to hot air dried crisps. However, the hot air dried crisps had significantly higher hardness and crispness values than those of freeze dried samples. A study showed that freeze drying was better than spray drying in producing durian powder whereby freeze dried durian powder had a better aroma and appearance (Che Man et al., 1999). This was due to the low temperatures used in freeze drying, thus most of the flavour volatiles were retained.

Athmaselvi et al. (2014) evaluated the thermal, structural and physical properties of freeze dried tropical fruit powders. Findings showed that freeze dried papaya powder was sticky, which could be due to the presence of pectin, as compared to guava and sapota powders. The thermal stability of guava powder was higher than papaya and sapota powders as investigated by using thermogravimetric analysis. The presence of A-type starch in guava, sapota and papaya indicated that the semi-crystalline nature of starch present in the fruit was not destructed after dehydration process.

Although freeze drying is one of the best methods for production of high quality dried fruits but the process is costly (Nunes et al. 2016). Zotarelli et al. (2012) stated that fruits processed by CMFD are as crispy as the freeze-dried fruits and at lower in costs than freeze drying. Therefore, incorporating other drying methods such as hot air drying, vacuum drying and microwave vacuum drying has been recommended since freeze drying is energy intensive and costly (Jiang et al., 2014; Pei et al., 2014).

2.6 SOLAR DRYING

Solar drying is an efficient system utilizing solar energy which evolves from traditional sun drying (Bala, 1998; Zaman and Bala, 1989). The first solar dryer was designed as a box shaped housing unit having a transparent sunlight cover to prevent product losses and quality degradation by wind-blown, debris, rain, insects and animals (Midilli, 2001; Kumar et al., 2016). In solar drying, the moisture is removed by the solar heated air having temperature range of 50 to 60°C (Kumar et al., 2016). Solar drying can be carried out using either natural or forced convection solar dryers. The airflow in the natural convection solar dryer is established by buoyancy induced airflow while in forced convection solar dryer it is provided by a fan operated by electricity/solar module or fossil fuel (Bala and Debnath, 2012).

Chowdhury et al. (2011) reported the production of jackfruit leather with the aid of solar tunnel dryer. The moisture content of the leather reduced from 76% (wb) to 11.88% for samples dried with a solar tunnel dryer. It was concluded that solar tunnel dryer was more efficient as the energy received by the sample was from both the collector and incident solar radiation. Meanwhile,
open sun drying resulted in a higher percentage of moisture content (13.8% wb) mainly due to loss of energy to the surrounding.

Amer et al. (2010) designed a hybrid solar dryer to produce dried banana slices by storing the solar energy in water tank to reduce drying cost. The hybrid solar dryer could accommodate approximately 30 kg of sliced banana and the moisture content of the banana reduced from 82% to 18% (wb) after 8 h of drying. In contrast, the moisture content of sliced banana produced by sun drying reduced to only 62% (wb). Besides, the colour, aroma and texture of the solar dried products were better than sun drying. Gudiño-Ayala and Calderón-Topete (2014) employed a solar hybrid dryer to dehydrate pineapple in which the drying time was shorter (6.0-6.8 h) than traditional solar dryer (8.0-8.8 h). The quality of the dried pineapple produced was satisfactory with only slight discoloration at the pineapples’ side which were exposed directly to the sun.

Bala and Janjai (2009) investigated solar drying of mango and results showed that after three days of drying, a greater reduction in moisture content was achieved by using solar drying (82.9%) as compared to those obtained by sun drying (71.5%). Bala et al. (2003) also reported similar results whereby the moisture contents of solar dried and sun dried pineapples after three days of drying reduced from 87.32% to 14.13% and 87.32% to 21.52%, respectively.

Based on the aforementioned discussion, Table 2.1 summarizes the recommended drying techniques for tropical fruits according to the type of finished products.
**Table 2.1:** Recommended drying techniques for tropical fruits

<table>
<thead>
<tr>
<th>Types of fruit</th>
<th>Possible drying techniques</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durian</td>
<td>Microwave-vacuum drying (MVD) Spray drying Freeze drying</td>
<td>Durian flour, durian chips durian powder</td>
</tr>
<tr>
<td>Banana</td>
<td>Microwave-vacuum drying (MVD) Microwave multi-flash drying (MMFD) Convective multi-flash drying (CMFD) Solar drying</td>
<td>Banana chips, Banana powder</td>
</tr>
<tr>
<td>Mango</td>
<td>Convective multi-flash drying (CMFD) Solar drying</td>
<td>Mango slices</td>
</tr>
<tr>
<td>Jackfruit</td>
<td>Freeze drying Solar drying</td>
<td>Jackfruit crisps, Jackfruit leather</td>
</tr>
<tr>
<td>Ciku</td>
<td>Spray drying</td>
<td>Ciku powder</td>
</tr>
<tr>
<td>Pineapple</td>
<td>Solar drying</td>
<td>Pineapple slices</td>
</tr>
<tr>
<td>Guava</td>
<td>Spray drying Freeze drying</td>
<td>Guava powder</td>
</tr>
<tr>
<td>Watermelon</td>
<td>Spray drying</td>
<td>Watermelon powder</td>
</tr>
<tr>
<td>Papaya</td>
<td>Freeze drying</td>
<td>Papaya powder</td>
</tr>
</tbody>
</table>
2.7 CONCLUSION

Drying technologies of fruits is evolving fast as new technologies are invented in the quest for greater production rate, energy efficiency and better food quality. However, literature coverage on drying of exotic tropical fruits is still relatively scarce. Hybrid drying methods which combine the strengths of multiple drying methods to overcome their limitations have been used in other food items with great success. Thus far there have only been few examples of such methods applied on tropical fruits i.e. microwave multi-flash drying and convective multi-flash drying. These hybrid methods could potentially produce better quality dried tropical fruit products and subsequently increases their availability at commercial market.

REFERENCES


Berk, Z. Freeze drying (lyophilisation) and freeze concentration. In Food Process Engineering and Technology; Berk, Z., Ed.; Academic Press,: San Diego, 2009; 511–523.

Caliskan, G.; Dirim, S.N. The effects of the different drying conditions and the amounts of maltodextrin addition during spray drying of sumac extract. Food Bioproducts and Processing 2013, 91 (4), 539-548.


Chong, S.Y.; Wong, C.W. Production of spray-dried Sapodilla (Manilkara zapota) fruit powder from enzyme-aided liquefied puree. Journal of Food Processing and Preservation 2015, 39 (6), 2604-2611.


Louka, N.; Juhel, F.; Allaf, K. Quality studies on various types of partially dried vegetables texturized by controlled sudden decompression general patterns.


Ng, L.Z.; Chong, P.H.; Yusof, Y.A.; Chin, N.L.; Talib, R.A.; Taip, T.S.; Aziz, M.G. Physicochemical and nutritional properties of spray-dried pitaya fruit powder as natural colorant. Food Science Biotechnology 2012, 2, 675-682.


Chapter 3

Alternative approaches in drying to improve nutritional and textural property of mango and jackfruit based snacks.

C. Borompichaichartkul and R. Impaprasert

Contents

3.1 Introduction 41
3.2 Improving nutritional property of dried mango by osmotic dehydration 42
3.3 Hybrid drying 47
3.4 Improving textural property of jackfruit by drying method 49
3.5 Conclusion 54
3.6 Acknowledgement 54
References 54
3.1 INTRODUCTION

Nowadays, the incident of non-communicable disease (NDCs) is increasing. The disease is associated mainly with foods and consumption behaviour, especially in consuming diets that is rich in sugar, carbohydrate, fat/lipid and salt. Sugar and lipid are the main ingredients that cause risk to overweight, obesity, hyperglycemia and hyperlipidemia (WHO, 2015). The unhealthy diets and life style are the main influences to NDCs. However, increasing the portion of fruit and vegetable in the diets may reduce the risk of NDCs due to presence of dietary fibres and micronutrients that help to delay absorption of glucose and lipid into the blood and body regulation system. Fernandes et al. (2011) reported that fruits rich in antioxidants may help to lower the incidence of degenerative diseases. The most abundant antioxidants in fruits are polyphenols, vitamin A, B, C and E. Carotenoids are present to a lesser extent in some fruits. These polyphenols, mostly flavonoids, are present in ester and glycoside forms (Fleuriet and Macheix, 2003 cited in Fernandes et al., 2011).

South East Asia is one of the regions that is rich in exotic and tropical fruits. Yet, shelf life of fresh tropical fruits is short and drying is one of the important approaches to reduce the moisture content of fruit for safe storage at ambient conditions. There are many methods of drying, and each method has both advantages and disadvantages. The common drying methods are natural drying such as sun drying or conventional hot air drying by tray dryer, tunnel dryer, fluidized bed dryer or spray dryer or solar drying. These dryers can dry food materials that can be in forms of powder, fibre, moulded food, semi-solid food, liquid and grain. However, hot air dryers consume a lot of energy and result in loss of nutritional values in food materials due to exposure to heat. Therefore, a reduction in atmospheric pressure to decrease boiling point of water is an alternative option to dry heat sensitive materials and improve their quality i.e vacuum drying and freeze drying. Some produce that undergo drying in large amounts such as grain and nut is generally dried by low temperature drying i.e. sun drying or in-store drying of paddy. For high value nuts such as macadamia nut, the preferred drying method is in-store dryer at 40 – 60 °C to prevent oxidation of fat and rancidity. However, single stage drying has some limitations and drawbacks. Freeze drying can maintain nutritional, chemical and physical quality of food materials but the drying period is long and energy intensive; high investment cost is also required. In microwave drying, drying rate can be accelerated but non-uniformity of microwave generation can result in burnt spots.

Pre-treatment such as osmotic dehydration is often used for improving the quality of dried products. Appropriate selection of pre-treatment process can improve the quality of dried fruit products i.e. as healthy snacks which could lower the risk of NDCs, or textural property of dried fruit could also be improved by combining osmotic pre-treatment with drying. In addition, hybrid drying is known for having high drying rate, short drying time and energy saving. The next section will give a review on hybrid drying methods for fruit and vegetable products and a study on the effect of hybrid drying on textural property of dried jackfruit. A review of osmotic dehydration to improve nutritional properties of mango is also given in the next section.
3.2 IMPROVING NUTRITIONAL PROPERTY OF DRIED MANGO BY OSMOTIC DEHYDRATION

Mango (*Mangifera indica* L.) is one of the important economical tropical fruits in South East Asian countries. It is available in different varieties and contains considerable amount of vitamin C, A and potassium as well as rich in dietary fiber, polyphenol and carotenoids (Telis and Telis-Romero, 2007). The taste of mango is sour and sweet. However, fresh mango can be kept at ambient temperature for only few days and 2-3 weeks at 13 °C, 85-90% RH conditions (Carrillo-Lopez, 2000). Preservation via drying is a common practice but this often reduces the quality of mango significantly in terms of texture, colour and nutritional value (Durance et al., 1999). For mango drying, osmotic dehydration is one of common drying practices.

Osmotic dehydration is a popular technique that has been used as an intermediate step in drying, dehydrofreezing and freeze-drying. Osmotic dehydration is based on the principle of partial removal of water from product, which is immersed in a hypertonic solution of sugar, salt, sorbitol or glycerol. The mechanism of osmotic dehydration can be divided into two phases namely (i) water outflow from product to solution (ii) solute transfer from solution to product. However, product own solutes, for example minerals, vitamins and pigments can also leach into the solution during osmotic dehydration. Nevertheless, conventional osmotic dehydration of dried fruit snack often has a drawback of high sugar content and hard texture.

There have been attempts to maintain the quality of dried mango as reported from literatures. Guiamba et al. (2015) studied the effects of infrared (IR) dry blanching (90 °C for 2 min and at 65 °C for 10 min) and compared with water blanching before hot air drying of mango in order to inactivate polyphenol oxidase (PPO) and ascorbic acid oxidase (AAO) enzymes. Results showed that IR dry blanching demonstrated potential to maintain a higher retention of vitamin C, however, lower retention of all-trans-β-carotene and a slightly darker color were detected in IR dry blanched mango. Moreover, PPO activity in mango was completely inactivated in all conditions, whereas AAO showed low remaining activity. De Medeiros et al. (2016) studied effects of the dual-stage (D3S) technique on quality of dried mango. This technique consisted of using high calorie sugars in the first stage and low calorie sugar (Stevia-derived) in the second stage of pretreatment to maintain the sweetness of mango prior to drying in a fixed bed dryer at 60 °C. Results indicated that this technique could reduce water activity of sample, showed better colour preservation and good sensorial acceptance. However, pretreated sample had lower phenolic and carotenoid contents and softer texture.

Pre-treatment of fruit prior to drying can add value or functions to the dried fruit snacks. Many researches tried to use osmotic solution that is produced from high antioxidant fruit juice to avoid the use of synthetic food additives. There are some researches on the use of natural anti-browning agents in dried fruits such as honey and pineapple juice. Oszmianski and Lee (1990) had reported anti-browning activity of honey in apple slices, grape juice and model systems. The inhibitory effect of honey due to the low molecular weight
peptides with an approximate molecular mass of 600 Da (Oszmianski and Lee, 1990) able to chelate the essential metal ion, copper, at the active site of PPO and form stable complexes with cupric ion (Cu^{2+}). Moreover, t-cinnamic and p-coumaric acids in honey acted as noncompetitive PPO-inactivating agents (Martyniuk, 1994). Pineapple juice is also used as enzymatic browning inhibitor in many researches. Lozano-de-Gonzalez et al. (1993) found that the anti-browning ability of pineapple juice in fresh and dried apple rings which are as effective as sulfite compounds. Chaisakdanugull et al. (2007), Zhang et al. (2007) and Sun et al. (2015) reported that major components of pineapple juice that are responsible for enzymatic browning inhibition are organic acids (e.g. citric acid and malic acid). However, the level of citric acid is the highest among the organic acids. As we know that enzymatic browning reaction occurs due to the phenolic compounds in the fruit that react with oxygen and transform to o-quinones which are the intermediate compound produced by PPO activity and change to melanin which is the brown pigment in fruit. Citric acid is also known as phenolase Cu-chelating agent, and the inhibition of PPO was attributed to the chelating action (Jiang et al., 1999 and Chaisakdanugull et al., 2007). Thus, the acidity of pineapple juice helps to retard enzymatic browning reaction.

Incorporating antioxidant agents such as vitamin C with osmotic solution can also increase nutritional quality of dried fruit-based snacks. There are many researches about using antioxidant agents such as ascorbic and citric acid (Villegas-Santiago et al., 2011), calcium chloride (Guiamba et al., 2016) and herb extracts in dried fruit such as aloe vera (Chakraborty and Samanta, 2015). Villegas-Santiago et al. (2011) reported treating mango samples with antioxidants solutions (ascorbic and citric acid) before the drying process using fluidized bed and tray drying of thinly sliced mango. Results indicated that 1% citric acid pre-treatment to 2-cm-diameter mango slice could maintain the colour of dried sliced mango closest to the colour of fresh mango. Guiamba et al. (2016) studied the retention of vitamin C and carotenoids in cv. ‘Tommy Atkins’ mango by using osmotic dehydration prior to hot air drying of mango. Results indicated that osmotic pretreatment before drying significantly reduced the drying time and prevented colour change in dried mango. When comparing the effects of using sucrose solutions of 45°BRIX osmotic dehydration without additives, osmotic dehydration with 1% calcium chloride, and osmotic dehydration with 1% ascorbic acid before drying the mango samples in an air convection oven at 50 °C or 70 °C, addition of calcium in the osmotic dehydration solution significantly improved vitamin C retention. However, the addition of ascorbic acid to the osmotic solution highly increased the retention of vitamin C content in the dried mango. Moreover, osmotic dehydration with and without additives reduced the ratio of 13-cis-β-carotene to all-trans-β-carotene. Results showed that the addition of calcium or vitamin C to the osmotic solution can improve the nutritional value of dried mango.

Aloe vera contains vitamin A, C and E which serve as antioxidants and also contains compounds such as phenols, riboflavin, niacin, proteins, minerals and polysaccharides (Ahlawat and Khatkar 2011), it is not only used in cosmetics and healthy drink but also can be used to fortify fruit products.
during dehydration without using any preservative. Chakraborty and Samanta (2015) reported improvement of nutritional value of dried Alphonso mango through enrichment with aloe vera. Results showed that using the sequential hybridized-drying protocol including osmotic dehydration (45 °Brix and 5% aloe vera at 45 °C for 60 min) and then downstream vacuum-drying under near-infrared radiation (90 W, 360–2,000 nm) at 0.005 mbar 45 °C for 120 min) produced appreciable increments in ascorbic acid (111.25%), total phenolic content (676%), total flavonoid content (89.85%) and radical scavenging activity (279.04%).

Study by Benjabunyongkul and Borompichaichartkul (2014) found that using pineapple juice could maintain the antioxidant properties of mango by hot air drying at 80 °C (Figure 3.1-3.2). The fact that pineapple contains not only fruit sugar (fructose, glucose, and sucrose), organic acids (citric acid, malic acid, tartaric acid, acetic acid, and quinic acid), and dietary fiber but also a good source of vitamins (vitamin A, vitamin C and vitamin B6) and polyphenolic compounds. The total phenolic contents of pineapples ranged from 25.71 to 72.57 mg GAE/100 g wb and the total flavonoid content varied from 10.40 to 50.57 mg RE/100 g wb. The bioactive components in pineapple such as gallic acid, catechin, p-hydroxybenzoic acid, chlorogenic acid, epicatechin, cumaric acid, ferulic acid, erucic acid, myricetin, cinnamic acid and also β-carotene showed great radical scavenging activity. Results indicated that the DPPH values, ABTS values and FRAP values of pineapple extracts varied from 125 to 444, 438 to 814, and 438 to 814 µmol Trolox, respectively. However, the metal-chelating capacity of fruit extracts varied from 4.9 to 13.3% (Sun et al., 2015).

It is interesting that the content of total phenolic compounds and flavonoids was found to increase after drying. This behavior was reported by Chism and Haard (1996), Chang et al. (2006) and Silva et al. (2013), which evaluated the content of phenolic compounds and flavonoids content in tomatoes and pineapples after drying and obtained higher values than the fresh ones. Since these compounds in plants act as metabolic intermediates and normally accumulate in vacuoles, and that the drying process accelerates the release of these compounds by breaking down the cellular constituents. Although, disruption of cell walls may also trigger the release of oxidative and hydrolytic enzymes that would destroy the antioxidants in fruits, however, high temperature processing would deactivate these enzymes and avoid the loss of phenolic acids which lead to the increase of bioactive compounds (Chism and Haard, 1996). Therefore, treating mango with pineapple juice and the drying condition play an important role in improving the nutritional values of dried mango snack and at the same time add values to the inexpensive pineapple juice.
Borompichaichartkul, C. and Impaprasert, R. - Alternative approaches in drying to improve nutritional and textural property of mango and jackfruit based snacks

During osmotic dehydration of mango slices, the exchange of water molecules and micronutrients, sugar and acid occur between the fruit flesh and osmotic solution. In fact, micronutrients can leach out from the flesh, subsequently, the amount of micronutrients in the fruit is reduced. When fresh pineapple juice is used to replace the syrup, it can retain micronutrients in the dried product better than sugar syrup at the same concentration.
For physical properties such as colour, it can be seen from Figure 3.3 that mango sample soaked in the pineapple juice exhibited better colour retention than that from sugar syrup. The dried mango from the best treatment, treated with 45 °Brix pineapple juice is illustrated in Figure 3.4.

![Color change value (ΔE) of dried mango treated with sugar syrup and pineapple juice from different treatments (Benjabunyongkul and Borompichaichartkul, 2014).](image)

**Figure 3.3:** Color change value (ΔE) of dried mango treated with sugar syrup and pineapple juice from different treatments (Benjabunyongkul and Borompichaichartkul, 2014).

As mango typically contains sucrose, glucose, fructose and many amino acids (Dar et al., 2015) which are the substrates of the Maillard reaction (a kind of non-enzymatic browning reaction) and also one of the major causes of color change in thermal processing of fruit products (Rattanathanalerk et al., 2005). It was observed that heating temperature and processing time had a marked effect on the formation of 5-hydroxymethylfurfural (HMF) and melanoidins (brownish nitrogen-containing polymers). HMF increased linearly with time and higher amounts were found at the higher heating conditions. However, the optimum pH for this reaction is between 3 and 10. At pH < 3, browning is low and increases with increasing pH to a maximum of 10. The reactivity of the amino group is higher when the amino acid is in anionic form which depends on the acid–base characteristic of the amino acid. Thus, pH of the product strongly influence the stereochemical configurations of amino acid and intensity of the Maillard reaction (Rufiañ-Henares, 2016). Therefore, using fruit juice that contain high organic acid and antioxidant substance can help to improve the nutritional value and add value to the dried mango as healthy snack based product.
Figure 3.4: Dried mango from the best treatment treated with 45 °Brix pineapple juice (Benjabunyongkul and Borompichaichartkul, 2014).

3.3 HYBRID DRYING

Kudra and Mujumdar (2009) provide the general concept of hybrid drying technology as it includes drying techniques that use multiple modes of heat transfer as well as those that use two or more stages of dryers of the same or different type. A wide range of successful new drying technologies fall into this category since they are based on intelligent combinations of well-known conventional know-how. Hybrid drying process can be divided into three categories; (1) combined modes of heat transfer (2) multistage dryers (3) multiprocessing dryers.

The use of combined or hybrid drying has the ability to combine advantages of various drying techniques and combination of different drying processes usually offers unique advantages that single drying process cannot achieve. For example, Devahastin (2004) reported the use of low pressure superheated steam drying (LPSSD) for drying fruits and vegetables. LPSSD is able to preserve better the quality of the product compared to those from conventional hot air dryer. For macadamia nut drying, Borompichaichartkul et al. (2009) found that a suitable drying condition for macadamia nut-in-shell required the use of heat pump drying at 40 °C to decrease the moisture content to 11.1% (d.b.); this should be followed by second-stage hot air drying at 50 °C until the moisture content was reduced down to 1–2% (d.b.). Combined heat pump and hot air drying shows benefit of time saving and natural quality preservation of macadamia nut. Chua et al. (2001) (cited in Fernandes et al., 2011) who studied the effect of stepwise change in drying air temperature on drying kinetics and product colour of banana slices found that the drying time and color degradation of banana slices were reduced when a step-down air temperature profile with a longer holding time was applied to batch drying of banana slices. Andrés et al. (2007) studied the osmotic
microwave drying of mango \((M. \text{ indica } \text{L.})\) and found that this technique reduced the drying time and energy requirement. However, microwave power influences the drying kinetics and produces uneven colour i.e. charred pieces under high microwave power level.

Microwave vacuum drying has recently become more widely used in the food industry. Heat generated by microwave energy occurs principally in the product, not in the oven walls or atmosphere. Therefore, heat losses from the oven to the surroundings are much lower. Fast start-up, shut-down and precise process controls are possible in microwave heating (Mullin, 1995; Vadiyambal and Jayas, 2007). Drying under application of microwave and vacuum can lead to shorter drying time at lower temperature and thus results in product with superior quality. In contrast, in conventional hot air drying when low temperature is applied the drying time is usually long and contributes to poor product quality. Thus, the quality of materials dried in a microwave vacuum dryer would be higher than that dried in conventional hot air dryers.

The low temperature and high mass transfer by vacuum (Yongsawatdigul and Gunasekaran, 1996), combined with rapid energy transfer by microwave heating, generate very rapid, low temperature drying. Moreover, the absence of air during drying may inhibit oxidation, and therefore, colour and nutrient content of products can be largely preserved (Lin et al., 1998; Kelen et al., 2006; Zielinska et al., 2013). Applying microwave energy under vacuum combines advantages of both vacuum drying and microwave drying as far as improved energy efficiency and product quality are concerned (Krokida and Maroulis, 1999). However, most of the microwave-vacuum drying studies focus on fruits and vegetables that need the ‘puffing’ quality to improve rehydration properties of the final product (Zhang et al., 2006). In particular, microwave-vacuum drying techniques are reported to be used successfully for the dehydration of many kinds of fruits and vegetables such as carrots (Lin et al., 1998), bananas (Maskan, 2000; Mousa and Farid, 2002), pumpkin (Liamkaew, 2006), garlic (Figiel, 2006), mushrooms (Giri and Prasad, 2007), potatoes (Bondaruk et al., 2007), mint leaves (Therdthai and Zhou, 2009), and green peas (Zielinska et al., 2013). These products possess excellent quality in terms of taste, aroma, texture and appearance. An example of pulsed microwave vacuum dryer is illustrated in Figure 3.5.

As for the limitations of microwave-vacuum drying (Kanlapong, 2006), non-uniformities in the microwave field and associated heating patterns can lead to non-uniformities in drying. Especially in regions that dry much earlier, non-uniformities in the microwave field can lead to high temperatures in certain regions and cause product degradation (Lu et al., 1999). However, various ways of averaging the microwave field to improve uniformity have been achieved such as by mechanical movement (Torrina et al., 1996), pneumatic agitation i.e. in a fluidize bed dryer (Kudra, 1989), or spouted bed dryers (Feng and Tang, 1998). Some of the limitations are specific sample size and shape (Liamkaew, 2006). For industrial applications, it is difficult to dry large size of food and agricultural products in the flow process because of microwave penetration and microwave leaking. The shape and size of objects
heated by microwave irradiation have much greater and completely different impact on temperature distribution than classical means of heating. Microwave energy is deposited directly in the heated material, so the interior of the object can be heated to a higher temperature than near the surface, especially for solids such as frozen meat with low thermal conductivity. A number of researchers have studied effects of drying foodstuffs using this technique with various degrees of success.

The next section provides a comprehensive study of different hybrid drying on textural property and sensory evaluation of dried jackfruit.

![A pulsed microwave vacuum dryer (MarchCool, Thailand).](image)

**Figure 3.5:** A pulsed microwave vacuum dryer (MarchCool, Thailand).

### 3.4 IMPROVING TEXTURAL PROPERTY OF JACKFRUIT BY USING HYBRID DRYING METHOD

Jackfruit (*Artocarpus heterophyllus*) is a tropical fruit that has a unique flavour and sweet taste that makes it a popular fruit in Asia. It is rich in energy, dietary fiber, minerals, and vitamins such as vitamin C, A, B-complex group, vitamin B-6 (pyridoxine), niacin, riboflavin, and folic acids as well as good source of flavonoid pigments such as β-carotene, xanthin, lutein and β-cryptoxanthin. Due to the short shelf-life, fresh jackfruit is often preserved and processed as canned, fried or dried products. Fried jackfruit is a popular snack among other fruit snacks. However, fried products are now becoming less popular due to absorbed oil content, health concerns and rancidity during improper packaging and storage. The quality of oil used in frying is also being monitored by WHO and USFDA by imposing regulations on repeated use of oils and trans-fats. Alternative preservation methods of jackfruit are drying and osmotic dehydration combined with hot air drying, which are common practices for fruit drying. However, osmotically dehydrated fruit often have hard texture, high sugar content, dark colour and long drying time.
3.4.1 Sample preparation and drying

Osmotic pretreatment

Jackfruit was selected such that total soluble solid was controlled to 13-14 °Brix. The jackfruit flesh was cut into 3 cm × 4 cm. Osmotically dehydrated jackfruit was prepared by soaking the jackfruit in a solution of 1% (w/v) citric acid, 0.5% (w/v) sodium metabisulfite and 2.5% (w/v) calcium chloride, using a jackfruit to brine ratio of 1:3, for 10 min. After that, the solution was drained off and pieces of jackfruit were boiled in water for 10 min. Then jackfruit was soaked in sugar solution at 50 °Brix mixed with 1% (w/v) NaCl for 24 h prior to drying at different conditions.

Drying experiment

Three drying methods (i) hot air drying at 60 °C for 420 min (ii) hot air drying at multistage temperatures (90 °C for 60 min, 70 °C for 150 min and 60 °C for 210 min) and (iii) microwave vacuum dryer (at 960 watt for 23 min) were studied.

3.4.2 Quality measurement and sensory evaluation

The quality measurements carried out were texture analysis (Stable Micro System Model TA.XT2i, UK), odour evaluation by electronic nose (E-nose, Nanotechnology Center, Thailand) and cross section image evaluation by using an image analyser (Nikon Corporation model ACT-1 version 2.63, Japan). Sensory evaluation was conducted by using acceptance test with 30 panelists. All of the experimental data were performed in triplicate and the average results were reported. The differences between means were estimated using analysis of variance (ANOVA) and Duncan’s multiple range test with a level of significant of $p< 0.05$ using the SPSS 16.0 software (IBM SPSS, Chicago, IL, USA).

3.4.3 Product Quality

Effect of drying methods on textural property and sensory evaluation of dried jackfruit demonstrated that using microwave vacuum drying has more advantages over hot air drying at 60 °C and multi-stage drying in terms of texture (Figure 3.6-3.7) and odour quality (Figure 3.9) of dried jackfruit. These are due to the low temperature and fast mass transfer offered by vacuum and rapid energy transfer by microwave heating, generate very rapid, low temperature drying. The cross section images (Figure 3.8) of dried jackfruit from different treatments also indicate that the crisp characteristic of osmotically dehydrated jackfruit under microwave vacuum drying is comparable to that of fried product. It was observed that microwave vacuum drying techniques encouraged porous structure interior in the dried jackfruit while the fresh and osmotically dehydrated samples had low porosity and tight pack structure. The more porous structure may be due to rapid vaporisation of water inside the granule during microwave vacuum drying. For this reason, mass transfer occurred by vaporization of water (Therdthai and Zhou, 2009).
Thus, hardness and crispness of jackfruit sample dried under microwave vacuum drying is the lowest when compared to other drying methods.

**Figure 3.6**: Texture measurement (Hardness value) of jackfruit from different treatments (Srinang et al., 2015).

_Different superscripts indicate significantly differences as per results of Duncan’s multiple range tests (p ≤ 0.05)_

**Figure 3.7**: Texture measurement (Crispness value) of jackfruit from different treatments (Srinang et al., 2015).

_Different superscripts indicate significantly differences as per results of Duncan’s multiple range tests (p ≤ 0.05)_
Figure 3.8: Images of dried jackfruit from different treatment from Image Analyser at 5X (Srinang et al., 2015).

Figure 3.9: Comparison of odour of jackfruit from different treatments by E-nose (Srinang et al., 2015).

Different superscripts indicate significantly differences as per results of Duncan’s multiple range tests \((p \leq 0.05)\)
Sensory evaluation and E-nose also revealed the acceptance of panellists that preferred microwave vacuum dried jackfruit in all attributes, with higher scores than other drying methods (Table 3.1). The odour of the dried jackfruit after treated with different treatments were analysed by using an E-nose with chemical sensor array technique (NANOTEC, Thailand) which uses principles of qualitative analysis to see patterns of the odour attribute to compare the similarities or differences of smell. The odour distance of dried jackfruit samples under different drying methods from fresh jackfruit (Figure 3.9) shows that microwave vacuum dried jackfruit sample has the shortest distance which means that the odour quality is close to the fresh jackfruit more than other dried jackfruit samples.

**Table 3.1:** Sensory evaluation of dried jackfruit.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Colour</th>
<th>Flavour</th>
<th>Overall taste</th>
<th>Texture</th>
<th>Overall acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osmotically dehydrated jackfruit 60°C</td>
<td>4.27 ± 1.78</td>
<td>4.57 ± 1.33</td>
<td>4.63 ± 1.16</td>
<td>4.43 ± 1.65</td>
<td>4.73 ± 1.20</td>
</tr>
<tr>
<td>Multi-stage osmotically dehydrated jackfruit</td>
<td>4.20 ± 1.50</td>
<td>4.60 ± 1.28</td>
<td>4.50 ± 1.46</td>
<td>4.37 ± 1.90</td>
<td>4.67 ± 1.49</td>
</tr>
<tr>
<td>Microwave vacuum dried jackfruit</td>
<td>5.60 ± 1.16</td>
<td>5.23 ± 1.04</td>
<td>4.87 ± 1.59</td>
<td>6.03 ± 0.77</td>
<td>5.50 ± 0.94</td>
</tr>
</tbody>
</table>

Significantly different samples are indicated by different letters on the column as per results of Duncan’s multiple range tests \((p \leq 0.05)\)

*Source: Srinang et al. (2015)*

![Figure 3.10: Microwave vacuum dried jackfruit (Srinang et al., 2015).](image-url)
3.5 CONCLUSION

Osmotic pre-treatment and hybrid drying method could improve the quality of dried fruit products and serve as a healthy snack. For example, mango which is one of the commercial fruits in Asia, pre-treatment of mango slices in pineapple juice can retain total phenolic compounds and antioxidant properties of dried mango as well as colour. During osmotic dehydration, the acidity of pineapple juice can help to slow down the Maillard reaction, subsequently reduces the darkening of fruit during drying.

Microwave vacuum drying can produce fruit snack comparable to frying. Texture of osmotically dehydrated microwave vacuum dried jackfruit was puffed with more porosity, which corresponds to results from texture and Image analysis. Evaluation of fruit odour with E-nose and sensory evaluation found that osmotically dehydrated microwave vacuum dried jackfruit has similar quality to fresh jackfruit. The panellists gave the highest overall acceptability to osmotically dehydrated microwave vacuum dried jackfruit as compared to other drying methods.

3.6 ACKNOWLEDGEMENT

The Authors would like to thank Research Council of Thailand for funding project number GRB_APS_17_56_23_05 and Chulalongkorn University for Special Task Force for Activating Research (STAR): Dehydration of Food and Biomaterials for research funding.

REFERENCES


Benjabunyongkul, V.; Borompichaichartkul, C. Effect of osmotic pretreatment on antioxidants and total phenolic compounds retention of dried mango. Department of Food Technology, Faculty of Science, Chulalongkorn University, 2014.


Kanlapong, A. Rapaid dehydration of carrot pulp by using microwave vacuum dryer. The Degree of Master of Engineering; Food Engineering 2006, King Mongkut's University of Technology Thonburi, Thailand.


Liamkaew, R. Application of microwave vacuum on drying pumpkin slices. [M.E. thesis], Department of Food Engineering, King Mongkut’s University of Technology Thonburi, Thailand, 2006.


Srinang, J.; Chatasuwankul, N.; Borompichaichartkul, C. Effect of drying methods on chemical and physical properties of osmotically dehydrated jackfruit. Acta Horticulturae 2015, 1088, 579-582


Chapter 4

Drying of Durian Flour and Product Quality

N. Therdthai and S. Bai-Ngew

Contents

4.1 Introduction 61
4.2 Durian Fruit 62
4.3 Drying Procedures 63
4.4 Drying Kinetics 65
4.5 Durian Flour Quality 66
4.6 Conclusion 71
4.7 Acknowledgement 71
4.8 Nomenclature 71

References 72
4.1 INTRODUCTION

Durian (*Durio zibethinus* Murr) is a tropical fruit containing a distinct and strong taste/aroma characteristic (Figure 4.1). The taste of durian is a combination of butter-like custard flavoured with almond (Jaswir et al., 2008). In addition to the unique odour and flavour, durian is nutritionally rich in carbohydrate, protein, fat, phosphorous, iron, and vitamin A (Leontowicz et al., 2007). Durian cv. Monthong can be a nutritional supplement (around 5 – 7%) to the normal diet (Poovarodom et al., 2010). Therefore, durian is in great demand worldwide and in Thailand, exportation value of durian was more than USD 199 million per year (Office of Agricultural Economics, 2013).

![Figure 4.1: Durian fruit (left) and pulps (right)](image)

Similar to other seasonal fruits, durian has problem of oversupply during the harvesting season. Drying is one of the most popular methods to preserve durian as dried flour for use during the off-season. Hot air drying (HAD) has been widely used in making durian flour. However, high temperature and long processing time causes some changes in physical, chemical, sensorial characteristics and the nutritional value in most food products. For example, pasting characteristics of HAD sweet potato starch were observed decreased (Yadav, et al., 2006) while an increase in drying temperature from 60°C to 65°C reduced swelling capacity of sweet potato (Ahmed et al., 2010). Additionally, increasing the drying temperature from 40°C to 60°C could increase enzymatic reaction of α-amylase, β-amylase and glucoamylase, resulting in increased amylase content of acorn flour. However, the increased drying temperature had non-significant effect on dimensions of starch granule (Correia et al., 2011).

To improve the quality of the flour, microwave vacuum drying (MVD) could be an alternative method. Microwave can penetrate deeply into food containing dipolar or ionic substance and heat is generated quickly inside the food.
Consequently, water is evaporated rapidly and the outward fluxes of escaping vapour are noticeable (Hu et al., 2006). In addition, decreasing the pressure during microwave drying can reduce the boiling point of water, speed up evaporation and possibly decrease burning spot problem. Compared to HAD, drying time of MVD could be reduced by 70 – 90% in mushroom drying (Giri and Prasad, 2007) and 85 % in mint drying (Therdthai and Zhou, 2009). Moreover, many studies reported the superior colour of MVD products to HAD products, such as potatoes (Bondaruk et al., 2007), honey (Cui et al., 2008), mint leaves (Therdthai and Zhou, 2009) and durian chip (Bai-Ngew et al., 2011).

According to many studies reported for flour making, microwave could affect the structure of protein resulting in reduction of energy consumption in the subsequent grinding step to make wheat flour (Walde et al., 2002), enhance the structure of the protein and starch, resulting in the decreased viscosity of maize flour suspension (Velu et al., 2006), change the X-ray diffraction pattern from the type B typical pattern of tuber starch to the type A typical pattern of cereal starch (Lewandowicz et al., 2000) and affect the morphology of the starch granule, resulting in an improvement in water absorption (Treppe et al., 2011).

As mentioned above, drying affects food in many aspects depending on the selection of materials and drying conditions. Therefore, this chapter aimed to present effect of HAD and MVD on durian fruit and product quality. This would provide useful information to develop semi-food (such as durian flour) for the desirable application.

**4.2 DURIAN FRUIT**

Durian is a climacteric fruit and changes in respiration rate during ripening can be observed and composition/properties of durian fruit can also vary during the growing stage. Normally, durian suitable for consumption should be from the mature stage but fully mature unripe durian can be processed to durian flour. This is because the mature unripe fruit has the greatest content of starch at three days before ripening (Limpisathian et al., 2008). Although it contains high starch, but its odour, flavour and taste were still not fully developed.

There are three major volatile compounds in durian fruit, including esters (responsible for strong fruity flavour/odour), sulphur compounds (responsible for sulphury odours) and Ketones (responsible for creamy flavour) (Jiang et al., 1998). As durian reaches the maturity stage, the concentration of esters increases, resulting in strong fruity odour. Upon ripening, esters and sulphur compounds increases, resulting in the strong fruity and sulphury flavour/odours (Chawengkijwanich et al., 2008). During the progression of ripening stage, the average dry matter, fat, and total sugar content increases but starch content decreases (Kalayanamitra et al., 2005). An increase in sugar content can increase water solubility and moisture retention of durian flour.
During HAD at high temperature, heat might cause losses of some volatile compounds in durian. Using low temperature and short drying time, MVD has been reported as the superior method to preserve the volatile compounds of dried materials. Therefore, drying condition should be optimally designed for each material to obtain the functionality and properties as required for product development.

4.3 DRYING PROCEDURES

Durian cv. *Monthong* including unripe (104 days after full bloom) and fully ripe (112 days after full bloom) were bought from a local supplier in Thailand. To make durian flour, durian pulp was obtained by de-husking the fruit and removing the seeds. Then, the pulp was ground using a food processor (Combimax 600, Braun, USA) to obtain durian slurry. The slurry (300 g) was formed in a block to prepare a durian sheet (255×380×3 mm) for HAD using a tray dryer (BWS-model; Frecon, Bangkok, Thailand) and MVD using a microwave vacuum dryer (MarchCool, Bangkok, Thailand) with a rotating tray (Figure 4.2). Drying conditions were set as in Table 4.1. During drying, moisture content of the HAD and MVD was determined using an oven method (AOAC, 2000) to observe changes in drying rate for both drying methods. After drying, the durian sheet was finely ground using an ultra-centrifugal mill (Retsch model ZM100, Haan, Germany) and sifted through a 100 mesh (0.149 mm) sieve to obtain durian flour.

**Table 4.1**: Drying condition of durian sheet.

<table>
<thead>
<tr>
<th>Drying method</th>
<th>Set condition</th>
<th>Variation</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAD</td>
<td>Air flow (horizontally to the durian sheet) at 1 m/s.</td>
<td>$T_{\text{air}} = 40^\circ\text{C}$, $t = 10.5\text{ h}$</td>
<td>HAD40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_{\text{air}} = 60^\circ\text{C}$, $t = 7\text{ h}$</td>
<td>HAD60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_{\text{air}} = 80^\circ\text{C}$, $t = 5\text{ h}$</td>
<td>HAD80</td>
</tr>
<tr>
<td>MVD</td>
<td>Frequency at 2,450 MHz and pressure at 13.33 kPa.</td>
<td>$P_{\text{microwave}} = 1200\text{ W}$, $t = 12\text{ min}$</td>
<td>MVD1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{\text{microwave}} = 1600\text{ W}$, $t = 9\text{ min}$</td>
<td>MVD1600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{\text{microwave}} = 2200\text{ W}$, $t = 7\text{ min}$</td>
<td>MVD2200</td>
</tr>
</tbody>
</table>

The durian flour from both HAD and MVD was brought to determine starch content, using the glucoamylase method (AACC, 1990) and amylose content, using amperometric titration with a potassium iodate solution as described by Gibson et al. (1997). To estimate the degree of crystallinity, X-ray diffraction pattern of durian flour was determined using X-ray diffractrometry (Bruker AXS model D8 Discover, Germany) with Cu tube. Structure of the durian flour was determined using a scanning electron microscope (JEOL, JSM 5600LV, Tokyo, Japan). Magnification was adjusted to 5,000×. Pasting properties of durian flour slurry (14% w/w, db) were determined using a Rapid Visco Analyzer (RVA; 4D, Parten Instruments Group, Hägersten, Sweden). Colour of flour was determined using a spectrophotometer (Minolta CM-3500d; Konica Minolta Holdings Inc., Tokyo, Japan). Details of all test conditions were explained in Bai-Ngew et al. (2015a; 2015b). Additionally, volatile compounds
of both unripe and fully ripe durian flour were analysed using an electronic nose (Fox 3000, Alpha M.O.S., Toulouse FR). The e-nose with MOS chambers and 12 sensors (LY/LG, LY/G, LY/AA, LY/Gh, LY/gCTL, LY/gCT, T30/1, P10/1, P10/2, P40/1, T70/2, PA2) was connected to auto sample (HS100). Detail of test condition was described in Bai-Ngew et al. (2013).

Figure 4.2: Diagram of dryers: hot air dryer (A) and microwave vacuum dryer (B).
All experimental data were analyzed for ANOVA using statistical package SPSS® version 12.0 (SPSS (Thailand) Co., Ltd., Bangkok, Thailand). Duncan’s multiple range test was used to carry out the multiple comparisons of mean values with the level of significance tested at P ≤ 0.05.

4.4 DRYING KINETICS

Figure 4.3 shows the drying profiles of durian sheet during HAD and MVD. Moisture content was observed decreased quickly at beginning stage of drying due to the high free moisture content that increases moisture diffusion. In addition, the high moisture content at the beginning could also enhance absorption of microwave energy and conversion of the microwave energy into heat. Therefore, the generated heat enhanced moisture diffusion at this stage.

Figure 4.3: Moisture change during HAD (A) and MVD (B)
Source: modified from Bai-Ngew et al. (2015a; 2015b).
In the later stage, drying removed more moisture and proceeded to a hygroscopic region. This could slow down drying rate of HAD and the MVD. Moreover, in the case of MVD, the low amount of water possibly reduced loss factor. The conversion of microwave energy into heat was not effective, compared with the beginning stage. Therefore, the maximum product surface temperature after MVD was in a range of 54 - 62 °C. Drying rate was observed declined at the last stage of MVD and HAD.

The fully ripe durian required a longer drying time during HAD than the unripe durian which was due to the high sugar content in the fully ripe durian. Increasing air temperature from 40°C to 80 °C could speed up the drying process. Thus, moisture diffusivity increased with increased air temperature (Table 4.2). However, HAD still required relatively longer time than MVD because the decrease in pressure in the dryer chamber and deep heat penetration during MVD enhanced moisture migration from the inner layer to the surface. Similarly, increasing microwave power from 1200 W to 2200 W could increase moisture diffusivity of both unripe and fully ripe durian. Therefore, drying time required for HAD40, HAD60 and HAD80 was 10.5 h, 7 h and 5 h, respectively. The MVD required only 7 min, 9 min and 12 min for MVD2200, MVD1600 and MVD1200, respectively.

Table 4.2: Moisture diffusivity during HAD and MVD

<table>
<thead>
<tr>
<th>Drying Condition</th>
<th>Unripe durian ($D_{eff} \times 10^{-7}$)</th>
<th>Fully ripe durian ($D_{eff} \times 10^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAD40</td>
<td>0.0729 ± 0.01</td>
<td>0.0182 ± 0.00</td>
</tr>
<tr>
<td>HAD60</td>
<td>0.1412 ± 0.01</td>
<td>0.0607 ± 0.05</td>
</tr>
<tr>
<td>HAD80</td>
<td>0.2187 ± 0.01</td>
<td>0.1000 ± 0.01</td>
</tr>
<tr>
<td>MVD1200</td>
<td>2.9339 ± 0.45</td>
<td>2.6909 ± 0.13</td>
</tr>
<tr>
<td>MVD1600</td>
<td>4.2460 ± 0.27</td>
<td>3.3803 ± 0.03</td>
</tr>
<tr>
<td>MVD2200</td>
<td>5.5991 ± 0.25</td>
<td>4.1913 ± 0.24</td>
</tr>
</tbody>
</table>

4.5 DURIAN FLOUR QUALITY

Upon drying and grinding, durian flour was produced with approximately 28% yield. From proximate analysis, the major component of durian flour was carbohydrate (63 - 71%) and its content decreased with increased in ripening. In contrast, the ash content (referred to as the mineral content) of the fully ripe durian was more than the unripe durian due to migration of inorganic ions from other parts of the plant to the fruit during ripening. Additionally, during respiration of climacteric fruits, 20% of the carbohydrate was used while the remainder was converted into sugar. As a result, starch content of the unripe durian was 40.08 – 40.42% while that of the fully ripe durian was 9.44 – 11.76%. The majority of durian starch was amylopectin (99%) (Bai-Ngew et al., 2014). Moreover, drying condition did not affect starch content in durian flour.
Due to the low starch content of fully ripe durian flour, water absorption capacity might be low. Thus, free water was available to facilitate the movement of particles. As a result, its peak viscosity was low (0.98 – 7.60 RVU) and varied depending on drying condition. An increase in air temperature from 40°C to 80°C reduced the peak viscosity from 2.42 to 0.98 RVU. Likewise, an increase in microwave power from 1200 W to 2200 W reduced the peak viscosity from 7.60 to 2.65 RVU. This was due to thermal degradation of amylose and amylopectin granules during heating. The effect of MVD and HAD on the trough and breakdown was the same as that on the peak viscosity. Similarly, for unripe durian flour, the increased air temperature in HAD and the increased microwave power could reduce the pasting properties. Due to the lowest temperature and the least thermal degradation effect, HAD40 had the highest peak viscosity (Figure 4.4).

**Figure 4.4:** Pasting profiles of durian flour from HAD (A) and MVD (B)

Source: modified from Bai-Ngew et al. (2014; 2015a; 2015b).
From the X-ray diffraction pattern, both HAD and MVD produced unripe durian flour with a type A crystalline containing peaks at 15.08°, 17.08°, 17.99° and 22.8° at 2θ (an angle where the beam is deflected) in the X-ray diffraction pattern. The degree of crystallinity calculated from the ratio of diffraction peak area and total diffraction area was 2.31 – 21.95% and 4.05 – 7.02% for durian flour produced from HAD and MVD, respectively (Bai-Ngew et al., 2015a). Compared with wheat flour and banana flour, the obtained durian flour had lower crystallinity because the crystalline size, the average chain length of amylopectin and the percentage of the short chain fractions of amylopectin of the durian flour differed from those flours (Gunaratne and Hoover, 2002). The degree of crystallinity of HAD flour reduced from 21.95% to 2.31% when air temperature was increased from 40°C to 80°C. This indicated disorganization of crystalline structure into amorphous structure under high drying temperature. In the case of MVD, the crystalline peak was smaller than that of HAD40 and HAD60 because of fast heating rate of MVD. However, the degree of crystallinity of HAD80 was not significantly different from that of MVD (P>0.05). For fully ripe durian, the X-ray diffraction pattern showed peaks at 8.33, 11.66, 12.74, 13.14, 15.50, 18.84, 19.61, 20.38, 20.84, 22.05, 23.54, 24.77 and 25.20 for 2θ. These peaks reflected sucrose and indicated the conversion of starch into sucrose during ripening stage. Both drying methods did not affect the degree of crystallinity of sucrose.

From SEM, starch granule of durian flour had angular and pentagonal shapes, varied in size (1 - 5 μm) and were clumped together (Figure 4.5). For the fully ripe durian, starch granule was not observed because starch was converted to sugar during the ripening stage. Therefore, a cake-like formation appeared indicating the interaction between the sugar and water vapour from the atmosphere. The water molecules could form liquid bridges between sugars to make them more cohesive. For the unripe durian, starch granule morphology of the MVD and HAD durian flour was slightly different. The starch granule of the HAD flour was smooth, whereas that of the MVD flour was broken and opened.

For unripe durian flour, HAD durian flour yielded higher redness (a*-value) than the MVD flour due to Maillard reaction that was enhanced by exposure to oxygen for a long drying time under high temperature. In contrast, MVD that used a shorter time under vacuum condition could maintain the natural colour of durian. For the fully ripe durian, yellowness (b*-value) of the flour was higher than the unripe durian flour (Figure 4.6). The flour with high lightness (L*-value) could be achieved by either MVD or HAD at 40°C. The increased microwave power from 1200 W to 2200 W did not reduce lightness or increased redness of the flour. Unlike, the increased air temperature from 40°C to 80°C reduced lightness and increased redness (Figure 4.7). Therefore, HAD flour was darker than MVD flour, particularly at high air temperature.
**Figure 4.5**: SEM of starch granules (5000x) in the durian flour from unripe durian (A) and fully ripe durian (B).

**Figure 4.6**: Durian flour: unripe durian flour (A) and fully ripe durian (B).
From E-nose analysis, both HAD and MVD decreased all sensor responses. Both fresh unripe and fully ripe durian had E-nose profiles related to ester, sulphur, alcohol and ketone compounds. However, intensity of the fully ripe durian odour was relatively higher than that of the unripe durian. After drying, the unripe durian flour from HAD60 had odour intensity closed to the fresh durian odour. An increase in air temperature to 80°C decreased the odour intensity. By changing drying method to MVD at 1200 W, odour intensity was higher than HAD. However, increasing the microwave power to 2200 W reduced the odour intensity. For the fully ripe durian containing high sugar content, high microwave power at 2200 W would yield high odour intensity with the similar odour pattern to HAD at 60°C (Bai-Ngew et al., 2013).

**Figure 4.7:** Color of durian flour from unripe durian (A) and fully ripe durian (B). Source: modified from Bai-Ngew et al. (2015a; 2015b).
4.6 CONCLUSION

Durian at two ripening stages, unripe and fully ripe, was dried by both HAD and MVD methods. Variation in the ripening stages caused variation in flour composition particularly starch. As the degree of ripening increased, crystalline structure changed from starch into sugar. Therefore, after drying, the fully ripe durian flour was darker than the unripe durian flour due to Maillard reaction. Although enhanced moisture diffusivity was observed in HAD, but the high temperature and long drying time would produce darker durian flour. To obtain light flour colour, MVD should be used regardless of microwave power. In addition, the high microwave power at 2200 W would yield high intensity durian odour. Therefore, with high sugar content, low viscosity and intense odour, the fully ripe durian flour from MVD should be used for making sweet and low-viscosity durian products.

For the unripe durian containing high starch content (mainly amylopectin), the increase in microwave power during MVD could increase moisture diffusivity and reduce drying time without any effect on the crystalline pattern, but crystallinity of starch and durian odour intensity were observed reduced. Compared with the unripe durian flour from HAD, the one from MVD had higher pasting properties possibly indicating re-association of amylopectin. Therefore, the unripe durian flour from MVD could slow down the staling mechanism in bakery products.

4.7 ACKNOWLEDGEMENT

Financial support from Thailand Research Fund (Royal Golden Jubilee Ph.D. programme) and Kasetsart University is gratefully acknowledged.

4.8 NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{eff}$</td>
<td>Moisture diffusivity ($m^2s^{-1}$)</td>
</tr>
<tr>
<td>HAD</td>
<td>Hot air drying</td>
</tr>
<tr>
<td>HAD40</td>
<td>Hot air drying at 40 °C</td>
</tr>
<tr>
<td>HAD60</td>
<td>Hot air drying at 60 °C</td>
</tr>
<tr>
<td>HAD80</td>
<td>Hot air drying at 80 °C</td>
</tr>
<tr>
<td>MVD</td>
<td>Microwave vacuum drying</td>
</tr>
<tr>
<td>MVD1200</td>
<td>Microwave vacuum drying at 1200 W</td>
</tr>
<tr>
<td>MVD1600</td>
<td>Microwave vacuum drying at 1600 W</td>
</tr>
<tr>
<td>MVD2200</td>
<td>Microwave vacuum drying at 2200 W</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>L*</td>
<td>Lightness value (light-dark)</td>
</tr>
<tr>
<td>a*</td>
<td>Color shade (positive value means redness, negative value means greenness)</td>
</tr>
<tr>
<td>b*</td>
<td>Color shade (positive value means yellowness, negative value means blueness)</td>
</tr>
</tbody>
</table>
REFERENCES


Chapter 5

Drying and Dehydration of Pitaya Fruits (Hylocereus spp.)


Contents

5.1 Introduction 77
5.2 Drying and Dehydration Methods 79
5.3 Drying Kinetics 92
5.4 Conclusion 96
5.5 Acknowledgement 97
5.6 Nomenclature 97

References 97
5.1 INTRODUCTION

Pitaya fruit, also known as dragon fruit, is a non-seasoning fruit native to Mexico, Central and South America, but currently cultivated at commercial scale in many Southeast Asian countries such as Malaysia, Vietnam, Thailand, and Cambodia. It has been identified by the Federal Agricultural Marketing Authority (FAMA), under Ministry of Agriculture and Agro-based Industry, Malaysia (MOA) as one of the new export earners to meet the global growing demand of pitaya fruit. This is due to its fast gaining popularity worldwide with an estimated market worth of over USD 10 billion every year (Adnan, 2010). Pitaya grows well under dry, tropical, and subtropical region. In Malaysia, Israel, and Taiwan, about 16,000 – 27,000 kg/ha of pitaya fruits have been produced by commercial pitaya plantation area (Peter, 2008). In Malaysia, about 927.4 ha of plantation area have been used for pitaya which is estimated to produce about 2534.2 t of pitaya fruits (Cheah and Zulkarnain, 2008). Worldwide, the average annual production of pitaya fruit is generally 4 to 20 t fresh mass/ha (Janick and Paull, 2008).

Pitaya fruit is ovoid in shape and has a leathery peel with unique layers that looks like scales or bracts. Its pulp colour can vary from white to red or even purple depending on the species and variety. Scattered within its pulp are numerous tiny black seeds that resemble black sesame seeds. The three common species of pitaya include *Hylocereus undatus* (red-skinned fruit with white flesh), *Hylocereus costaricensis* or also known as *Hylocereus polyrhizus* (red-skinned fruit with red flesh) and *Hylocereus megalanthus* (yellow-skinned fruit with white flesh).

Figure 5.1: Common species of pitaya (left: H. undatus, right: H. polyrhizus)

Pitaya fruit being a highly delicate and perishable fruit has a moisture content up to 91.19 % and 85.05 % for peel and flesh, respectively (Chia and Chong, 2015a; Ramli and Rahmat, 2014). Drying is one of the oldest food preservation techniques that dehydrate perishable food by removing free and bound water to a safe level, preventing growth and reproduction of food spoilage microorganisms. Drying also retards moisture-mediated chemical reactions such as enzymatic activity that can deteriorate food (Mujumdar, 2014). However, application of inappropriate drying conditions, either inadequate or excessive drying, may cause undesirable changes in dried and
dehydrated food. These changes involve both external and internal quality attributes. External quality attributes are related to appearance (size, shape, colour, gloss, and consistency), texture and flavour characteristics, while internal quality attributes are related to physical, bioactive chemical, physicochemical and microbiological characteristics. Notwithstanding, with the various drying methods available, the understanding of the target fruit properties to be dried is of utmost importance prior to selection of drying methods to allow efficient and effective drying and to ensure good product quality.

Generally, pitaya fruit is processed into juices, cordials, jams apart from being consumed fresh. The processing of pitaya into these various products has created a large amount of waste i.e. fruit peels as it contributed approximately 22% of whole fruit weight (Bakar, et al., 2011). Pitaya seed is also discarded in wine making and juice processing. Since fruit waste is one of the main sources of municipal waste, there is now a trend towards research and exploration of the hidden quality of these wastes particularly the fruit peels and seeds, aiming to benefit from waste minimization and conversion. It had been found that pitaya whole fruit (including peel and seed) has the potential as source of micronutrients and antioxidants (Ariffin et al., 2009; Lim et al., 2010; Lim et al., 2007; Mahattanatawee et al., 2006; Ruzainah Ali et al., 2009; Wu et al., 2006). The summary of bioactive compounds’ distribution in pitaya fruit, polyphenol composition and antioxidant activity of *H. polyrhizus* extract fractions are as shown in Table 5.1 and Table 5.2, respectively.

**Table 5.1:** Summary of bioactive compounds’ distribution in pitaya fruit

<table>
<thead>
<tr>
<th>Parts of pitaya fruit</th>
<th>Bioactive compounds</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peel</td>
<td>Betacyanin</td>
<td>(Esquivel et al., 2007; Wu et al., 2006)</td>
</tr>
<tr>
<td></td>
<td>Fiber (good insoluble to soluble ratio)</td>
<td>(Bakar et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>Pectin</td>
<td>(Bakar et al., 2011)</td>
</tr>
<tr>
<td></td>
<td>Vitamin C</td>
<td>(Wu et al., 2006)</td>
</tr>
<tr>
<td>Flesh</td>
<td>Betalains (betacyanin, betaxanthins)</td>
<td>(Wybraniec and Mizrahi, 2002; Wybraniec et al., 2001)</td>
</tr>
<tr>
<td></td>
<td>Beta-carotene</td>
<td>(Charoensiri et al., 2009)</td>
</tr>
<tr>
<td></td>
<td>Lycopene</td>
<td>(Charoensiri et al., 2009)</td>
</tr>
<tr>
<td></td>
<td>Oligosaccharides</td>
<td>(Wichienchot et al., 2010)</td>
</tr>
<tr>
<td></td>
<td>Vitamin C</td>
<td>(Wu et al., 2006)</td>
</tr>
<tr>
<td></td>
<td>Vitamin E</td>
<td>(Charoensiri et al., 2009)</td>
</tr>
<tr>
<td>Seed</td>
<td>Essential fatty acids (C18:2, C18:3)</td>
<td>(Ariffin et al., 2009)</td>
</tr>
</tbody>
</table>
Table 5.2: Polyphenol composition and antioxidant activity of *H. polyrhizus* extract fractions. Adapted from (Tenore et al., 2012)

<table>
<thead>
<tr>
<th>Polyphenol composition and antioxidant activity</th>
<th>Peel</th>
<th>Flesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total phenolic content fractions (mg/100g fw)</td>
<td>Betacyanins: 654.6 (about 10 times more than flesh)</td>
<td>78.1</td>
</tr>
<tr>
<td></td>
<td>Flavonoids: 96.5 (comparable to flesh)</td>
<td>70.8</td>
</tr>
<tr>
<td></td>
<td>Phenolic acids: 2.0 (comparable to flesh)</td>
<td>1.3</td>
</tr>
<tr>
<td>DPPH radical scavenging activity (µmol TE/100g fw)</td>
<td>Betacyanins: 805.1 (comparable to flesh)</td>
<td>999.8</td>
</tr>
<tr>
<td></td>
<td>Flavonoids: 25.6</td>
<td>39.7</td>
</tr>
<tr>
<td></td>
<td>Phenolic acids: 1.0</td>
<td>12.8</td>
</tr>
<tr>
<td>Ferric reducing antioxidant power (FRAP) (µmol TE/100g fw)</td>
<td>Betacyanins: 478.0 (comparable to flesh)</td>
<td>436.7</td>
</tr>
<tr>
<td></td>
<td>Flavonoids: 109.6</td>
<td>56.7</td>
</tr>
<tr>
<td></td>
<td>Phenolic acids: 2.1</td>
<td>23.7</td>
</tr>
</tbody>
</table>

In spite of the abundancy of bioactive compounds from whole pitaya fruit, the ideal consumption of whole pitaya fruit (including peel which holds some vital bioactive compounds like fibre) may not be practical due to the unacceptable bitter bulky peel as well as food safety issues due to the waxy peel and insecticides that may still reside deeply in the peel. With increasing demand of high-quality convenient food and functional food in the market driven by global increase in health awareness, food abounded with nutrients and bioactive compounds would be more attractive. Therefore uncomplicated approach to fruit (including peel) processing achieved by cost effective drying into various forms of ingredient and products might be more appealing to both food industry and consumers.

Therefore, this chapter will serve as a review on various drying and dehydration methods that have been applied to pitaya fruit, the underlying principles of each drying and dehydration method as well as their effects on product quality of dried pitaya.

5.2 DRYING AND DEHYDRATION METHODS

Various drying methods have been applied to dry fruits into different forms ranging from chips, cubes, bars to even powders. Generally, the selection of drying methods is firstly based on the initial fruit physical form (liquid suspension, paste, solid chunks) as some dryers can only handle certain physical form of fruits. Secondly, the thermal stability of fruits to be dried assists further in deciding the suitable operating conditions. The drying and dehydration methods that have been applied on pitaya fruit are as follow:

(a) Oven drying / hot air drying

This is the simplest and most economical type of drying method in which the heated air is brought into contact with the fruits. Convection involved mainly simultaneous heat and mass transfer in this method. Drying time up to days is often required till equilibrium moisture content. In a study conducted by Yusof...
et al. (2012), it was found that drying at 70°C inside an oven for 48 hours, semi-circular red pitaya slices finally became crisp and turned into powder after being blended. The mean particle size of powder particle was 184.01 µm with medium flowability and moisture content of 5.77 %.

(b) Vacuum drying

In this method, a reduced pressure environment is generated within drying chamber by a vacuum pump. This helps to lower boiling point of fluids close to room temperature which allows thermolabile substance to be dried at lower temperature. Heating occurs through direct contact of fruit with the heated shelf surface that holds the fruit. The lowest starting temperature operated in chamber can be from 5 - 15°C above room temperature. The characteristics of low drying temperature and oxygen deficient environment help to maintain quality and nutritive value of dried products upon drying. In a study conducted by Nordin et al. (2014) on drying of red pitaya, the studies coupled vacuum drying with microwave to enhance thermal efficiency. Less than 4 hours of drying of red pitaya into similar final moisture content (10%) was observed when microwave-vacuum drying was used as compared to microwave-hot air drying. The microwave-vacuum dried pitaya showed the least total color changes and higher retention of ascorbic acid compared to microwave-hot air dried pitaya.

(c) Spray drying

Spray drying involves atomization of liquid into fine mist followed by contact with the hot air, moisture evaporation and subsequent separation of dried powdered product in a cyclone separator. This method had been suggested as one the best methods for antioxidant preservation in red pitaya although the temperature applied in this method was high (180 - 185°C) compared to oven cooking at 95°C (30 and 60 minutes) and 105°C (60 minutes) (Omidizadeh et al., 2011). This could be due to the shorter drying time involved in spray drying. It was suggested that the length of exposure time of red pitaya to a certain temperature is more damaging to the bioactive compounds and its activity than shorter exposure time to high heating temperature (Omidizadeh et al., 2011). Due to the high concentration of low molecular weight sugars and organic acids which contribute to low glass transition temperature (Tg) in natural fruit juices, often high molecular weight carrier such as maltodextrin is required to be added to juices to increase Tg of the mixture solution in order to reduce stickiness that improves end product flowability, thus minimizes occurrence of sample adhering to the chamber wall which also improves powder yield.
(d) Drum drying

In this method, liquid suspension to be dried is applied as thin layer (0.5 – 2 mm) onto steam-heated surface (up to 200°C) of revolving drums/hollow cylinders which are made of high grade cast iron or stainless steel. The dried material on the surface of revolving drums will then be removed by a static scraper. This drying method is suitable for drying ground pitaya peel whereby no special formulation of peel slurry was needed due to the highly viscous and mucilaginous peel slurry caused by pectin exposure after mechanical peel grinding (Chia and Chong, 2015a). Although the usual temperature applied in this method is high, the short drying time involved is able to give higher retention of bioactive compounds and their activity (radical scavenging activity, total antioxidant activity) in red pitaya as compared to drying methods which employed lower temperature but longer time (Omidizadeh, et al., 2011). It was suggested by Chia and Chong (2015a) that high temperature during drum drying helped to degrade pectin which facilitated the high recovery of betacyanin since high concentration of pectin might hinder the betacyanin extraction process. This had led to higher yield (2 folds) of betacyanin as compared to fresh peel.
(e) Microwave drying

In this type of drying, heat will be generated within fruit when chemical constituents of fruit such as liquid water or ions interacts with radio frequency energy (915 and 2450 MHz) (Mujumdar, 2014). Advantages of this method include good penetrating and selective heating. Due to selective absorption of radiation by liquid water or ions within fruit, there will be only selective heating of fruit interior without affecting the fruit exterior. Right selection of microwave power input, amount of drying material and drying time, microwave drying could save up to 50 % of energy consumption with good retention of volatile organic compound as compared to conventional drying (Maskan, 2001; Rodríguez et al., 2005). In industrial drying, booster (microwave connection) and dryer are connected to run microwave drying in different mode for
instance, microwave hot air drying, microwave vacuum drying and microwave freeze drying. This combined mode can bring intermittent drying which improves energy efficiency, for instance in microwave hot air drying, the microwave can be automatically switched on when temperature of dried fruit dropped below the pre-set temperature.

**f) Freeze drying**

In this type of drying, initial freezing of fruit is required as drying occurs through sublimation of ice into water vapour. Advantages of this method include minimization of shrinkage, minimization of movement of soluble solids within fruit, porous structure of freeze dried fruit that facilitates fast rehydration and high retention of volatile compounds. However it will incur high cost for commercial application and it is a time consuming process.

![Schematic diagram of freeze dryer.](image)

**Figure 5.5:** Schematic diagram of freeze dryer.

**g) Explosion puffing**

Due to the seedy creamy pulp of pitaya fruit which may have their cell structure collapsed after drying, causing sticky and very soft structure in final dried product, Chong and Law (2010) had suggested drying technique with puffing effect for this type of fruit. In this method, initial partial drying of fruit is required to reduce moisture content up to a level to avoid fruit damage during sudden depressurization in explosion puffing. The puffing effect will create porosity in the dried product where moisture diffusion is easier and hence reduce subsequent drying time in other drying stage. In explosion puffing, a rotating cylindrical pressure chamber will be heated externally where inside the chamber fruit pieces will be exposed to high pressure steam (600-800
kPa). Upon heating, the remaining moisture will be superheated relative to the atmospheric pressure. It is during the sudden depressurization of chamber to atmospheric pressure that causes the moisture within the pieces to flash into steam. The escaping steam causes channels and fissures which gives porous structure to the fruit pieces (Mujumdar, 2014; Zotarelli et al., 2012).

**(h) Osmotic dehydration**

This method involves placing fruit to be dehydrated in a hypertonic solution. Since the hypertonic solution has higher osmotic pressure and lower water activity, there will be a driving force for moisture removal from fruit to solution through a semipermeable membrane (natural cell wall) with a simultaneous uptake of external solute as well. Common osmotic agents are such as salt and sugar solutions. Sucrose is deemed as one of the best osmotic agents especially when osmotic dehydration is to be employed prior to drying (Ayala-Aponte et al., 2014). About 50% reduction in fresh weight of food can be achieved with this method through osmosis. Therefore this method has been used for production of intermediate moisture food or as drying pre-treatment in order to reduce drying time and energy consumption. This method had been applied as pre-treatment for hot air drying of yellow pitaya slices and it was found to lower initial moisture content of slices, therefore reducing the drying time required in hot air dryer compared to those not subject to pre-treatment (Ayala-Aponte et al., 2014). This could be due to internal structure modification of pitaya slices that affect the mass transport mechanism, therefore improving moisture diffusion out of the slices (Chiralt and Fito, 2003).
Table 5.3: Summary of drying and dehydration methods applied on pitaya fruit.

<table>
<thead>
<tr>
<th>Drying methods</th>
<th>Part</th>
<th>Initial pitaya physical form</th>
<th>Pre-treatment</th>
<th>Drying parameters studied</th>
<th>Dehydrated form</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air drying</td>
<td>Peel</td>
<td>Solid</td>
<td>Peels were either blanched or not blanched</td>
<td>Temperature (60 - 80°C)</td>
<td>Powder</td>
<td>(Sengkhamparn et al., 2013)</td>
</tr>
<tr>
<td>Hot air drying</td>
<td>Flesh</td>
<td>Solid</td>
<td>Flesh was either osmotic dehydrated in 55 % sucrose or not treated</td>
<td>Drying temperature (50 - 70°C)</td>
<td>Dried slices</td>
<td>(Ayala-Aponte et al., 2014)</td>
</tr>
<tr>
<td>Hot air drying, Microwave - hot air drying, Microwave - vacuum drying</td>
<td>Flesh</td>
<td>Solid</td>
<td>-</td>
<td>Hot air drying (Temperature 55°C), Microwave-hot air drying (Temperature 55°C, microwave power density 1 W/g), Microwave-vacuum drying (Temperature 50°C, microwave power density 1 W/g)</td>
<td>Dried slices</td>
<td>(Nordin et al., 2014)</td>
</tr>
<tr>
<td>Oven drying</td>
<td>Flesh</td>
<td>Solid</td>
<td>-</td>
<td>Drying temperature 70°C for 48 hours</td>
<td>Powder</td>
<td>(Yusof et al., 2012)</td>
</tr>
<tr>
<td>Drying methods</td>
<td>Part</td>
<td>Initial pitaya physical form</td>
<td>Pre-treatment</td>
<td>Drying parameters studied</td>
<td>Dehydrated form</td>
<td>Reference</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------</td>
<td>------------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------</td>
<td>-----------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>Oven cooking, Drum drying, Spray drying</td>
<td>Flesh</td>
<td>Liquid suspension</td>
<td>Extracted for juice, added with 14% maltodextrin 20 DE before spray drying</td>
<td>Oven cooking (95°C 30 minutes, 95°C 60 minutes, 105°C 60 minutes), Drum drying (125 - 135°C), Spray drying (Inlet air temperature 180 - 185°C, outlet air temperature 90 - 95°C)</td>
<td>Powder</td>
<td>(Omidizadeh et al., 2011)</td>
</tr>
<tr>
<td>Microwave drying</td>
<td>Flesh</td>
<td>Solid</td>
<td>-</td>
<td>Microwave power density 5.47 - 19.02 W/g</td>
<td>Dried slices</td>
<td>(Nordin et al., 2008a)</td>
</tr>
<tr>
<td>Drum drying</td>
<td>Peel</td>
<td>Slurry/Paste</td>
<td>Peel was ground into paste</td>
<td>Rotation drum speed (1 - 3 rpm), Steam pressure (1 - 3 bar)</td>
<td>Flake/powder</td>
<td>(Chia and Chong, 2015b)</td>
</tr>
<tr>
<td>Spray drying</td>
<td>Peel</td>
<td>Liquid suspension</td>
<td>Blending with water, filtered, added 15% maltodextrin 10 DE</td>
<td>Inlet air temperature 165°C, outlet air temperature 80°C</td>
<td>Powder</td>
<td>(Ee et al., 2014)</td>
</tr>
<tr>
<td>Spray drying</td>
<td>Peel</td>
<td>Liquid suspension</td>
<td>Blending with water, filtered, added maltodextrin 10 DE, homogenized, held for an hour for homogeneity</td>
<td>Inlet air temperature (155 - 175°C), outlet air temperature (75 - 85°C), Maltodextrin concentration (8 – 22 % w/w)</td>
<td>Powder</td>
<td>(Bakar et al., 2012)</td>
</tr>
<tr>
<td>Drying methods</td>
<td>Part</td>
<td>Initial pitaya physical form</td>
<td>Pre-treatment</td>
<td>Drying parameters studied</td>
<td>Dehydrated form</td>
<td>Reference</td>
</tr>
<tr>
<td>----------------</td>
<td>------</td>
<td>-----------------------------</td>
<td>---------------</td>
<td>---------------------------</td>
<td>----------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Spray drying</td>
<td>Flesh</td>
<td>Liquid suspension</td>
<td>Extracted for juice, filtered, added with maltodextrin 9 - 12 DE</td>
<td>Inlet air temperature (120 - 180 °C), Maltodextrin concentration (30 - 50% w/v)</td>
<td>Powder</td>
<td>(Lee et al., 2013)</td>
</tr>
<tr>
<td>Spray drying</td>
<td>Flesh</td>
<td>Liquid suspension</td>
<td>Extracted for juice, filtered, mixed with water, added with maltodextrin, suspension was put into 70 °C water bath for 5 minutes.</td>
<td>Inlet air temperature (145 - 175 °C), Maltodextrin concentration (20 - 30% w/w)</td>
<td>Powder</td>
<td>(Tze et al., 2012)</td>
</tr>
<tr>
<td>Spray drying</td>
<td>Flesh</td>
<td>Liquid suspension</td>
<td>Extracted for juice, diluted with water which has dissolved maltodextrin 12 DE, homogenous mixture was filtered</td>
<td>Inlet air temperature (156 - 224 °C), Feed flow rate (16.6 - 33.4 ml/min), Maltodextrin concentration (31.6 - 48.4 %)</td>
<td>Powder</td>
<td>(Yunus et al., 2011)</td>
</tr>
<tr>
<td>Spray drying</td>
<td>Seed oil</td>
<td>Liquid suspension</td>
<td>Oil was extracted by Soxhlet extractor using petroleum ether, oil was added into wall material that was dispersed in water, followed by soy lecithin</td>
<td>Wall material (protein/gum Arabic/saccharides at ratio 1:9)</td>
<td>Powder</td>
<td>(Lim et al., 2011)</td>
</tr>
</tbody>
</table>
Table 5.4: Dried pitaya fruit quality as affected by different drying methods.

<table>
<thead>
<tr>
<th>Drying methods</th>
<th>Water activity</th>
<th>Effective moisture diffusion coefficient</th>
<th>Shrinkage</th>
<th>Rehydration ratio</th>
<th>Ascorbic acid content</th>
<th>Colour changes</th>
<th>Betacyanin content</th>
<th>Total phenolic content</th>
<th>Fibre content</th>
<th>Antioxidant activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air (60, 70, 80°C) (Sengkhamparn, et al., 2013)</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Smaller changes at lower temperature</td>
<td>Higher at lower temperature</td>
<td>n.d.</td>
<td>Higher at lower temperature</td>
<td>Higher DPPH activity at higher temperature</td>
<td></td>
</tr>
<tr>
<td>Drying methods</td>
<td>Water activity</td>
<td>Effective moisture diffusion coefficient</td>
<td>Shrinkage</td>
<td>Rehydration ratio</td>
<td>Ascorbic acid content</td>
<td>Colour changes</td>
<td>Betacyanin content</td>
<td>Total phenolic content</td>
<td>Fibre content</td>
<td>Antioxidant activity</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>----------------</td>
<td>------------------------------------------</td>
<td>-----------</td>
<td>-------------------</td>
<td>-----------------------</td>
<td>------------------------</td>
<td>--------------------</td>
<td>----------------------</td>
<td>---------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Blanched + Hot air (60, 70, 80°C) (Sengkhamparn, et al., 2013)</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>Least for blanched, dried at 80°C and unblanched, dried at 60°C</td>
<td>Blanched, dried at 80°C had comparable amount as unblanched, dried at 60°C</td>
<td>n.d.</td>
<td>Increased</td>
<td>DPPH activity is reduced, highest DPPH activity for unblanched, dried 80°C</td>
</tr>
</tbody>
</table>
Lee et al. - Drying and Dehydration of Pitaya Fruits (*Hylocereus* spp.)

Density 5.47 - 19.02 W/g
(Nordin, et al., 2008b)

Drying methods | Water activity | Effective moisture diffusion coefficient | Shrinkage | Rehydration ratio | Ascorbic acid content | Colour changes | Betacyanin content | Total phenolic content | Fibre content | Antioxidant activity
--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
Oven cooking (95 °C 30 minutes; 95 °C 60 minutes; 105 °C 60 minutes) (Omidizadeh, et al., 2011) | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 60 % retention, comparable among different time temperature set | Total fibre is reduced (lowest reduction in 95 °C 30 minutes) | 30 - 40 % DPPH activity retention; 39 - 47 % FRAP activity retention
Drum drying (125 - 135 °C) (Omidizadeh, et al., 2011) | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 93 % retention | Total fibre is reduced | 94 % DPPH activity retention; 87 % FRAP activity retention
Drum drying (1 rpm with 2 bar steam pressure) | Acceptable low | n.d. | n.d. | n.d. | n.d. | Darkening | 2 folds higher than fresh peel | 98.6 % retention | Crude fibre is reduced | 56.8 % DPPH activity retention
<table>
<thead>
<tr>
<th>Drying methods</th>
<th>Water activity</th>
<th>Effective moisture diffusion coefficient</th>
<th>Shrinkage ratio</th>
<th>Rehydration ratio</th>
<th>Ascorbic acid content</th>
<th>Colour changes</th>
<th>Betacyanin content</th>
<th>Total phenolic content</th>
<th>Fibre content</th>
<th>Antioxidant activity</th>
</tr>
</thead>
</table>

n.d means not determined.
5.3 DRYING KINETICS

5.3.1 Effective diffusion coefficient and activation energy

Estimation of effective diffusion coefficient ($D_{\text{eff}}$) is part of drying kinetics study to identify the extent of mass transport along the fruit slab or cylinder under various drying temperatures. Based on solution of Fick’s second law of diffusion model, Ayala-Aponte, et al. (2014) observed that osmotic dehydrated yellow pitaya slices that subjected to hot air drying had higher effective diffusion coefficient compared to those not osmotic dehydrated. This could be due to alteration of cell wall, splitting of lamella, membrane lysis and tissue shrinkage after osmotic dehydration that improves mass transport during drying.

Figure 5.6: Changes of a plant cell when dehydrated (a) fresh cell; (b) shrunken and plasmolyzed cell; (c) debonded cell / cell with detached middle lamella and (d) ruptured cell and cavity formation.
Activation energy is a measure of dependence of mass transfer process on temperature. The higher the activation energy implies greater temperature sensitivity and smaller change of temperature is required for rapid mass transport. Activation energy can be determined through the Arrhenius-type equation (Equation 1) which can be linearized by plotting $\ln D_{\text{eff}}$ versus $T^{-1}$.

$$D_{\text{eff}} = D_{\infty} \exp \left( \frac{-E_a}{RT} \right)$$  \hspace{1cm} (1)

Where $D_{\infty} =$ pre-exponential factor ($\text{m}^2 \text{s}^{-1}$)
$E_a =$ activation energy ($\text{kJ mol}^{-1}$)
$R =$ universal gas constant ($8.314 \text{ J K}^{-1} \text{ mol}^{-1}$)
$T =$ absolute temperature ($\text{K}$)

Osmotic dehydrated yellow pitaya slice subjected to hot air drying was found to have 1.7 times higher activation energy compared to those not osmotic dehydrated at 29.56 kJ mol$^{-1}$ and 16.94 kJ mol$^{-1}$, respectively (Ayala-Aponte et al., 2014).

### 5.3.2 Experimental drying kinetics of pitaya fruit

Drying kinetics study by Nordin et al. (2014) found that there was significant difference on drying time of red pitaya slices dried using hot air drying, microwave-hot air drying and microwave-vacuum drying. Conventional hot air drying took the longest time (12 hours) in order to reach similar final moisture content. In contrast, it took only half of the time required (6 hours) for slices dried using microwave-hot air dryer and only 2 hours for microwave-vacuum drying. The related drying kinetics is further explained as shown in Table 5.5.

<table>
<thead>
<tr>
<th>Drying methods</th>
<th>Temperature progression of pitaya slices along drying</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air drying</td>
<td>Temperature of pitaya slices increased slowly until constant but still never achieved pre-set drying temperature (55°C) although system had been operated for hours at steady state temperature.</td>
<td>Slow diffusion process at final stage of drying that is often faced by conventional hot air drying.</td>
</tr>
<tr>
<td>Microwave-assisted drying (400 W microwave generator operating at 2450 MHz, same microwave tuner, microwave absorber, and cavity)</td>
<td>Microwave-hot air: Temperature of pitaya slices increased immediately from ambient to pre-set drying temperature 55°C. The pitaya slices temperature even reached higher than the pre-set air inlet temperature. Microwave-vacuum: Temperature of pitaya slices increased immediately from ambient</td>
<td>Absorption of microwave energy during drying to maintain the pitaya slices temperature at pre-set drying temperature. Microwave energy absorbed can be used for selective heating of interior parts of pitaya</td>
</tr>
</tbody>
</table>

Table 5.5: Temperature progression of pitaya slices when drying under different drying methods.
to pre-set drying temperature 50 °C. The pitaya slices temperature even reached higher than the pre-set air inlet temperature.

slices containing moisture, improving moisture loss at final stage of drying process, therefore increasing the drying rate.

Understanding of drying kinetics of pitaya is therefore important to select the suitable drying method which allows optimum drying rate and economics in term of energy and time saving.

5.3.3 Factors affecting drying kinetics

(A) Drying parameters

(i) Temperature

The application of higher temperature in drying will result in higher effective diffusivity of moisture due to higher drying rate. A study conducted by Ayala-Aponte et al. (2014) has reported shorter drying time was required for the yellow pitaya slices when dried at higher temperature (70 °C) in hot air drying. Similar trend was observed for pitaya slices that had been osmotic dehydrated prior to hot air drying. The effective diffusion coefficient of moisture of pitaya had doubled up when dried at higher temperature. However, in a study conducted by (Nordin et al., 2014), lower temperature applied in microwave-vacuum drying of pitaya slices gave a higher drying rate compared to those dried under higher temperature using hot-air drying.

(ii) Microwave power density

Nordin et al. (2008a) has reported that the higher microwave power density applied, the shorter time was needed for drying of pitaya slices. Drying with the administration of the lowest microwave power density (5.47 W/g) completed drying in 5 hours while only 15 minutes were required at the highest microwave power density (19.02 W/g). It was observed that the temperature of microwave ambient cavity varied from 40 - 70 °C when various power densities (5.47 to 19.02 W/g) were applied on pitaya slices. Therefore, the final temperature achieved at surface and interior of treated pitaya slices could vary significantly (surface: 95 - 160 °C and interior: 97 - 220 °C).

(iii) Drying air velocity

High air velocity will result in shorter drying time due to enhanced convective heat and mass transfer. However, no significant improvement in convective drying time for kiwi was observed when air velocity was increased from 0.3 to 0.9 m/s (Kaya et al., 2008). Currently, there is still no study reported on the effect of drying air velocity on drying rate of pitaya fruit in convective drying.

(iv) Combined mode of heat input
This may include combination of infrared, convection, conduction, and microwave for drying. Application of microwave-vacuum drying had found to successfully reduce the drying time of pitaya as high as 83 % compared to single convection mode. Addition of microwave to conventional hot air drying also found to reduce drying time by 50 % compared to those using single convection mode (Nordin et al., 2014).

(B) Non-drying parameters

(i) Inherent fruit factor: maturity

Corzo et al. (2008) reported that maturity of mango affected moisture transport during hot air drying whereby the effective diffusion coefficient was found to be the lower in green mango ($1.74 \times 10^{-10}$ to $3.15 \times 10^{-10} \text{ m}^2 \text{s}^{-1}$) than half-ripe mango slices ($2.30 \times 10^{-10}$ to $3.28 \times 10^{-10} \text{ m}^2 \text{s}^{-1}$). This is possible due to structural differences between unripe and half ripe mango that affects the moisture diffusivity during drying. However, to the best of our knowledge, no studies have been conducted on the effect of maturity of pitaya on the drying kinetics. This could be due to uncommon practice of unripe pitaya consumption among consumers therefore such research may not be practical. In fact, pitaya will be harvested on the 25th to 45th days after flowering (Nerd et al., 1999). Sew et al. (2013) suggested red pitaya fruit harvested on the 25th to 35th day after flowering with optimum maturity stage suggested on the 30th day for use in drying studies.

(ii) Pre-treatments

(a) Non-chemical pre-treatment

This may include blanching, chilling, freezing, and abrasion. Blanching removes the waxy layer, destroys internal cell wall which caused softer fruit texture to improve moisture diffusivity at material surface. The heating applied also causes internal moisture to migrate to the surface in vapour form. Therefore, drying occurred faster for blanched sample during drying (Yong, et al., 2006). Blanching had been applied as pre-treatment for pitaya before hot air drying as reported by Sengkhamparn et al. (2013). Drying time in hot air oven at 60 °C, 70 °C, 80 °C for blanched pitaya peel was found to be shorter (18 hours, 17 hours and 10 hours, respectively) as compared to unblanched pitaya peel (25 hours, 22 hours and 11 hours, respectively). The equilibrium moisture content reached was even lower for blanched pitaya peel. Abrasion also helps to remove the waxy layer which improves moisture diffusivity.

(b) Mechanical pre-treatment

This may include making pinholes or drilling holes in fruit chunks or whole fruit. This is considered a new method of pre-treatment which had been studied on different food commodities i.e. pitaya fruit (Yong, et al., 2006). It was found that by drilling 12 (1 mm diameter) holes onto pitaya fruit slice (surface 25 mm x 25 mm), it improved drying rate by 64 % compared to untreated pitaya fruit slice while the drilling of 24 (2.5 mm diameter) holes
onto pitaya fruit slice of the same surface dimension further improved drying rate up to 3 folds during convective drying inside a heat pump dryer. This was due to the larger exposed surface area in the pitaya fruit for moisture evaporation during drying. With this pre-treatment, the main concern might be the physical appearance of dried fruit but shrinkage would cause the holes unnoticeable after drying. Another concern might be possible contamination of the fruit as the process for making pinholes especially to fruits that are inherently soft and fleshy would drain out excess juices which could attract insects and also grow mold if the juice stains are left untreated. However, this could be avoided by ensuring a controlled and hygienic environment during processing.

5.4 CONCLUSION

Based on the review carried out, suffice it to say that the selection of drying method should be firstly based on the target fruit properties, for instance, the cell structure, part of fruits to be dried (high or low moisture content), sugar content and the bioactive compounds. Inappropriate drying methods and operating conditions may result in unfavorable dried product characteristics such as collapsed cell structure, stickiness, intense browning due to caramelization and substantial nutrient and bioactives degradation. Such undesirable changes in dried fruit should be minimized. Secondly, desired form of final dried fruit product (either chip, cube, bar or powder) decides the type of drying method as certain dryers can only handle certain physical form/shape of fruit. Thirdly, understanding of the drying kinetics is important for process optimization in terms of process economics i.e. cost, drying time and energy.

From the review of various drying methods applied on pitaya fruit, it could be seen that there is a trend towards application of combined drying rather than single drying for improvement of product quality and process economics. The capability of combined drying technology is attributed to efficient drying in falling rate period compared to single drying technology. Rapid surface moisture removal with excessive shrinkage would result in lower moisture transfer especially in conventional convective drying which prolongs the exposure time of fruit in dryer, therefore causing substantial degradation of internal and external quality attributes of dried fruit.

Explosion puffing and puffing drying which have not been applied on pitaya fruit could be an option for conserving cell structure of pitaya which is prone to structural collapse. Combined techniques involving puffing drying could also be considered for pitaya fruit. Puffing drying that utilizes pressurized carbon dioxide (not necessary up to supercritical stage) to puff dry fruits during depressurization process may also suggest usage of supercritical carbon dioxide as drying medium. However, it is believed that the drying kinetics involving supercritical fluid would be different compare to other drying methods.
5.5 ACKNOWLEDGEMENT

Support given by the Faculty of Food Science and Technology, Universiti Putra Malaysia, Serdang, Selangor, Malaysia is highly acknowledged.

5.6 NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABTS</td>
<td>2,2’-azino-bis-3-ethylbenzthiazoline-6-sulphonic acid</td>
</tr>
<tr>
<td>D$_{\text{eff}}$</td>
<td>Effective diffusion coefficient of moisture (m$^2$ s$^{-1}$)</td>
</tr>
<tr>
<td>D$_{\infty}$</td>
<td>Pre-exponential factor of Arrhenius-type equation (m$^2$ s$^{-1}$)</td>
</tr>
<tr>
<td>DE</td>
<td>Dextrose equivalent</td>
</tr>
<tr>
<td>DPPH</td>
<td>1,1-Diphenyl-2-picryl-hydrazyl</td>
</tr>
<tr>
<td>E$_a$</td>
<td>Activation energy (kJ mol$^{-1}$)</td>
</tr>
<tr>
<td>FRAP</td>
<td>Ferric reducing antioxidant power</td>
</tr>
<tr>
<td>fw</td>
<td>Fresh weight (g)</td>
</tr>
<tr>
<td>R</td>
<td>Universal gas constant (J K$^{-1}$ mol$^{-1}$)</td>
</tr>
<tr>
<td>rpm</td>
<td>Revolution per minute (min$^{-1}$)</td>
</tr>
<tr>
<td>T</td>
<td>Absolute temperature in Arrhenius equation (K)</td>
</tr>
<tr>
<td>T$_g$</td>
<td>Glass transition temperature (°C)</td>
</tr>
<tr>
<td>TE</td>
<td>Trolox equivalent</td>
</tr>
</tbody>
</table>

REFERENCES


Lee, K.-H.; Wu, T.-Y.; Siow, L.-F., Spray drying of red (Hylocereus polyrhizus) and white (Hylocereus undatus) dragon fruit juices: physicochemical and antioxidant properties of the powder. *International Journal of Food Science & Technology* 2013, 48 (11), 2391-2399.


Lim, H. K.; Tan, C. P.; Karim, R.; Ariffin, A. A.; Bakar, J., Chemical composition and DSC thermal properties of two species of Hylocereus cacti


Chapter 6

Drying of Ciku (Manilkara zapota) Using Advanced Hybrid Dryers

Chien Hwa Chong, Adam Figiel, Aneta Wojdyło, Chung Lim Law

Contents

6.1 Introduction 105
6.2 Drying Procedures and Quality Evaluation 106
6.3 Drying Kinetics and Product Quality 112
6.4 Conclusions 119
6.5 Nomenclature 119
References 120
6.1 INTRODUCTION

Ciku (Manilkara zapota) is a small fruit with diameter ranging from 4.0 to 10.0 cm. It is ellipsoidal or round in shape with rough and extremely short hairy brown skin encloses a soft, sweet, light brown to reddish-brown pulpy flesh. It is native to Mexico and tropical America and now it is well spread throughout tropical countries such as South East Asia and West India (Mickelbart, 1996). India and Mexico are known as the largest and second largest producers in the world at production capacity of 1,744,300 tons and 20,000 tons, respectively (Indian Horticulture Database, 2014; SAGARPA, 2011). Ciku (local name in Malaysia) is also commonly known as sapodilla (United States), chicku, chiku (India), chicopote, chicozapote (Mexico), dilly (Bahamas), kauki (Southeast Asia), mespel (Virgin Islands), mispu, mispel, mispelboon (Surinam), muyozapot (El Salvador), naseberry (British West Indies), nispero (Puerto Rico), sapodilla plum, sapodille (Dutch West Indies), sapota, sapotilha (Brazil) and sapotille, sapotillier (French West Indies) (Mickelbart, 1996).

Ciku is a well-known nutritious fruit which contains micronutrients and high amount of total polyphenols content (TPC). According to Swaminathan (1979), a typical 100 g of ciku contain 0.70 g, 1.1 g, 2.6 g and 21.4 g of protein, fat, fiber and carbohydrates, respectively. The author also reported that micronutrients such as phosphorous, iron, calcium thiamine, riboflavin and carotene are also found in ciku in small amount at 72 mg, 1.25 mg, 28 mg, 0.02 mg, 0.03 mg and 97 mg, respectively. The TPC are methyl 4-O-galloylchlorogenate, 4-O-galloylchlorogenic acid, methyl chlorogenate, dihydromyricetin, quercitrin, myricitrin, (+)-catechin, (-)-epicatechin, (+)-gallocatechin and gallic acid (Ma et al., 2003; Shui et al., 2004). According to Leong and Shui (2002), the TPC of unripe ciku is about 2000 mg GAE/100g of sample. However, TPC would decrease with natural ripening of fruit (De Brito and Narain, 2002).

Ciku is a highly perishable fruit with a short shelf life. Mohamed et al. (1999) reported that the storage duration is within thirteen days after harvest. Other researchers tried to store ciku at different temperatures and conditions. From Table 6.1, the longest storage duration is 24 days at short-term holding less than 4°C and then store at 20°C. Therefore, the preservation of the fruit into dried product is essential to reduce post-harvest losses and to retain nutritional content.

Hence, studies have been carried out with the aims to dry ciku using conventional and hybrid drying techniques and to investigate its effect on the drying kinetics and product quality. The research questions were how to retain the polyphenol content of ciku and how was the acceptability level of dried ciku by consumer through sensory evaluation studies. Mechanical and rheological tests were carried out to quantify the textural attributes of dried ciku. The hypothesis was that hybrid drying technique was able to retain higher amount of TPC and received higher acceptability from panels compared to other drying techniques.
Table 6.1: Storage duration of ciku at different temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Storage duration (days)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 to 16</td>
<td>7 to 14</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>Broughton and Wong, 1979</td>
</tr>
<tr>
<td>15</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Short-term holding — less than 10 h at 4 °C then storage at 20 °C</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>26.7°C, Gamma irradiation at 0.1</td>
<td>3 to 5</td>
<td>Salunkhe and Desai, 1984</td>
</tr>
<tr>
<td>10°C, Gamma irradiation at 0.1</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

6.2 DRYING PROCEDURES AND QUALITY EVALUATION

6.2.1 Sample preparation

Fresh Ciku (Manilkara zapota) were purchased from local fruit supplier in Semenyih, Selangor, Malaysia (Latitude 20°57' 0N and Longitude 101°50'60'E) (Figure 6.1). The outer skin of ciku was peeled and cut into prism shape of 2.0 cm (W) x 3.0 cm (L) x 0.5 cm (H) by using a stainless steel knife.

Figure 6.1: Fresh ciku and cutting shapes of ciku in prism shape.

6.2.2 Drying techniques

Drying techniques applied in this study were continuous heat pump drying (HP), hybrid heat pump vacuum-microwave drying (HP/VM), hybrid hot air vacuum-microwave drying (H/VM) and hybrid hot air-cold air drying (CTP).
6.2.2.1 Convective air dryer

Convective air dryer (Memmert, DO6836, Germany) with forced air circulation were selected in this study as a pre-drying unit prior combined with heat pump and vacuum microwave dryers. It could continuously adjust the pre-heated fresh air mixture with vent connection using a restrictor flap. It also consisted of a microprocessor auto diagnostic system with fault indicator, one Pt100 sensor class A in four wire circuit, integrated digital timer to off heating to standby mode and a digital LED-display.

6.2.2.2 Heat pump dryer

Figure 6.2 shows the schematic diagram and image of a heat pump dryer. The dryer was a closed system HP dryer with a water bath. Processing air transfered heat to the evaporator and became cold processing air. Then, heat was transferred from compressor to preheat the cold processing air through a water bath. To dehumidify the processing air, a heater was installed to further dehumidify the cold processing air. Thus, processing air that flowed through the drying chamber was low temperature dehumidified air (LTDA).

![Figure 6.2](image)

Figure 6.2: (a) Schematic diagram: 1-drying chamber, 2-heat exchanger, 3-throttling valve, 4-compressor, 5-valve (Chong et al., 2013) and (b) image of a HP dryer.

For heat pump drying, the fruit prisms were placed on a tray with mesh size of 0.5 cm x 0.5 cm in the middle section of the drying chamber. Low temperature dehumidified air (LTDA) flow vertically through the sample during drying. The processing air temperature and relative humidity were 35°C and 20%, respectively. Fruit samples were weighed every 30 minutes for the first hour of drying and every hour thereafter until equilibrium moisture content.

6.2.2.3 Hybrid hot air-cold air (CTP) dryer

A schematic diagram of a CTP dryer (Located at the University of Nottingham Malaysia Campus, Selangor, Malaysia) is as shown in Figure 6.3. A heat
pump was mounted on the dryer and it consisted of a power supply system, a compressor, an electrical heater, an air conditioning unit, two hygrometers (HygroFlex, RS232, USA) and two Hygrolog (Rotronic, DS-U-2, USA) anemometer probes. Hot air and cold air were processing air that exchanged heat from the refrigerant of the heat pump system, which could be channelled alternately to the desired chambers. In addition, an external heater was installed as a temperature control system of the dryer. The duration to swap the hot air and cold was adjustable.

Hybrid hot air and cold air drying technique was applied in drying of heat sensitive product. The features of this drying technique were cold air could be supplied to the samples in the middle or at the beginning of drying. This dryer allowed tempering period to be conducted at temperature as low as 12°C. It could also be classified as an intermittent dryer whereas cold air tempering could be applied at any drying stages i.e. cold air tempering could be sandwiched in between two hot air drying periods.

Details settings of CTP drying of fruits are as shown in Table 6.2. For instance, intermittent drying at 2H-2C-H means hot air (HA) was supplied continuously for the first two hours followed by two hours of cold air (CA) tempering and thereafter hot air (HA) drying until equilibrium moisture content is reached.

<table>
<thead>
<tr>
<th>Drying conditions</th>
<th>1st period</th>
<th>2nd period</th>
<th>3rd period</th>
</tr>
</thead>
<tbody>
<tr>
<td>2H–2C–H</td>
<td>2 hours of hot air drying</td>
<td>2 hours of cold air drying</td>
<td>hot air drying</td>
</tr>
</tbody>
</table>

6.2.2.4 Vacuum-microwave dryer

Figure 6.4 shows the schematic diagram and image of a vacuum-microwave (VM) dryer (Wrocław, Plazmatronika SM-200, Poland). It is connected to a vacuum system, which consisted of a vacuum pump (Tepro, Koszalin BL 30P, Poland), vacuum gauge (Elvac, Bobolice MP 211, Poland) and compensation reservoir with volume of 0.15 m³. The pressure in the container can be varied from 4.0 to 6.0 kPa and rotation speed of the container was 6 rpm. An electric fan was installed at the bottom of the dryer which generated air temperature and velocity of 22°C and 1.0 m/s, respectively. The rotation of container and air stream were necessary to avoid local over-heating at sample during drying.

For HP/VM drying, the processing air temperature and relative humidity of the heat pump dryer (Located at The University of Nottingham Malaysia Campus, Selangor, Malaysia) were 35°C and 20%, respectively. The fruit samples were placed on a perforated tray and weighed at 30 min intervals for first hour of drying until equilibrium moisture content. Then, the samples were further dried by using a vacuum-microwave dryer at 120 W.
For H/VM drying, the fruit samples were dried initially in a convective dryer (Memmert, DO6836, Germany) at 70°C to equilibrium moisture content (approximate eight hours). The fruit samples were placed on a perforated tray separately. The direction of the air flux was perpendicular to the oven door and weight loss of the samples were recorded using an electronic balance (Adventure OHAUS, AR3130, USA) with weighing range of 0–310 g and...
system error of ± 0.001g at interval of 30 min for the first 60 min of drying. The velocity of the air approaching to the sample was 0.965 m/s. Then, the samples were further dried by using a vacuum-microwave dryer.

6.2.3 Quality attributes

Sensory evaluation is extremely important to assess the quality of dried fruits for attributes such as flavour, colour, hardness, crispiness and taste. The intensity and consumer acceptance of the attributes as mentioned above are covered as well. To determine the flavour and taste of fruit dried using different drying techniques, the samples were held close to the nose, then, it was put on the tongue, rolled around the mouth and chewed slightly. The volatile compounds that are sensed in the nose (flavour) and non-volatile compounds that are sensed on the tongue (taste) along with compounds and structures that are perceived in the mouth as mouth feel. Both sensory tests enable panels to smell and taste the aroma/flavour released in the mouth, thereafter estimate it through hedonic scale. In terms of colour, the appearance was determined by using hedonic scale based on the darkness level of the samples. In addition, hardness and crispiness were determined through hedonic scale by chewing the dried samples in the mouth. The range of scale for intensity evaluation was from 0 to 10 (0 = the lowest, 10 = the highest) while the range for acceptance of a particular attribute was from 0 to 5 (0 = the best, 5 = the worst).

Compression test was carried out on the ciku samples using a texture analyzer (TA.XT Plus, Stable Micro System, UK). The pre-test, test and post-test speeds were 1.0, 5.0 and 5.0 mm/s, respectively. A cylindrical probe with diameter of 75 mm was positioned 10 mm above the surface of the sample. During the analysis, the probe was compressed on the samples at a depth of 50% of its original thickness. The Texture Profile Analysis (TPA) for ciku samples was performed by using a 2.0 mm diameter probe. Two-compression cycles were used in this texture analysis. The first maximum force enabled determination of hardness, while the second maximum force was applied at the same position to determine the springiness and cohesiveness values.

In stress relaxation test, ciku samples were compressed by using a strength testing machine (Instron 4455, High Wycombe, UK), equipped with a 2.0 mm diameter probe. The compression was stopped when the load corresponded to 50% of breaking stress which was determined earlier as the ratio of breaking force to the cross-section surface area of cylindrical probe. As soon as the compression stopped, the decrease in stress under constant strain was observed for 90 seconds (constant time). The stress relaxation function was fit to the experimental points obtained (equation 1). The parameters of this function enabled determination of the Generalized Maxwell Model parameters such as modulus of elasticity, $E_i$ (equation 2) and final modulus of elasticity, $E_o$ (equation 3) as well as viscosity coefficients $\eta_i$ (equation 4). Constant strain $\varepsilon$ was calculated using the equation 5. Stress relaxation tests were performed at 10 replicates.
\[ \sigma(t) = \sum_{i=1}^{n} \sigma_i \cdot e^{-\frac{t}{T_i}} + \sigma_0 \]  

(1)

\[ E_i = \frac{\sigma_i}{\varepsilon} \]  

(2)

\[ E_0 = \frac{\sigma_0}{\varepsilon} \]  

(3)

\[ \eta_i = E_i \cdot T_i \]  

(4)

\[ \varepsilon = \frac{\Delta h}{h_0} \]  

(5)

where \( t \) is time (sec); \( \varepsilon \) is strain (mm×mm\(^{-1}\)); \( T \) is time constant (sec); \( i \) is number of exponential terms (-); \( \Delta h \) is deformation at breaking point (mm); \( h_0 \) is initial height of individual sample (mm).

Total polyphenol content (TPC) was determined using the Folin-Ciocalteu colorimetric method as described by Gao et al. (2000). Dried fruits (1.0 g) were ground and weighted before placing it in a test tube. A total of 10 ml of 80% aqueous methanol was added to the samples and stirred well. Then, the samples were sonicated for 15 minutes in an ultrasonic bath (BAS-10, Poland) and left for 24 hour at temperature of 4°C in a refrigerator (Bosh, Germany). Upon first sonication, the samples were further sonicated for another 15 minutes. Thereafter, the samples were centrifuged for 10 minute (15000 rpm) to collect the supernatants. The extract (100 mL) was mixed with 0.2 ml of Folin-Ciocalteu reagent and 2.0 ml of H\(_2\)O. Then, the mixture was incubated at room temperature for 3 minutes and 1.0 ml of 20% sodium carbonate was added to the mixture. Total polyphenol content (TPC) was determined after one hour of incubation at room temperature. The absorbance of the resulting blue colour was measured at 765 nm using an UV-VIS spectrophotometer (Shimadzu UV-2501PC, Japan). Quantification was done with respect to the standard curve of Gallic acid and the results were expressed as gallic acid equivalents (GAE), milligrams per 100g of dry mass. All determinations were performed in triplicates.

Results obtained from experiments were statistically evaluated using Statistica v.8 software (StatSoft, Inc. East 14th Street, Tulsa, OK 74104, USA) One-way analysis of variance was carried out and homogeneous groups were determined with Duncan’s multiple range test at significance level \( \alpha = 0.05 \).
6.3 DRYING KINETICS AND PRODUCT QUALITY

6.3.1 Drying kinetics

Drying kinetics of ciku dried using H/VM, CTP, HP/VM and HP drying were carried out to identify the critical moisture content that distinguished different drying period and total drying time. All the drying kinetics are as shown in Figure 6.5. HP drying characteristics of ciku exhibited one constant rate period and followed by two falling rate periods. The constant rate period only occurred at the first 30 minutes of drying with rate at 0.105 g H₂O/ (g DM · m² · s). The drying rate of HP dried ciku decreased with decreasing moisture content mainly due to the low relative humidity environment. According to Pal et al. (2008), relative humidity is an important driving force during initial stage of drying because of high vapour pressure between the surface and the surrounding. In addition, high air velocity also increased drying rate of HP dried sample by removing the surface moisture. At later stage of HP drying, temperature acted as the main driving force for moisture diffusion because of the harder fruit surface and cell structure.

For ciku dried using H/VM drying, an obvious inflection point can be clearly seen during vacuum-microwave drying period. The greater increment of drying rate during vacuum-microwave drying was due to the rapid removal of water from the inner vicinity by microwave energy (Wojdyło et al., 2009). During vacuum-microwave final drying, microwave energy was absorbed by moisture located in the internal part of ciku. This created a relatively large vapour pressure in the middle of the material, allowing rapid transfer of moisture to the surrounding and preventing structural collapse. This process is known as microwave puffing phenomenon which creates a porous texture of the food (Sham et al., 2001).

The puffing phenomenon is also applicable to HP dried ciku using vacuum-microwave final drying. The drying rate of ciku increased significantly to 1.4 g H₂O/ (g DM · m² · s) from 0.09 g H₂O/ (g DM · m² · s) at moisture content of 0.029 g H₂O/ g DM due to the puffing effect. The application of vacuum-microwave drying could reduce drying time to achieve lower moisture content and deactivate polyphenol oxidase (PPO) activity of fruit.

For ciku dried using CTP drying, a sudden decreased in drying rate occurred mainly due to cold air tempering. The drying rates dropped significantly from 0.10 to 0.05 g H₂O/ (g DM · m² · s). However, this tempering period is useful in increasing the drying rates of samples at lower moisture content and keeping the product surface wet. By resuming of hot air drying, this increased the drying rate to 0.1 g H₂O/ (g DM · s) at moisture content of 2.8 g H₂O/ g DM.

The drying kinetics of ciku dried using HP drying technique exhibited initial transient, first falling rate and second falling rate periods because the samples were dried at constant temperature and relative humidity. The drying kinetics of ciku dried using different drying temperature and relative humidity exhibited multiple distinctive drying rate periods; for instance, CTP drying exhibited falling rate, increasing rate and falling rate periods. The occurrence of
increasing rate period was due hot air drying that was resumed after cold air tempering. In addition, the application of different modes of heat input created an obvious increasing rate period. The drying kinetics of ciku dried using H/VM exhibited initial transient, first falling rate, increasing rate and second falling rate periods. An obvious increasing rate period could be observed from drying kinetics of ciku dried using HP/VM drying. The drying kinetics of ciku dried using HP/VM drying exhibited initial transient, first falling rate, second falling rate and increasing rate periods.

![Figure 6.5](image1.png)

**Figure 6.5:** Drying rate versus moisture content for ciku dried using H/VM, CTP, HP and HP/VM drying techniques.

![Figure 6.6](image2.png)

**Figure 6.6:** Moisture ratio of ciku dried using H/VM, CTP, HP and HP/VM drying techniques.

Overall drying time to produce dried ciku using H/VM drying technique was around 500 minutes, about 38% shorter than the other drying techniques (Figure 6.6). However, short drying duration could not produce dried fruit with
the desired specifications. Drying duration of HP/VM was much longer (about 800 minutes) and this could improve the quality of dried fruits.

6.3.2 Product quality

6.3.2.1 Effects of different drying techniques on textural attributes of ciku

Hybrid drying techniques were used to overcome issues related to biochemical compounds, textural attributes (mechanical and rheology properties), physical appearances and colour of dried ciku. These can be assessed using texture profile analysis (hardness, springiness, cohesiveness and chewiness), stress relaxation stress (modulus of elasticity and viscosity coefficient), physical appearance, colour and TPC.

The change in physical structure of ciku is dependent on the enzyme and cellular structure of the ciku. Table 6.3 shows the hardness values of ciku dried using continuous HP, H/VM, HP/VM and CTP drying. The changes of physical structure during vacuum-microwave drying increased the hardness of some selected fruits. However, this was not applicable to HP/VM drying of ciku. The hardness values of HP/VM dried ciku was 4800 g. This revealed that the application of low temperature dehumidified air at the initial stage of drying and short vacuum-microwave drying did not significantly damage or change the cell structure of ciku.

Table 6.3: Hardness, Cohesiveness, Springiness of ciku dried using CTP, HP, H/VM, HP/VM drying.

<table>
<thead>
<tr>
<th>Drying methods</th>
<th>Hardness</th>
<th>Cohesiveness</th>
<th>Springiness</th>
<th>Chewiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTP</td>
<td>1208 ± 61&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.34 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.88 ± 0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>360 ± 23&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>HP</td>
<td>972 ± 45&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.36 ± 0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.92 ± 0.08&lt;sup&gt;a&lt;/sup&gt;</td>
<td>320 ± 35&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>H/VM</td>
<td>29961 ± 2707&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.57 ± 0.05&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.95 ± 0.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>15637 ± 1076&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>HP/VM</td>
<td>4800 ± 442&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.23 ± 0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.75 ± 0.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>797 ± 125&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>The value indicates mean ± standard error of six measurements. Values within the same column with similar letters are not significantly different.

Springiness is significantly affected by the combined processes than one stage drying process. Springiness values were not significantly different (<i>p</i>&gt;0.05) for dried ciku. Springiness values of ciku were observed affected by different cell wall structure or pectin content. According to Waldron <i>et al.</i> (1997), cell wall elasticity depends on the pectin substances of the middle lamella of the sample while Figiel (2009) reported that vacuum-microwave dried garlic cellular wall were stiffer. Therefore, we can presume that some structural changes may occur as well during vacuum microwave treatment of ciku.
Cohesiveness value reflects the alteration degree of the dried fruit membrane cell structure by measuring the ability of the material to deform before it ruptures. The cohesiveness values of ciku varied with the drying techniques due to the different pectin content as discussed in the hardness value.

### 6.3.2.2 Effects of different drying techniques on rheology properties of ciku

Stress relaxation test is another test enabling determination of textural attributes that represents the viscoelastic behaviour of fruit. The modulus of elasticity and viscosity coefficient can be obtained from the Generalized Maxwell Model. The parameters $E_1$, $E_2$ and $E_0$ are determined from the shape of stress relaxation curve by fitting the stress relaxation function to the experimental points. The entire modulus of elasticity, which can be determined after compression test is the sum of the $E_1$, $E_2$ and $E_0$. Asymptotic value of stress obtained after 90 second of the stress relaxation test equals the product of constant strain, $\varepsilon$ and $E_0$. Therefore, $E_1$ and $E_2$, viscosity coefficients $\eta_1$ and $\eta_2$ represented viscoelasticity, while $E_0$ only determined elasticity.

**Table 6.4**: Rheology properties of ciku dried using CTP, H/VM, HP and HP/VM techniques.

<table>
<thead>
<tr>
<th>Drying techniques</th>
<th>Initial modulus elasticity, $E_1$ Mpa</th>
<th>Modulus elasticity, $E_2$ MPa</th>
<th>Final modulus elasticity, $E_0$ Mpa</th>
<th>Viscosity coefficient, $\eta_1$ MPa.s</th>
<th>Viscosity coefficient, $\eta_2$ MPa.s</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTP</td>
<td>3.829±0.867</td>
<td>5.318±1.346</td>
<td>7.439±2.907</td>
<td>5.588±1.596</td>
<td>110.9±35.20</td>
</tr>
<tr>
<td>H/VM</td>
<td>5.535±1.858</td>
<td>6.429±1.727</td>
<td>4.768±1.249</td>
<td>8.307±3.189</td>
<td>140.7±45.70</td>
</tr>
<tr>
<td>HP</td>
<td>2.143±0.550</td>
<td>2.527±0.651</td>
<td>2.709±0.743</td>
<td>2.588±0.638</td>
<td>48.89±12.99</td>
</tr>
<tr>
<td>HP/VM</td>
<td>43.90±11.11</td>
<td>35.85±7.32</td>
<td>29.37±14.50</td>
<td>412.7±168.4</td>
<td></td>
</tr>
</tbody>
</table>

The value indicates mean ± standard deviation of five measurements. Values within the same column with similar letters are not significant different.

**Table 6.4** shows the rheological properties of ciku dried using different drying techniques. $E_1$, $E_2$ and $E_0$ of HP/VM dried ciku were found ranging from 14.5 to 43.9 MPa, which were significantly higher ($p>0.05$) compared to the other modulus of elasticity values ranging from 2.1 to 7.4 MPa. Within 90 minutes of relaxation, HP/VM dried ciku was recorded at 14.5 MPa, which was still extremely high compared to others and $E_0$ value of HP dried ciku was 2.71 MPa. This showed that HP/VM dried ciku had higher rigidity compared to the others. According to Nicoleti *et al.* (2005), higher final modulus of elasticity characterizes samples with greater rigidity. In addition, $\eta_1$ and $\eta_2$ of the same...
samples were 29.37 MPa.s and 412.7 MPa.s, respectively. It showed that HP/VM dried ciku was more viscous due to the lowest moisture content retained in the sample. An increase in moisture content makes the samples less viscous and elastic (Bhattacharya & Narasimha, 1997; Bhattacharya, 2009). This finding is also in agreement with Karathanos et al. (1994) who found that an increase in moisture content did affect the rheology properties of raisin by decreasing the relaxation time, thus decreasing the viscosity of raisins. At very low moisture content, the increase in modulus of elasticity was probably due to part of the sugar that converts into crystalline state. According to Kostaropoulos et al. (1997), the stress with strain increased at moisture content as low as 9% partly due to sugar crystallization.

6.3.2.3 Effects of different drying techniques on biochemical property of dried ciku

The retained TPC of ciku from different drying techniques is as shown in Figure 6.7. HP/VM drying could retain the highest amount of TPC compared to other drying techniques but it was 45% lower than the fresh ciku. The TPC of fresh ciku reported by Chong et al. (2009) was 336.0 mg GAE/100 g DM. The main reason for degradation was because polyphenol oxidase (PPO) activity of ciku was relatively active even at drying temperature of 30°C. According to Donovan et al. (1998) and Ferreira et al. (2000), the TPC of fresh fruits may destroy or convert to non-antioxidant forms during drying. This can be seen from the results in drying of figs, apricots, cranberries, dates, raisins and plums, where average of 84% reduction in TPC was observed (Vinson et al. 2005). Referring to the retained TPC of CTP of dried ciku, results showed that it was not significantly different (p>0.05) compared to HP dried ciku. These drying techniques could only retain 12% of TPC compared to fresh ciku. This was because some of the polyphenol oxidase (PPO) of ciku remained active even at mild and low drying temperature. 4-O-galloylchlorogenic acid, catechin, quercetin, gallocatechin and gallic acid are the main polyphenol compounds found in ciku. According to Altunkaya & Gökmen (2008), the maximum substrate specificity of PPO was found for chlorogenic acid then catechol, catechin, quercetin, caffeic acid and gallic acid. Therefore, PPO activities of these polyphenol compounds are extremely significant at low and mild drying temperature.

3.2.4 Sensory Assessment

Flavour compounds can fall under any class of chemical compounds such as neutral compounds, acids, nitrogen compounds, sulfur compounds, high volatility compounds, low volatility compounds and etc (Fisher & Scoot, 1997). Table 6.5 shows the flavour intensity and acceptance scores of ciku dried using different drying techniques. The flavour intensity scores of CTP, HP, H/VM and HP/VM dried ciku were not significantly different (p>0.05) since ciku had strong and exotic aroma/flavor not common to the consumer residing outside Southeast Asia. In terms of acceptance scores, CTP dried ciku was less preferred, which could be due to the volatilisation of flavour compounds of ciku during drying at mild temperature of 53°C. Laohakunjit et al. (2007) reported that fresh ciku contains 29.30% of ethyl acetate, 21.62% of
acetaldehyde, 11.93% of benzyl alcohol and 7.37% of 2-butenyl benzene. It was found that heating of ciku at 50°C for 35 minutes causes all the benzyl-related compounds volatised and other flavour compounds such as ethyl acetate and acetaldehyde increased to 49.22% and 33.31%, respectively (Laohakunjit et al. 2007). Table 6.5 shows that the intensity and acceptance scores of ciku were found not significantly different (p>0.05).

![Figure 6.7: TPC of ciku dried using CTP, HP, H/VM and HP/VM drying process.](image)

From Table 6.5, the colour intensity scores of CTP and H/VM were the highest compared to the others which indicated that the colours of dried ciku were darker. On the other hand, the acceptance scores show that the colour of CTP dried ciku was desirable due to Maillard reaction and oxidation of ascorbic acid that occurred during H/VM drying which were significant compared to ciku dried using CTP. Figure 6.8 shows the samples dried using different advanced drying techniques.

The hardness intensity scores of HP dried ciku was the lowest compared to others and texture of HP dried ciku was the softest. On the other hand, the hardness intensity score of H/VM dried ciku was higher which could be due to the longer final vacuum-microwave drying duration which was four times longer than HP/VM. During vacuum-microwave drying, the pressure developed in the cells caused the cell walls to expand, enabling the material inside to gain volume. Removal of water from cellular walls resulted in stiffer cell wall structure (puffing) (Figiel, 2009). The longer the puffing effect, the stiffer the ciku cell wall structure. In terms of acceptance score, H/VM shows very high score (e.g. less preferred) because it was difficult to chew compared to other samples. The crispiness intensity score of H/VM dried ciku was lower which could be due to the higher elasticity or springiness (Table 6.6). Based on the crispiness acceptance scores, the crispiness exhibited by ciku dried using H/VM was desirable.
**Table 6.5:** Sensory attributes (flavour, colour and taste) of ciku dried using CTP, HP, H/VM and HP/VM drying techniques.

<table>
<thead>
<tr>
<th>Drying techniques</th>
<th>Flavour Intensity</th>
<th>Acceptance</th>
<th>Taste Intensity</th>
<th>Acceptance</th>
<th>Colour Intensity</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTP</td>
<td>7.47 ± 2.60&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.39 ± 1.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.24 ± 3.06&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.89 ± 1.39&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.84 ± 1.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.82 ± 0.79&lt;sup&gt;abc&lt;/sup&gt;</td>
</tr>
<tr>
<td>HP</td>
<td>6.13 ± 2.49&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.50 ± 1.43&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>5.16 ± 2.51&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.95 ± 1.85&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.16 ± 1.84&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.34 ± 0.46&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>H/VM</td>
<td>7.08 ± 2.11&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.68 ± 1.36&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>5.00 ± 3.45&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.39 ± 1.87&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.55 ± 0.83&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.34 ± 1.52&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>HP/VM</td>
<td>5.50 ± 2.08&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.08 ± 1.09&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.82 ± 2.84&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.66 ± 1.55&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.50 ± 1.63&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.63 ± 0.94&lt;sup&gt;bc&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

The value indicates mean ± standard deviation of eleven measurements. Values within the same column with similar letters are not significantly different. Hedonic score for intensity (0- the lowest, 10- the highest) and acceptance (0-the best, 5-the worst).

**Table 6.6:** Sensory attributes (hardness and crispiness) of ciku dried using CTP, HP, H/VM and HP/VM drying techniques.

<table>
<thead>
<tr>
<th>Drying techniques</th>
<th>Hardness Intensity</th>
<th>Acceptance</th>
<th>Crispiness Intensity</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTP</td>
<td>6.26 ± 1.65&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.63 ± 1.17&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.45 ± 2.19&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>1.66 ± 1.33&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>HP</td>
<td>2.45 ± 1.06&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.53 ± 1.60&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.21 ± 3.20&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>2.08 ± 1.97&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>H/VM</td>
<td>9.63 ± 0.56&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.79 ± 1.34&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.34 ± 2.70&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.37 ± 0.96&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>HP/VM</td>
<td>6.53 ± 2.33&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.84 ± 1.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.29 ± 3.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.92 ± 1.66&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

The value indicates mean ± standard deviation of ten measurements. Values within the same column with similar letters are not significantly different. Hedonic score for intensity (0- the lowest, 10- the highest) and acceptance (0-the best, 5-the worst).
6.4 CONCLUSIONS

Based on the studies, HP/VM, H/VM and CTP drying were found having multiple distinctive falling rate periods and increasing rate periods. An obvious inflection point can be observed from the drying kinetic of ciku dried using the hybrid techniques. The greatest increment in drying rate could be found from hybrid techniques with final vacuum-microwave drying due to the rapid removal of water from the internal structure of fruit by microwave energy.

It was found that ciku dried using HP/VM gave the highest TPC compared to others due to the fact that the first group of polyphenol compounds is the substrate of PPO. This group of polyphenol compounds will convert to intermediate antioxidant compounds, therefore, an immediate inhibition of PPO is vital. It is very important to retain TPC of dried fruit but at the same time, flavour, taste, colour, texture attributes of dried ciku have to be taken into account as it will affect consumer purchasing decision.

Sensory assessment showed that high or mild temperature drying produced less preferred dried fruit compared to low temperature drying. It was found that CTP could produce dried ciku with higher acceptance score compared to other drying techniques. In terms of taste, the intensity and acceptance scores were not significantly different ($p<0.05$).

Textural attributes are important criteria affecting consumer preference. Result obtained showed that dried ciku with lower moisture content had higher hardness, cohesiveness, springiness, chewiness, modulus of elasticity and viscosity coefficient values. Further to this, it was found that ciku dried using HP/VM showed a higher preference compared to other techniques.

6.5 NOMENCLATURE

| DR | Drying rate (g H$_2$O/g DM. m$^2$. s) |
| DM | Dry matter |
| HA | Hot air |
| l  | Thickness of the prism (cm) |
| W  | Width of the prism (cm) |
| H  | Height of the prism (cm) |
HP     Heat pump
H/VM   Hybrid hot air vacuum-microwave drying
HP/VM Hybrid heat pump vacuum-microwave drying
CTP   Hybrid hot air-cold air drying
PPO   Polyphenol oxidase
TPC   Total polyphenol content
S     Springiness
Δt    Time difference (s)

REFERENCES


Chong, C.H.; Figiel, A.; Law, C.L.; Wojdyło, A. Combined drying of apple cubes by using of heat pump, vacuum-microwave, and intermittent techniques. Food and Bioprocess Technology 2013, 7, 975– 989.


Swaminathan, M. Food Science and Experimental Foods; Ganesh and Co.: Madras India, 1979, 45–63.

Waldron, K.W.; Smith, A.C; Parker, M.L. New approaches to understanding and controlling cell separation in relation to fruit and vegetable texture. Trends Food Science Technology 1997, 8, 213–221.


Chapter 7

Drying of Mango Products

Rachna Sehrawat and Prabhat K. Nema

Contents

7.1 Introduction ........................................... 125
7.2 Different Drying Techniques ......................... 129
7.3 Dried Products ......................................... 135
7.4 Effect of Drying on Quality of Dried Mango Products 137
7.5 By-Product Utilization .................................. 140
7.6 Conclusions ........................................... 140

References ................................................. 141
7.1 INTRODUCTION

Mango (*Mangifera indica* L.) is a tropical and subtropical fruit having nutritional, economic and ayurvedic importance. It belongs to kingdom plantae having class mangoliopsida (*Figure 7.1*) (Shah et al., 2010). Besides its delicious taste and flavour, it is rich source of nutrients like vitamin A and C, and popularly known as king of fruits. It also has very good substrate of carbohydrates (around 16%) and high moisture that varies between 80-85%. It is very popular among masses in raw as well as in processed forms and revered/cherished by consumer (Kusuma and Basavaraja, 2014). The composition of raw mango is as shown in *Table 7.1*. It has been reported that mango possesses anti-oxidant, anti-diabetic, anti-viral, hypotensive, cardiotonic, anti-inflammatory properties. Various researchers have studied the anthelmintic, anti parasitic, anti HIV, anti-bone resorption, anti-tumor, antispasmodic, immunomodulation, anti-pyretic, anti-diarrhoeal, anti-allergic, hypolipidemic, gastroprotective, anti microbial, anti fungal, anti-bacterial, hepatoprotective, properties of mango (Shah et al., 2010). Mango fruit is also called drupe and it consists of endocarp (pit, woody portion), mesocarp (flash edible part) and exocarp (outer skin) (*Figure 7.2*). It has been observed that gustatory quality, color, size, shape (round, oval, ovoid-oblong) and postharvest behavior of mango is highly variable. Some of the pre-harvest factors influencing these properties are temperature, light, water and carbon availabilities. These can be regulated by different practices such as fruit thinning, tree pruning, irrigation management and etc (Léchaudel and Joas 2007).

![Taxonomical classification](image-url)
India ranks first in production of mango with around 44 per cent of the total world production (Sekhar et al., 2013; Kusuma and Basavaraja, 2014). Other major mango producing countries include China, Thailand, Pakistan, Brazil, Mexico and Nigeria. Country-wise production of mango is shown in Table 7.2. A number of varieties of mango are grown throughout the world as well as in India and a brief list is given in in Table 7.3 and Table 7.4, respectively.

Table 7.1: Nutritional value of mango and products (Nigam et al., 2007).

<table>
<thead>
<tr>
<th>Nutrients</th>
<th>Ripe mango</th>
<th>Unripe mango</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein (g)</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Fat (g)</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Minerals (g)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Fiber (g)</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Carbohydrates (g)</td>
<td>16.9</td>
<td>10.1</td>
</tr>
<tr>
<td>Energy (kcal)</td>
<td>74</td>
<td>44</td>
</tr>
<tr>
<td>Vitamin C</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Total carotene (mcg)</td>
<td>2210</td>
<td>90</td>
</tr>
<tr>
<td>Beta carotene</td>
<td>1990</td>
<td>-</td>
</tr>
<tr>
<td>Potassium (mg)</td>
<td>205</td>
<td>83</td>
</tr>
<tr>
<td>Sodium (mg)</td>
<td>26</td>
<td>43</td>
</tr>
<tr>
<td>Calcium (mg)</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Iron (mg)</td>
<td>1.3</td>
<td>0.33</td>
</tr>
<tr>
<td>Phosphorous (mg)</td>
<td>16</td>
<td>19</td>
</tr>
</tbody>
</table>

Figure 7.2: Mango parts.
Table 7.2: Production data of major mango producing country in the world (Sekhar et al., 2013).

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Name of the country</th>
<th>Area (1000 Ha)</th>
<th>Production (1000 tonnes)</th>
<th>Productivity (Tonnes/Ha)</th>
<th>Percentage share on Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>India</td>
<td>2021</td>
<td>12538</td>
<td>6.20</td>
<td>40.10</td>
</tr>
<tr>
<td>2</td>
<td>China</td>
<td>434</td>
<td>3676</td>
<td>8.47</td>
<td>11.80</td>
</tr>
<tr>
<td>3</td>
<td>Thailand</td>
<td>285</td>
<td>1800</td>
<td>6.32</td>
<td>5.80</td>
</tr>
<tr>
<td>4</td>
<td>Mexico</td>
<td>183</td>
<td>1679</td>
<td>9.18</td>
<td>5.40</td>
</tr>
<tr>
<td>5</td>
<td>Pakistan</td>
<td>165</td>
<td>1606</td>
<td>9.73</td>
<td>5.10</td>
</tr>
<tr>
<td>6</td>
<td>Others</td>
<td>1280</td>
<td>9952</td>
<td>52.66</td>
<td>31.8</td>
</tr>
<tr>
<td>7</td>
<td>Total</td>
<td>4368</td>
<td>31251</td>
<td>92.56</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 7.3: Different varieties of mango grown by major mango producing country in the world.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Name of the country</th>
<th>Varieties grown</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>India</td>
<td>Alphonso, Amrapali, Alampur Baneshan, Badshah pasand, Bangalora, Banganapalli, Bombay, Bombay Green, Badami, Cheruku Rasalu, Chinna Rasalu, Chokanan, Thalimango, Chitooor, Rumani, Maharaja Pasand, Chinnarasam, Undamanfa, Dusehri, Ela Mango, Gaddamar, Gadam Mary, Fajri Kalan, Fernandian, Fajli, Husan Nara, Gulabkhas, Himayath, Himsagar, Imam Pasand, Imam Hussain Mango, Jehangir, OttuMangai, Mulgoba, LangraBenarsi, PeddaRasalu, Surkha, Totapuri, Kalepad, KishenBhog, Komanga, Kothapalli Kobbari, Kuttiyattor, Kalami, Kesar, Lalbaug, Langra, Maldah, Malgis, Mallika, Malgoa, Mankur (Goa), Mankurad, Moovandan, Nattuma, Nannari, Neelum, Neeleshan, Panchadara Kalasa, Puliyan, Panduri Mamidi, Payri, Priyor, Rani, Rajapuri, Raspuri, Ratna, Rayal Special, Sindhooram, Safeda, Sammar Bahisht, Suvarnarekha, Totapuri Vanraj, Yahya Mariam Mango, Zardalu</td>
</tr>
<tr>
<td>2</td>
<td>China</td>
<td>Baiyu, Guixiang, Huangpi, Huangyu, Macheco, Sannian, Yuexi</td>
</tr>
</tbody>
</table>
Thailand: Boribo, Muyini, Dodo, Mawazo, Sindano

Mexico: Ataulfo, Haden, Irwin, Kent, Manila, Palmer, Sensation, Tommy Atkins, Van Dyke, Petakon, Oro, Criollo, Niño, Miyako.


Indonesia: Arumanis/Harumanis, Gadung/Gedong, Manalagi, Cengkir/Indramayu, Gajah, Bapang, Lalijiwo, Kueni, Golek, Kemiri, Boled, Bengkulu, Situbondo, Kelapa, Alor, Selaputih

Brazil: Coquinho, Haden, Manga Espada, Manga Rosa, Palmer, Tommy Atkins

Philippines: Apple Mango, Carabao or Kinalabaw, Indian, Piko, Paho, Pahohutan

Egypt: Alphonso, Hindi, Hindi Besennara, Beid El Agl, Oweisi, Fuss Oweis, Taymoor, Zebdiah, Mesk

Table 7.4: Production of mango in different states of India and varieties grown (National Horticulture Database 2014).

<table>
<thead>
<tr>
<th>State</th>
<th>Area</th>
<th>Production</th>
<th>Productivity</th>
<th>Varities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uttar Pradesh</td>
<td>262.16</td>
<td>4300.98</td>
<td>16.4</td>
<td>Bombay Green, Dashehari, Langra, Safeda Lucknow, Chausa, Fazli</td>
</tr>
<tr>
<td>Andhra Pradesh</td>
<td>304.11</td>
<td>2737.01</td>
<td>9.0</td>
<td>Allumpur Baneshan, Banganapalli, Bangalora, Cherukurasam, Himayuddin, Suvernarekha, Neelum, Totapuri</td>
</tr>
<tr>
<td>Karnataka</td>
<td>180.53</td>
<td>1755.58</td>
<td>9.7</td>
<td>Alphonso, Bangalora, Mulgoa, Neelum, Pairi, Baganapalli, Totapuri</td>
</tr>
<tr>
<td>Telangana</td>
<td>190.88</td>
<td>1717.88</td>
<td>9.0</td>
<td>Allumpur Baneshan, Banganapalli,</td>
</tr>
</tbody>
</table>
### 7.2 DIFFERENT DRYING TECHNIQUES

Mango, being rich source of nutrients, as well as high moisture content makes it highly susceptible to microbial growth and spoilage. It was found by Gonzalez-Aguilar et al. (2007) that ripe mango (Hadin) without any treatment or processing deteriorated by severe fungal damage within 18 days at 25°C.

<table>
<thead>
<tr>
<th>State</th>
<th>Average Price</th>
<th>Total Revenue</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bihar</td>
<td>149.00</td>
<td>1367.57</td>
<td>9.2</td>
</tr>
<tr>
<td>Maharashtra</td>
<td>485.00</td>
<td>1212.50</td>
<td>2.5</td>
</tr>
<tr>
<td>Gujrat</td>
<td>142.60</td>
<td>1125.61</td>
<td>7.9</td>
</tr>
<tr>
<td>Tamil Nadu</td>
<td>161.58</td>
<td>785.50</td>
<td>4.9</td>
</tr>
<tr>
<td>Odisha</td>
<td>197.52</td>
<td>751.02</td>
<td>3.8</td>
</tr>
<tr>
<td>Jharkhand</td>
<td>51.33</td>
<td>517.92</td>
<td>10.1</td>
</tr>
<tr>
<td>Kerala</td>
<td>74.44</td>
<td>441.03</td>
<td>5.9</td>
</tr>
<tr>
<td>West Bengal</td>
<td>93.50</td>
<td>430.71</td>
<td>4.8</td>
</tr>
<tr>
<td>Others</td>
<td>223.23</td>
<td>1288.04</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Handling also plays a major role in preventing the deterioration of this perishable commodity. Mangoes during their flush supply or seasonal over production including partly defected mangoes can be processed and preserved. Drying is one of the common and promising techniques utilized at both small and large scale, with aims to preserve the commodities for longer duration of time. It can be converted into slices, flakes, powder, pulp and concentrates to extend their shelf-life and to retain their functionality. In developing countries it is an opportunity for processors to preserve mango using drying as it involves low capital investment. Ample opportunity exists in domestic market as well as for export trade.

Drying is an effective unit operation which can reduce the moisture content to level below which microbial spoilage is hindered. It involves heating medium (air or steam) which can increase the temperature of product and evaporate the moisture. Reducing the moisture content of the product has several benefits like reduction in the weight of product, reduction in transportation as well as packaging cost and easier handling due to reduced volume. Moreover, shelf life is enhanced by restricting the microbial growth due to reduced water activity.

It has been observed that drying rates can be enhanced by using pre-treatments such as sulphitation, blanching and osmotic dehydration etc (Goyal et al., 2006). This also helps to prevent darkening of fruits and vegetables. Pre-treatments suppress microbial growth and also retard the activity of polyphenol oxidase enzyme, which is mainly responsible for enzymatic browning of fruits and vegetables. Non enzymatic browning mainly Maillard reaction is also inhibited by controlling water activity, pH and reactive carbonyl compounds (Pott et al., 2005). Some of the works where mango was pre-treated before drying is reported by Goyal et al. (2006), Ismail and Nagy (2012) and Zou et al. (2013).

Effect of thin-layer drying (55, 60 and 65°C) and pre-treatment (blanching 50°C/2 min and blanching in 1% potassium metabisulphide solution) was studied by Goyal et al. (2006) on raw mango slices (2.8±0.3 mm) in a laboratory model tunnel dryer. The least drying time was found in the samples blanched in 1% potassium metabisulphide solution at 65°C and the moisture diffusivity observed was the highest. Pre-treatments of mango slices were carried out by Ismail and Nagy (2012) using sodium metabisulfite and sucrose and further drying was carried out. Lesser color changes were observed in samples treated using sodium metabisulfite than sucrose and control samples. Osmotic dehydration as pretreatment was carried out on mango chips for duration of 30-120 min and effect on physicochemical and thermal properties like the glass transition, texture, color, expansion and rehydration were analyzed (Zou et al., 2013). It was inferred using sensory evaluation that overall quality was better in the pretreated samples in comparison to non-pretreated samples.

Most commonly used drying techniques for raw and ripe mangoes are open sun drying, solar drying, freeze drying, vacuum drying, foam mat drying and
refractance window drying etc. These are discussed in the following subsections and are also summarized in Table 7.5.

7.2.1 Open sun drying and solar drying

Open sun drying involves drying of the product in an open area where sunlight is easily available. It does not involve much of infrastructural investment as it requires only flat surface where abundant sunlight is available. Metal racks or mesh screens can be placed on the ground to avoid any contamination. However, sun drying has several limitations like contamination from air, soil, rain etc; intermittent availability of sunlight and longer drying time. Sometimes, the product is prone to microbial contamination due to long drying duration or keeping the semi dried product in shade when sun light is not available. Solar dryer is a better option which utilizes free energy of sun to dry the material kept in a cabinet with enhanced drying rate and reduced drying time. It also has limitation when sunlight is not available but hygienically it is better than sun drying in open.

By using natural convection solar drying, Santis-Espinosa (2015) could reduce 95.6% moisture of mango in a solar dryer in 28 h. The minimum and maximum temperature during drying was 21°C and 56°C, respectively. Drying rate at the peak of radiation was 0.060gH₂O/gdry mass/min. Effect of open sun drying; visqueen-covered solar dryer and polyethylene-covered solar dryer on β-carotene of mango fruit was studied by Ndawula et al. (2004). Highest β-carotene loss was found in open sun drying followed by polyethylene-covered solar dryer and the least was in visqueen-covered solar dryer.

7.2.2 Hot air drying

Hot air drying is the most commonly used preservation technique to extend the shelf life of mango. It also overcomes the limitation of intermittent and slow drying rate as well as unhygienic end product in sun and solar drying systems. The inlet air from the blower is heated to the desired temperature to evaporate the moisture content from the samples to be dried. Hot air drying (60-80°C) was carried out by Akoy (2014) on mango slices and it was found that drying time has significant effect on rehydration ratio and color change. To study the drying kinetics of mango, effect of slice thickness (3-9 mm) and temperature (60-80°C) of hot air drying was analysed by Kabiru et al. (2004). Drying data was fitted into Newton, Page, Modified Page and Henderson and Pabis but page model was the best suited model.

7.2.3 Vacuum drying

Hot air drying was effective in reducing the drying time and environmental contamination but the color of the dried product is sometimes becomes unacceptable at higher temperature. It was also found that at high temperature important bio-active components like ascorbic acid and β-carotene are lost during the drying process. Vacuum drying is able to overcome the problem of color which involves drying at low temperature under
reduced pressure. Jaya and Das (2003) used vacuum drying (30-50 mm of mercury absolute pressure) to dry mango and studied effect of pulp thickness (2-4 mm) and plate temperature in the chamber (65-75°C) and concluded that 2.6 mm of pulp thickness of and 72.3°C temperature of vacuum chamber led to lower color changes. A patent was filed by Durance et al. (2000) on process for drying of mango and it was stated that vacuum microwave dehydration resulted in a "fresh", uncooked flavor and a unique crunchy texture with less or no shrinkage which was not achieved using conventional air drying.

7.2.4 Freeze drying

In freeze drying the sample to be dried is frozen first and dried further by sublimation process, which involves direct conversion of moisture from solid form to vapour state without passing through liquid state. It was found to be a very effective technique to retain the nutrient components of fruits and vegetables, but suffered limitation of longer drying time, batch processing and higher cost. Freeze drying (0.13 mbar/30°C/12 hrs and secondary drying temperature was 38°C) of mango pulp (5 mm thickness) was carried out by Marques et al. (2006) and observation showed that the macroscopic volume was practically unchanged and also effective in retaining the other nutritional qualities. The values of vitamin c, phosphorous and calcium in natural pulp were 31.79, 10.86 and 8.89, respectively. In freeze dried mango pulp vitamin c, phosphorous and calcium recorded (in mg/100g) were 10.33, 7.97 and 19.72, respectively.

7.2.5 Refractance Window drying

It is a novel technology which utilizes thermal energy of hot water to transfer heat to the product and hot water is also reused to improve efficiency of process. A thin layer of product is generally spread over a mat/plastic conveyor belt and the mat is partially transparent to infrared radiations. Lower surface of mat over which product is spread is in contact with hot water reservoir, which supplies heat from hot circulating water. It has advantages of continuous operation, lesser drying time, lower drying temperature and suitable for all types of liquids. It is found to be very effective in concentrating the purees to form films or flakes. As compared to freeze drying, refractance window consumed 50% lesser energy as well as 50-70% lesser capital investment (Nindo et al., 2003, Nindo and Tang, 2007).

Drying of mango pulp using refractance window technique was investigated by Zotarelli et al.(2015) using different process parameters such as water temperature (75- 95°C), thickness of product (2-5 mm) and radiant source (transparent and painted Mylar film). It was concluded that increase in water temperature enhanced drying rate and compared to black film process refractance window was more efficient up to pulp thickness of 3 mm. It was also inferred that refractance window drying was found to be a very efficient drying process. It was also reported by Caparino et al. (2012) among the different drying techniques studied the effect of refractance window drying on properties of mango powders were comparable to freeze drying process and superior to that of spray and drum drying.
7.2.6 Foam mat drying

Foam is defined as a mass of small gas cells coming close together but separated by thin films of liquid to form the bubbles, giving a gas dispersed in a liquid (BIS, 1983). This is simply a technique that involves whipping of food concentrate along with foaming agent to form foam which is spread in the form of sheet and further dried by heated air. Due to large liquid-gas interface area, rate of drying is much faster despite of fact that foamed mass contains large volume of gas (Sharada, 2013). This is most commonly used for heat sensitive products and those containing high sugar content. After foaming, the tiny bubbles of foaming mass increases the area exposed for moisture removal and yield more porous product. Foam mat drying was carried out on mango pulp using egg white (0-9%) as foaming agent and further dried using hot air dryer (65-85°C) by Wilson et al. (2012). After pulverizing the pulp into powder it was stored for 6 months and physicochemical analysis was carried out. Different parameters like ascorbic acid, pH, reducing sugar, total carotenes, phosphorous, iron and water solubility index decreased but even after 6 months no bacterial and fungal contamination was observed. Foam mat drying of mango pulp (Alphonso) of 1 mm thickness was studied out by Rajkumar et al. (2006) using egg albumen (10%) with stabilizing agent methyl cellulose (0.5%) and was dried at 60°C with batch type cabinet dryer. It was found that higher heat utilization factor and less changes were observed in the foam dried flakes as compared to non-foam dried flakes.

7.2.7 Superheated steam drying (SSD)

Steam beyond its boiling point is used as a drying medium in a dryer to evaporate moisture from the food is known as SSD. The evaporated moisture becomes part of superheated steam (SS) which on removal is condensed readily so that heat can be utilized for other unit operations and SS can be recycled (Ezhil, 2010). When water is heated at specific pressure, it forms saturated steam at its boiling point. At specific pressure, decrease in temperature of superheated steam does not get condensed till the temperature is maintained above saturation temperature where as saturated steam get condensed as soon as temperature is lowered.

SSD can be carried out at high pressure, low pressure or at atmospheric pressure. Generally in case of fruits and vegetables, to prevent loss of nutrients SSD at low pressure is most commonly used. The schematic diagram of superheated steam dryer is shown in Figure 7.3. There are several advantages associated with SSD like lesser net energy consumption, utilization of exhaust steam for other unit operations, effective in retaining nutrients, does not emit any dust, dirt, hazardous gas into environment and oxidative reaction does not occur due to absence of oxygen under low pressure (Sehrawat et al., 2016).
### Table 7.5: Effect of drying technique on mango.

<table>
<thead>
<tr>
<th>Product</th>
<th>Drying technique</th>
<th>Parameters studied</th>
<th>Remark</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mango juice powder</td>
<td>Spray drying (maltodextrin, gum arabic and starch waxy were used as carriers)</td>
<td>Microstructure, stickiness, solubility</td>
<td>Independent effect of carriers was found on the functional properties of the mango juice powder.</td>
<td>Cano-Chauca et al.(2005)</td>
</tr>
<tr>
<td>Mango pulp</td>
<td>Vacuum drying (65-75°C/30-50 mm of mercury absolute pressure)</td>
<td>Modelling, color</td>
<td>Lower color changes were observed when drying of pulp having thickness of 2.6 mm was carried out at 72.3°C</td>
<td>Jaya and Das (2003)</td>
</tr>
<tr>
<td>Mango pulp</td>
<td>Foam mat drying (egg white)</td>
<td>Moisture content, total sugar, reducing sugar, ascorbic acid, total carotenoids, iron, phosphorous</td>
<td>No microbial contamination was found even after 6 month of storage, but nutritional value decreased linearly during storage period.</td>
<td>Wilson et al.(2012)</td>
</tr>
<tr>
<td>Mango pulp</td>
<td>Refractance window</td>
<td>Effect of variables on refractance window</td>
<td>Effective technique to save the energy</td>
<td>Zotarelli et al.(2015)</td>
</tr>
<tr>
<td>Mango chips</td>
<td>Explosion puffing drying (Pre-treatment using osmotic dehydration)</td>
<td>Glass transition, texture, color, expansion and rehydration</td>
<td>Sensory evaluation revealed that overall quality of pretreated sample was better than that of</td>
<td>Zou et al.(2013)</td>
</tr>
<tr>
<td>Product</td>
<td>Drying Method</td>
<td>Kinetics</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>----------------------------------------</td>
<td>----------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Mango slices</td>
<td>Convective multi-flash drying and freeze drying</td>
<td></td>
<td>They reported that convective multi-flash drying is an effective technology to replace freeze drying. [\text{Zotarelli et al. (2012)}]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Microwave drying and air drying (60-80)</td>
<td>Drying kinetics</td>
<td>Using microwave drying time was reduced to 70-75% as compared to air drying. [\text{Akoy and von Höresten (2015)}]</td>
<td></td>
</tr>
<tr>
<td>Mango peel and seed</td>
<td>Freeze drying (with extraction using ethanol:water)</td>
<td>Antioxidant activity</td>
<td>Effective in stabilising seed and peel without diminishing the antioxidant activity. [\text{Dorta et al. (2012)}]</td>
<td></td>
</tr>
<tr>
<td>Mango slice</td>
<td>Laboratory dryer</td>
<td>Simulation of drying, diffusivity and shrinkage</td>
<td>Model effective at predicting moisture diffusivity of samples. [\text{Janjai (2008)}]</td>
<td></td>
</tr>
</tbody>
</table>

### 6.3 DRIED PRODUCTS

#### 6.3.1 Powder

Dried products in the form of powder are convenient in handling, reduced transportation cost and offer chemical and microbiological stability. It can be prepared by using drum drying, spray drying, freeze drying or hot air drying. Mango powders obtained after drying can be utilized in various innovative formulations for new product development, to prepare pre-mix for ready to eat or cook foods. It is widely utilized in yoghurt, health drinks or flavoured beverage, sauces, baby foods, baked foods, ice-cream, cereals and nutrition bars (Rajkumar et al., 2007, Caparino et al., 2012). It also has wide applications in pharmaceutical and cosmetic industries.
6.3.2 Flakes/cubes/slices

Flakes are obtained by drying mango with or without starch in a drum dryer. Mango can be dried in cubes or slices of different thickness using different techniques like solar drying, hot air drying (Chen et al., 2007, Yan et al., 2008), vacuum drying (Sogi et al., 2015), microwave drying (Akoy and von Höresten, 2015) and freeze drying (Chen et al., 2007). It is also dried by combination of different drying (Andres et al., 2007). Andres et al. (2007) used osmotic dehydration followed by microwave-assisted hot air drying and studied quality evaluation and modeling. It is considered as healthy snacks which are widely utilized as ingredient in yogurt, cereal, pie filling, cakes, sauces, fruit bars, pastries and juices.

6.3.3 Other mango products and utilization

6.3.3.1 Green mango powder:

Green mango powder is a spray dried/sun dried product of green mangoes. Juice is prepared from green mangoes and then dried in a spay dryer. It has good retention of aroma and flavor of fresh green mango. The product is suitable for instant mango juice/shake and as soup base (Ravani and Joshi, 2013).

6.3.3.2 Ripe Mango Products:

As un-processed mango has short shelf life, it is processed in different forms to achieve extended shelf life i.e. pulp, jam, jelly, marmalades, juices, squash, slices pickles and mango leather. It is also incorporated into bakery products, puddings, corn flakes, yoghurt, ice-creams and also as flavourant.
6.4 EFFECT OF DRYING ON QUALITY OF DRIED MANGO PRODUCTS

6.4.1 Color

Color of any food commodity is of prime importance to consumers and concern for the processors. It is the foremost criteria to judge the quality of food commodity. Degradation of pigment and browning reaction (Millard or caramelization) generally occurs during thermal treatment in commodities rich in sugar leading to change in color.

Effect of hot air drying and freeze drying with and without pre-treatment on color of mango slices was reported by Chen et al. (2007). No significant effect of pre-treatment was observed on color of dried mango using hot air drying. In freeze drying the pre-treatment resulted in higher redness and yellowness but lightness was less compared to untreated samples. On comparing hot air drying (deep orange) and freeze drying (pale yellow), hot air drying could produce darker color due to enzymatic browning.

Mango puree was dried by Caparino et al. (2012) using spray drying, freeze-drying, drum drying and refractance window drying till moisture content was reduced below 0.05 kg water/kg dry solids. It was reported that lightness value of reconstituted powder obtained using drum drying and spray drying had significant difference from the reconstituted puree but were comparable to freeze dried and refractance window powder.

Among the different drying temperature (60-80°C) used for drying of mango (var. Kent) by Akoy (2014), the least color change was observed in the mango slices (3 mm) at 80°C as lesser time was required to dry the product. It was found that lightness, yellowness value decreased and redness value increased. At all the temperatures used for drying browning was not observed but insignificant differences were reported between the fresh and dried samples.

Drying of mango slices was carried out using vacuum (80°C for 4 hours) and normal drying oven (58°C for 28 hours) by Ismail and Nagy (2012). They reported that colour changes were higher in vacuum oven which might be due to high temperature.

6.4.2 Rehydration

Rehydration process involves imbibitions of water into the dried product and then leaching out of soluble solids from dried food samples (Jamradloedluk et al., 2007) and also indicates degree of damage to cell structure.

Comparison was made between two varieties of mango (Seddik and Fajri kalan cv.) dried using normal drying and vacuum drying (Ismail and Nagy (2012). Normal dried samples had higher rehydration percentage in comparison to the vacuum dried samples. Akoy (2014) found that at 80°C (3 hrs) highest rehydration was obtained compared to 60°C (7 hrs) and 70°C (5 hrs) at a fixed velocity of 0.5 m/s. As the drying time was increased there was
decrease in the rehydration ratio because longer drying time might have affected the structure of slices. Freeze drying (13 kPa/-30°C and secondary temperature of 35°C) of mango slices was carried out by Marques et al. (2006) and rehydration ability was found at 0.129. It was reported that among the three equations (Exponential, Peleg and Weibull) used to describe rehydration behaviour, Weibull equation fitted well to experimental data.

6.4.3 Microstructure

Thermal processing techniques have profound influence on microstructure, rheology and nutritional aspects of food material and cause alteration in product structure. Therefore, it is necessary to study the effect of these techniques on microstructure of food commodities (Sehrawat et al., 2016). Using Scanning Electron Microscopy (SEM) microstructure evaluation was carried out by Caparino et al. (2012) and Zotarelli et al. (2012) on mango pulp which helped in better understanding the mechanism of drying and dehydration.

Among the different drying techniques (spray drying, freeze-drying, drum drying and refractance window) studied by Caparino et al. (2012), the X-ray diffractograms exhibited amorphous structure of mango puree powder as broad background were observed, also crystalline peaks were absent. Generally, crystalline products exhibit sharp peaks. Porosity was higher in freeze dried samples while powder obtained by refractance window showed uniform thickness and were smooth and flaky. Spherical shape was observed in the spray dried powder whereas sharp edges and irregular shape was reported in drum dried powder. Among all the dried samples using different techniques no substantial difference were observed in hygroscopicity of powders, which was confirmed by absence of sharp or crystalline peaks.

A comparison of convective multi-flash freeze drying (combination of convective drying and flash evaporation) and freeze-drying process was carried out using mango slices by Zotarelli et al. (2012). Micrographs taken by scanning electron microscopy depicts heterogeneous and larger pore sizes in the dried samples by convective multi-flash but structure were similar to freeze dried samples. It was also reported that convective multi-flash freeze drying is an effective technique to produce crispy product and an alternate drying method to freeze drying.

6.4.4 Carotenoids Retention

β-carotene is an antioxidant and also a precursor of vitamin A and has anticancer activities. However, it also gets degraded at higher temperature. Drying process should be effective and aim to retain important nutrients.

Effect of pre-treatment (1% sodium hydrogen sulfite solution or 1% ascorbic acid solution) on carotenoid retention in mango pieces was studied by Chen et al. (2007) using hot air drying and freeze drying. Freeze-drying with 1% sodium hydrogen sulphite showed the highest retention of epoxy-containing carotenoids whereas highest yield of all-trans- β-carotene and its cis isomers,
all-trans-zeaxanthin and its cis isomers, as well as cis-lutein were obtained using freeze-drying with 1% ascorbic acid solution. Sogi et al. (2015) found highest retention of carotenoids in the freeze dried samples followed by conventionally dried, vacuum dried and Infra-red dried mango powders. Foam-mat drying at different temperature using different concentrations of egg white had significant effect on the carotene content. Decrease in carotene content was observed with increase in concentration. Effect of egg white (0-9%) as foaming agent and hot air drying on carotenoid content of mango powder was carried out by Wilson et al. (2012). As concentration of egg white and temperature increase, the carotenoid content decreases. It could be due to isomerization, epoxide forming and photosensitive nature of carotenoids. As storage time increases there was linear decrease in carotenoids of mango powder which could be due to auto-oxidation, moreover dehydrated products during storage are more susceptible to thermal degradation and oxidation due to increase in surface area. Shofian et al. (2011) observed considerable effect of freeze drying (487.34 ± 29.72 µg/100g) on β-carotenoid content of mango as compared to the fresh samples (660.27 ± 61.06 µg/100g).

6.4.5 Ascorbic acid

Preservation of ascorbic acid is very important as it is one of the essential micronutrients which acts as an antioxidant, is water soluble, gets oxidized readily and is prone to degradation at high temperatures (Tewari et al., 2016). It can be used as a quality index for dehydrated mango or other products.

Among the different drying techniques used for drying of mango slices (10 mm cubes) ascorbic content of powders decreased due to heat damage in conventional drying, vacuum drying and Infra-red drying and was highest in freeze dried samples (Sogi et al., 2005). While foam mat drying (65-85°C) using egg powder (0-9%), it was reported by Wilson et al. (2012) that with increase in temperature the ascorbic acid content of mango powder decreased and significant effect were observed at 75-85°C. It might be due to the heat labile nature of ascorbic acid, but effect of different concentration of foaming agent was insignificant on ascorbic acid except for a decline with 3% egg white at 65°C. Effect of open sun drying, visqueen-covered solar dryer and polyethylene-covered solar dryer was studied by Ndawula et al. (2004) on vitamin C content of mango fruit. Vitamin loss was highest in open sun drying (84.5%) and least in visqueen-covered solar dryer (53%). In the ascorbic content mango samples after freeze drying (8.34 ± 1.74 mg/100g) no significant difference were observed as compared to the fresh samples (8.36 ± 2.33 mg/100g) by Shofian et al. (2011).

6.5 BY-PRODUCT UTILIZATION

Around 40-50% of total fruit weight (peel and stone) is generated as waste during processing of mango but these materials are rich source of nutrients.
6.5.1 Peels

The skin of mango is smooth and leathery and varies in color from pale-yellow to deep-orange. Skin is widely used to produce edible fibre, pectin, vinegar and for extraction of citric acid. Enzyme like cellulase and pectinase can also be obtained from mango peel. Authors (Ajila et al., 2007; Kim et al., 2010) reported that peel also has important components like carotenoids, polyphenols, vitamin E, vitamin C and dietary fibre. Jam was prepared by Larrauri et al. (1994) using mango peel and mango peel was also incorporated into macaroni by Ajila et al. (2007) to enhance the dietary fibres. Mango peel as an alternative substrate was optimized for butanol production by Avula et al. (2015) and it was found effective to increase butanol production.

6.5.2 Kernels

Mango fruit has kidney-shaped seed enclosed in a woody husk which is large and flattened. The seed of mango is rich source of cellulose and is a potential materials for pulp and paper industry. Efforts were carried out by Mahale and Goswami-Giri (2015) to use cellulose from mango waste to prepare paper and were compared to standard paper from wood pulp. Upon analysing the performance (tensile strength, porosity, absorbency) of paper from mango waste, it was concluded that it could partly replace standard cellulose papers as it showed the enhanced or similar physical properties. Starch of mango kernel is utilized in confectionary sector and it is also utilized for making chapattis, in combination with maize or wheat flour. Mango seed contains good quality fat around 8-10% which could be utilized by cosmetic purpose or for saponification of soap. Enzyme amylase can also be obtained from mango seed. Mango peel and kernel was reported utilized to produce pectin (Tandon and Kalra, 1991; Pedroza et al., 1994), vinegar (Ethiraj and Suresh, 1992) and biscuit (Ashoush and Gadallah, 2011)

6.6 CONCLUSIONS

Mango is a nutritious fruit exhibiting potent anti-oxidative and ayurvedic properties but the fruit is perishable in nature. In order to extend the shelf life it is processed into different forms like powder, pulp, beverage, jam, jelly, pickles. Drying is one of the effective techniques to convert the ripe/raw mango into powder, slices and cubes which can be utilized for different purposes. Different drying techniques like sun drying, solar drying, drum drying, foam mat drying, hot air drying, vacuum drying, freeze drying and superheated steam drying can be used. Various drying techniques have variable effect on properties of dried mango like microstructure, β-carotene, ascorbic acid, color and rehydration. Mango kernel and peel are also incorporated into products like biscuit, macroni and vinegar which acts as good source of dietary fibres, phyto-chemicals and also exhibits potent antioxidant properties.
REFERENCES


Dorta, E.; Lobo, M.G.; González, M. Using drying treatments to stabilise mango peel and seed: Effect on antioxidant activity. LWT - Food Science and Technology 2012, 45, 261-268.
http://www.google.co.in/patents/US5962057.


National Horticulture Databse 2014
http://nhb.gov.in/report_files/mango/MANGO.htm


Pedroza-islas, R.I.; Aguilar-esperanza, E.; Vemon-carter, E.J. Obtaining pectin from solid wastes derived from mango processing. AICHE symposium Series 1994, 90(300), 36-41

Pott, I.; Neidhart, S.; Muhlbauer, W.; Carle, R. Quality improvement of non-sulphited mango slices by drying at high temperatures. Innovative Food Science and Emerging Technologies 2005, 6, 412-419.


Sekhar, C.; Selvarajan, M.; Pounraj, A.; Prahadeeswaran, M. Production and export of mango in India-a paradigm to the developing nations. American International Journal of Research in Humanities, Arts and Social Sciences 2013, 4(1), 78-87


Sogi, D.S.; Siddiq, M.; Dolan, K.D. Total phenolics, carotenoids and antioxidant properties of *Tommy Atkin* mango cubes as affected by drying techniques. LWT - Food Science and Technology 2015, 62, 564-568.


Chapter 8

Drying Process and Quality Evaluation of Guava (*Psidium guajava* L)

S. P. Cuervo-Andrade, D.C. Sinuco-León, C.J. Cortés-Rodríguez and J.M. Castellanos-Olarte

Contents

8.1 Introduction 147
8.2 Drying process and Quality Evaluation 148
8.3 Drying and Effect in Product Quality 152
8.4 Conclusion 167
8.5 Acknowledgement 168
8.6 Nomenclature 168

References 168
8.1 INTRODUCTION

Guava (*Psidium guajava* L.) is a tropical fruit characterized by its nutritious, sensory and functional properties. It is commonly referred to as a super fruit because of its high antioxidant capacity (Sanda et al., 2011). It is a rich source of vitamin C which is four times higher than orange (Hassimoto et al., 2005), vitamin A, niacin, riboflavin, iron, dietary fiber and antioxidant compounds (Patthamakanokporn et al., 2008). It also contains flavonoids, triterpenoids and other biologically active secondary compounds. The types of sugars and their amount depend on harvesting and environmental conditions such as climate and soil. Harvesting also influences the flavor compounds accumulation during ripening (Ali and Lazan, 1997). Considering soluble fibers, the amount of pectin is normally higher in comparison with other fruits.

In Latin America, after Brazil and Mexico, Colombia is one of the largest producers of guava with annual production of 135000 ton and harvested area of about 12000 ha (Agronet, 2016). Yields are low due to lack of technical practices like adequate pruning, bagging of fruits, adequate fertilization and pests/insects control among others. The largest production area is located in the north-east region, where several varieties with differences in shape, size, and flesh color are grown. The most common variety is the Pink Guava but the others are characterized by their colored white flesh (White and Victoria) (Sinuco et al., 2010). Most of this guava production supply domestic consumption i.e natural fruit juices, fruit pulps and jellybars and mostly are also exported to the EU countries. However, the volumes are quite low at 3600 ton/year in average between 2007 and 2011 (Ministerio de Comercio Industria y Turismo, 2011).

The regional varieties are spherical in shape, about 4–10 cm in diameter, and covered by a leathery green to yellowish skin, with either a white or a pink flesh, which is visible only when the fruit is cut. Because these varieties exhibit a high soluble solid to acid ratio, they are mainly used for the production of jellybar, which provides an important agroindustry income for small farmers (Sinuco et al., 2010). Unfortunately, the moisture content of guava makes it highly perishable and ripening increases its sugar content and skin softening. Drying processes can help in extending the shelf life and preserving sensory, physical and chemical properties of guava (Nunes et al., 2016). However, as convective air drying is the most common method used to reduce water activity, characterization of fruit samples during this process is necessary to assess the effects of drying on the final product quality. Furthermore, the experimental behavior of guava samples can be described by fitted mathematical models for dryer design purposes.

Therefore, this chapter focuses on quality assessment of guava samples using chemical, color and shrinkage analyses. The kinetics of guava during convective drying is presented and fitted with mathematical models.
8.2 DRYING PROCESS AND QUALITY EVALUATION

8.2.1 Sample preparation and drying

Red pear guava fruits were obtained from the state of Santander, Colombia. Fruits in good condition with degrees of ripeness 5 and 6 were selected for the study using colour charts. Figure 8.1 shows the fresh fruit and slices used in the study.

![Figure 8.1: Guava samples used in the study.](image)

Selected fruits were washed with water to remove foreign material and possible contaminants before being disinfected and processed with a 1% water-vinegar solution. Afterwards, the fruits were peeled and minced to obtain a homogeneous pulp that was later passed through a sieve to remove seeds and to obtain the pulp samples for drying. For the sliced samples, 4 mm-thick slices were cut. Concurrently, a weight evaluation was carried out to obtain the pulp, peel and seed percentages for a representative group of fruits. To do so, a sample of ten fresh guava fruits was taken from the main sample used in the study. Each of these guavas were independently weighted. Afterwards, every fruit was peeled and weighted again. Using a blender, a homogeneous guava puree was obtained and passed through a sieve to separate seeds. These seeds were weighted as well as the remaining pulp. Pulp, peel and seeds weights were averaged and their percentages were computed in relation to the fresh guava average weight.

Initial characterization of guava samples

Initial characterization to determine the initial moisture content of the samples was carried out using the oven method, which consists of taking 100g of the studied material inside an oven (BINDER APT.line FD) at 103 ± 2°C, until the weight of the sample remained constant. The total soluble solids were determined using an analog refractometer (Hanna HI 96801 brand) and the pH was determined using pH-meter (Hanna IT 9425 brand).
Characterization of guava

The guava used in the experiments had wet basis moisture that ranged between 89% and 91%; in the range of 6.9 to 8.5 Brix at 26°C and pH 4.0. The average fresh weight of the fruits was 145g (19% skin, 8% seeds and 73% pulp).

Drying procedure

Pulp samples and guava slices were dried in a forced air oven that flowed parallel towards the samples (BINDER APT.line FD) at three different temperatures (50°C, 60°C and 70°C) and three different masses (100g, 125g and 150g) using a 27.3 cm x 16.2 cm plastic trays. The mass of the samples were determined with a digital weighing scale (OHaus, resolution 0.001g) which measured the mass reduction during drying. At each repetition, the weight of the products on the tray was recorded. Measurements were taken every 15min during the first hour of the experiment; every 30min in the following two hours, and then every hour until the end of drying (final moisture content of 1.5% or equilibrium moisture depending on the specific assessment). The surface temperature of the samples was monitored during drying with a Fluke 62 MAX infrared thermometer. The experiments were conducted as a completely randomized single-factor experiment in three replicates.

Drying curves

The objective of this part of the work was to analyse at a given temperature the behaviour of the guava pulp and slices during drying i.e. moisture content vs. drying time and drying rate vs. drying time. Subsequently, thin layer mathematical models were fitted for moisture ratio vs. drying time. Additionally, the drying kinetics differences between the guava pulp and slices were observed, and the relationship between the guava surface temperature and the drying time was analyzed. Moisture ratio ($MR$) and drying rate ($R_d$) of the guava pulp and slices samples were calculated by using the following equations: (1) and (2) (Mujumdar, 2015)

$$MR = \frac{(X_t - X_e)}{(X_i - X_e)}$$  \hspace{1cm} (1)

$$R_d = \frac{dX}{dt}$$  \hspace{1cm} (2)

Where: $X_e$ is equilibrium moisture content, $X_i$ is initial moisture, $t$ is drying time, $X$ is the moisture content (g water/g dry matter). For mathematical modeling, several thin layer drying models were fitted to select the best model.
8.2.2 Quality evaluation

Color analysis

Both guava pulp and slices were evaluated using a chromameter (calibrated before each measurement) before and after the moisture content was 1.2% ± 0.2%. The color of the fresh product was measured prior to drying. The color analysis was based on chromaticity values in the CIELAB color space. The color parameters were expressed as L* describing lightness (L*=100 for white, L*=0 for black), a* describing intensity in green-red (a*<0 for green, a*>0 for red) and b* describing intensity in blue-yellow (b*<0 for blue, b*>0 for yellow).

Two additional parameters were determined for the image analysis. The first one was Chrome (C*), indicating color saturation (normally proportional to its intensity) and the second one was Hue (h*), used for the color classifications (where an angle of 0° or 360° indicated red hue, while angles of 270°, 180° and 90° indicated blue, green and yellow hues respectively). These parameters were calculated as:

\[ C_{ab} = \sqrt{(a^*)^2 + (b^*)^2} \]  

\[ h^* = \tan^{-1} \frac{b^*}{a^*} \]  

\[ \Delta E = \sqrt{\Delta L^*^2 + \Delta a^*^2 + \Delta b^*^2} \]  

\[ \Delta H = \sqrt{(a^*)^2 + (b^*)^2 + \Delta C^*^2} \]

Volatile compounds analysis

Extraction by Headspace-Solid Phase Micro Extraction (HS-SPME).

The solids obtained from guava pulp and slices after drying were homogenized and placed in a 100ml vial containing a magnetic stirring bar. About 50ml of water were added, and cinnamic acid and ethyl ester were used as internal standards (50ul, 100ppm). The vial was sealed by an air-tight Teflon septum and an aluminium cap and incubated at 30°C for 30 min in a water bath. A 2-cm SPME fiber (50/30um DVB/CAR/PDMS; Supelco, Bellefonte, PA, USA) was manually inserted into the headspace of the sample vial and exposed for 30 min. The volatile compounds were thermally desorbed in the GC injection port (splitless mode) for 5 min at 250°C.

Gas Chromatography-Mass Spectrometry (GCMS) analysis

GCMS analyses of the SPME fiber were conducted using an Agilent GC7890 chromatograph coupled with an Agilent MS5975 mass spectrometer. After desorption of volatile compounds from SPME fiber, the analyses were separated on a HP-FFAP column (30m x 0.25mm i.d., 0.25 um df) (Agilent
Technologies, USA) according to the following temperature program: started at 40°C held for 3 min, and then increased to 180°C at a rate of 6°C/min, then increased to a 250°C at a rate of 12°C/min, with a final holding time of 5 min. Helium was used as a carrier gas at a flow rate of 1.0ml/min, injector and detector temperature at 250°C. MS was operated in electronic impact (EI) mode 700eV, mass range 40-350 atomic mass units, source temperature 280°C and transfer line temperature 250°C.

**Volatile compound identification**

Tentative identification was attempted by comparison of the retention index (RI) and mass spectra against NIST spectrum data base using NIST MS Search 2.0 (NIST, Gaitherburg, MD, USA). Retention indices (RI) were calculated using a homologous series of C10-C25 alkanes standard solution. Chemical authentic standards, when available, were analyzed under the same chromatographic conditions and their RI and mass spectra confirmed compounds identities.

**Shrinkage analysis**

The shrinkage presented in the product was observed by monitoring the total surface area (\(\text{\(A\)}\)) of the samples of guava pulp and slices during the convective drying process. Samples were photographed with a digital camera. The lighting conditions, distance and optics were standardized to ensure repeatability.

A methodology based on image analysis was used to determine the surface area (\(\text{\(A\)}\)) of the pulp. The methodology allows finding the edges of the sample, in addition to defining contour and the surface area (\(\text{\(A\)}\)) within it. The thickness (\(\text{\(T_h\)}\)) of the samples was measured (in different points of the sample) with a digital micro-meter for heights in the rubbery state and with a digital micro-meter for the outsides in the glassy state. The volume of the sample is determined as follows:

\[
V = AT_h
\]  

The estimation of size reduction (shrinkage) and shape change (deformation) for the different samples was accomplished by using the described dimensional measurement strategy.

The volume ratio that represents the shrinkage is determined as follows:

\[
\text{Volume ratio} = V/V_o
\]

Where \(V_o\) is the initial volume of the sample.
8.3 DRYING AND PRODUCT QUALITY

8.3.1 Drying

Drying kinetics describes the heat and mass transfer mechanisms between the hot air and the guava samples. The analysis serves to understand its behaviour and to determine drying parameters.

**Drying time**

The effects of both drying-air temperature and sample mass on the time required to reach the final moisture content (0.8 to 1.2% wet basis) are shown in Figure 8.2. The total drying time is inversely proportional to the air temperature, being 450 min the shortest one. This time corresponds to the lower mass and higher temperature condition; and it was 52% lower than the higher mass and lower temperature condition. When mass was kept constant, the shortest time (70°C) was 29% lower than the longest one (50°C).

![Figure 8.2: Drying time versus drying temperature for guava pulp.](image)

**Drying kinetics**

The variation of drying rate with dry basis (\(db\)) moisture content during thin layer drying at 60°C (Figure 8.3) indicates that molecular diffusion is the mass transfer mechanism governing the process. It can be observed that there is no constant rate drying period.
In the glassy state, the temperature is the most influential factor. The diffusivity increases as the temperature increases, in consequence so does the transfer of vapour to the hot air. The drying air temperature has a significant effect on the evolution of the moisture content. Figure 8.4 shows the variation of moisture content with time for the different samples evaluated.

As shown in Figure 8.3, the regime of drying process of pulps and slices is at decreasing speed. In this period, moisture removed is the one that is linked to the material. Under these conditions, the material has a hygroscopic behaviour. In treatments for slices and pulps, the drying rate varied and drying periods could not be clearly identified.

**Figure 8.3:** Plot of the drying rate versus moisture content of guava pulp and slices at 60°C and layer thickness corresponding to 100g of product.

**Fitting to mathematical models**

In mathematical modelling, some models are commonly used to describe the falling rate period of drying. These include the diffusion model based on the diffusion transport of water, the receding front model based mostly on capillary transport and the model based on the complete conservation equations, which give mathematically complex formulations. The complexity levels of the models depend on considering shrinkage or non-shrinkage, assuming isothermal conditions or non-isothermal conditions and assuming moisture concentration dependence of the diffusion coefficient. Two major boundary conditions distinguishing these models are the moving boundary condition, which takes shrinkage into account, and the equilibrium boundary condition at the surface, which is associated with no external resistance. Most models are usually based on the assumptions that the external surface of the material is
at equilibrium and the geometry (shape) is unchanged (no shrinkage) (Srikiatden & Roberts, 2007).

Figure 8.4: Plot of the moisture content versus drying time of guava pulp and slices at 60°C.

Figure 8.5 shows plot of the experimental moisture ratio versus drying time of guava pulp and slices for drying conditions at 60°C. From the data, we can observe that there are no significant differences in the drying kinetics considering the two strategies. Table 8.1 shows the results of the nonlinear regression analysis upon fitting the experimental data with thin layer models. The experimental data correspond to 100g guava pulp and slices dried at 60°C. In both cases, Wang and Singh model shows the best fit.
Figure 8.5: Plot of the moisture ratio versus drying time of guava pulp and slices at 60°C and layer thickness corresponding to 100g of product.

Table 8.1: Best-fit models for convective drying of guava.

<table>
<thead>
<tr>
<th></th>
<th>Pulp</th>
<th>Chi²</th>
<th>R²</th>
<th>Slices</th>
<th>Chi²</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wang and Singh</td>
<td>$1 - 0.0036888t + 3.382257t \times 10^{-4}t^2$</td>
<td>0.0005</td>
<td>0.9854</td>
<td>$1 - 0.0043388t + 4.6508421t \times 10^{-4}t^2$</td>
<td>0.0011</td>
<td>0.9736</td>
</tr>
<tr>
<td>Lewis</td>
<td>$e^{-0.00478515t}$</td>
<td>0.0039</td>
<td>0.8739</td>
<td>$e^{-0.00551025t}$</td>
<td>0.0047</td>
<td>0.8606</td>
</tr>
<tr>
<td>Fick's</td>
<td>$1.06531577e^{-1.2046641t}$</td>
<td>0.0032</td>
<td>0.9433</td>
<td>$1.07612498e^{-1.003662t}$</td>
<td>0.0039</td>
<td>0.9424</td>
</tr>
</tbody>
</table>

Figure 8.6 summarizes the values of moisture ratio obtained experimentally by drying both guava pulp and slices at 60°C. These data were used to fit the mathematical models of thin layer drying. Other known models were tested (Henderson and Pabis, Page, Two Term, Midilli and Kucuk) but not showing any acceptable fit.
Figure 8.6: Plot of the best fitted thin layer drying model of guava pulp and slices at 60°C and layer thickness corresponding to 100g of product.

Surface temperature of guava samples during the drying process has great influence in quality characteristics. Figure 8.7 shows the surface temperature of guava pulp and the drying air temperatures as a function of time. It can be observed that the temperature of the surface is below the air drying temperature due to evaporative cooling. At the beginning of the process, the temperature difference is higher and diminishes as the drying time increases. This is related to the decrease of the moisture content of the product and
consequently to the decrease of free water on the surface of guava pulp that produces a decrease in the process of evaporative cooling.

Figure 8.7: Plot of the surface temperature of guava pulp versus drying time for layer thickness corresponding to 100g.

8.3.2 Product quality

Drying increases the product’s shelf life but quality can be negatively affected by temperature and drying time. High-temperature drying activates a great number of physical and chemical reactions that are closely related to product alterations in color, composition and loss of volatile compounds. Knowledge about the product during drying contributes to improving this process and consequently to having better dried products. The following sections discuss the drying effect on three different quality characteristics of guava pulp and slices.

Color analysis

Changes in color during drying at 60°C can be observed in Figure 8.8. On the other hand, Table 8.2 presents the statistical results of color measurement (CIELAB color parameters) at different temperatures. The drying air temperature has a significant effect on the color of the dried samples as suggested by the $h^*$ value in Table 8.2.

Samples of guava pulp and slices show the highest $h^*$ values for air drying temperature of 60°C and masses of 100g (50.06 and 55.55 respectively). This
indicates that the final color is much more yellowish and therefore almost similar to the color of the fresh samples (reference).

**Figure 8.8:** Color changes in the samples during drying of the guava pulp and slices at 60°C and layer thickness corresponding to 100g.

Considering drying temperature at 50°C, 150g of samples of guava pulp and slices showed the highest color variations of 21.45 and 19.21, respectively; at 60°C, 150g of guava pulp and slices presented the highest color variations of 16.8 and 11.18, respectively. Finally, at 70°C, 150g of guava pulp and 125g of guava slices presented the highest variations of 13.38 and 15.81, respectively.
### Table 8.2: CIELAB color parameters for drying slices and pulp of guava at different air drying temperatures.

<table>
<thead>
<tr>
<th></th>
<th>PULP</th>
<th></th>
<th></th>
<th>100g</th>
<th>125g</th>
<th>150g</th>
<th>100g</th>
<th>125g</th>
<th>150g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L*</td>
<td>a*</td>
<td>b*</td>
<td>L*</td>
<td>a*</td>
<td>b*</td>
<td>L*</td>
<td>a*</td>
<td>b*</td>
</tr>
<tr>
<td>Fresh</td>
<td>54</td>
<td>49</td>
<td>30</td>
<td>50</td>
<td>46</td>
<td>28</td>
<td>50</td>
<td>46</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>57.45</td>
<td>53.85</td>
<td></td>
<td>53.85</td>
<td>53.85</td>
<td>53.85</td>
<td>53.85</td>
<td>53.85</td>
<td>53.85</td>
</tr>
<tr>
<td>50°C</td>
<td>L*</td>
<td>45</td>
<td>35</td>
<td>24.00</td>
<td>26</td>
<td>29</td>
<td>14.63</td>
<td>15.07</td>
<td>21.45</td>
</tr>
<tr>
<td></td>
<td>a*</td>
<td>35</td>
<td>38</td>
<td>31.00</td>
<td>37</td>
<td>32</td>
<td>48.10</td>
<td>51.66</td>
<td>39.20</td>
</tr>
<tr>
<td></td>
<td>b*</td>
<td>33</td>
<td>35</td>
<td>22.00</td>
<td>26</td>
<td>29</td>
<td>38.41</td>
<td>40.69</td>
<td>33.21</td>
</tr>
<tr>
<td></td>
<td>C*</td>
<td>48.10</td>
<td>51.66</td>
<td>45.22</td>
<td>43.19</td>
<td>44.05</td>
<td>48.10</td>
<td>51.66</td>
<td>39.20</td>
</tr>
<tr>
<td></td>
<td>h*</td>
<td>41.59</td>
<td>58.59</td>
<td>67.65</td>
<td>44.89</td>
<td>21.34</td>
<td>41.59</td>
<td>43.53</td>
<td>58.59</td>
</tr>
<tr>
<td>60°C</td>
<td>L*</td>
<td>56</td>
<td>53</td>
<td>53</td>
<td>57</td>
<td>55</td>
<td>56</td>
<td>56</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>a*</td>
<td>39</td>
<td>33</td>
<td>40</td>
<td>39</td>
<td>36</td>
<td>39</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>b*</td>
<td>26</td>
<td>32</td>
<td>29</td>
<td>27</td>
<td>24</td>
<td>26</td>
<td>32</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>∆E*</td>
<td>10.95</td>
<td>16.79</td>
<td>9.27</td>
<td>8.66</td>
<td>11.18</td>
<td>10.95</td>
<td>13.30</td>
<td>16.79</td>
</tr>
<tr>
<td></td>
<td>C*</td>
<td>46.87</td>
<td>48.17</td>
<td>49.41</td>
<td>47.43</td>
<td>43.27</td>
<td>46.87</td>
<td>48.17</td>
<td>48.17</td>
</tr>
<tr>
<td></td>
<td>H*</td>
<td>15.52</td>
<td>19.25</td>
<td>12.44</td>
<td>11.88</td>
<td>15.69</td>
<td>15.52</td>
<td>16.35</td>
<td>19.25</td>
</tr>
<tr>
<td></td>
<td>h*</td>
<td>72.82</td>
<td>32.06</td>
<td>64.67</td>
<td>69.10</td>
<td>72.82</td>
<td>72.82</td>
<td>46.51</td>
<td>32.06</td>
</tr>
<tr>
<td>70°C</td>
<td>L*</td>
<td>53</td>
<td>45</td>
<td>36</td>
<td>39</td>
<td>31</td>
<td>53</td>
<td>56</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>a*</td>
<td>38</td>
<td>35</td>
<td>39</td>
<td>31</td>
<td>34</td>
<td>38</td>
<td>45</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>b*</td>
<td>32</td>
<td>27</td>
<td>33</td>
<td>32</td>
<td>29</td>
<td>32</td>
<td>35</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>∆E*</td>
<td>11.22</td>
<td>13.38</td>
<td>9.11</td>
<td>15.81</td>
<td>15.03</td>
<td>11.22</td>
<td>6.71</td>
<td>13.38</td>
</tr>
<tr>
<td></td>
<td>C*</td>
<td>49.68</td>
<td>57.01</td>
<td>51.09</td>
<td>44.55</td>
<td>44.69</td>
<td>49.68</td>
<td>57.01</td>
<td>51.09</td>
</tr>
<tr>
<td></td>
<td>H*</td>
<td>13.69</td>
<td>18.31</td>
<td>9.98</td>
<td>18.59</td>
<td>18.05</td>
<td>13.69</td>
<td>7.01</td>
<td>18.31</td>
</tr>
<tr>
<td></td>
<td>C*</td>
<td>-7.78</td>
<td>-12.45</td>
<td>-2.76</td>
<td>-9.30</td>
<td>-9.16</td>
<td>-7.78</td>
<td>-0.45</td>
<td>-12.45</td>
</tr>
<tr>
<td></td>
<td>h*</td>
<td>51.14</td>
<td>61.50</td>
<td>50.72</td>
<td>34.23</td>
<td>50.04</td>
<td>51.14</td>
<td>58.18</td>
<td>61.50</td>
</tr>
</tbody>
</table>

**Volatile compounds**

Volatile compounds of guava pulps and slices after hot air drying with three different sample masses and three different temperatures were extracted by Headspace-Solid Phase Micro Extraction (HS-SPME). Table 8.3 and Table 8.4 show the volatile compounds, retention indices (HP-FFAP) and concentration (ug/Kg sample) of 9 samples of guava slices and guava pulp respectively. A total of 28 volatile compounds from guava powders were identified.
Table 8.3: Volatile compounds of guava slices (*Psidium guajava* L.) obtained by hot air drying using HS-SPME and GC-MS analysis.

<table>
<thead>
<tr>
<th>No. a</th>
<th>Compound</th>
<th>RI exp a</th>
<th>50-100 d</th>
<th>50-125 d</th>
<th>50-150 d</th>
<th>60-100 d</th>
<th>60-125 d</th>
<th>60-150 d</th>
<th>70-100 d</th>
<th>70-125 d</th>
<th>70-150 d</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acetic acid, ethyl ester</td>
<td>&lt;1000</td>
<td>225.5</td>
<td>354.4</td>
<td>376.3</td>
<td>338.0</td>
<td>39.8</td>
<td>11.3</td>
<td>100.0</td>
<td>257.4</td>
<td>138.0</td>
</tr>
<tr>
<td>2</td>
<td>Butanal, 2-methyl</td>
<td>&lt;1000</td>
<td>24.7</td>
<td>27.0</td>
<td>25.6</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>112.5</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Butanal, 3-methyl</td>
<td>&lt;1000</td>
<td>45.4</td>
<td>61.0</td>
<td>68.4</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>285.0</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Furan, 2-ethyl-Butanoic acid, ethyl ester b,c</td>
<td>1024</td>
<td>386.5</td>
<td>443.5</td>
<td>355.7</td>
<td>99.1</td>
<td>nd</td>
<td>nd</td>
<td>80.7</td>
<td>178.0</td>
<td>115.5</td>
</tr>
<tr>
<td>5</td>
<td>Hexanal b,c</td>
<td>1045</td>
<td>681.3</td>
<td>867.8</td>
<td>782.3</td>
<td>132.7</td>
<td>68.6</td>
<td>76.3</td>
<td>208.2</td>
<td>301.8</td>
<td>301.4</td>
</tr>
<tr>
<td>6</td>
<td>1-Butanol, 3-methyl-, acetate</td>
<td>1091</td>
<td>20.7</td>
<td>50.5</td>
<td>53.0</td>
<td>459.4</td>
<td>150.5</td>
<td>nd</td>
<td>nd</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Hexanoic acid, methyl ester c</td>
<td>1194</td>
<td>154.5</td>
<td>95.9</td>
<td>49.8</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2-Hexenal, (E)-c</td>
<td>1216</td>
<td>nd</td>
<td>nd</td>
<td>30.3</td>
<td>112.2</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2-Hexen-1-ol, (E)-c</td>
<td>1235</td>
<td>275.6</td>
<td>nd</td>
<td>511.9</td>
<td>nd</td>
<td>nd</td>
<td>124.0</td>
<td>278.5</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Hexanoic acid, ethyl ester c</td>
<td>1241</td>
<td>1583.3</td>
<td>2436.6</td>
<td>1687.4</td>
<td>269.4</td>
<td>nd</td>
<td>87.8</td>
<td>124.2</td>
<td>191.7</td>
<td>139.5</td>
</tr>
<tr>
<td>11</td>
<td>Acetic acid, hexyl ester</td>
<td>1281</td>
<td>72.2</td>
<td>176.2</td>
<td>159.7</td>
<td>265.2</td>
<td>202.2</td>
<td>49.9</td>
<td>81.0</td>
<td>249.4</td>
<td>91.0</td>
</tr>
<tr>
<td>12</td>
<td>3-Hexan-1-ol, acetate, (Z)-c</td>
<td>1317</td>
<td>299.8</td>
<td>1269.9</td>
<td>1396.2</td>
<td>325.5</td>
<td>316.8</td>
<td>66.1</td>
<td>137.6</td>
<td>664.3</td>
<td>nd</td>
</tr>
<tr>
<td>13</td>
<td>5-Hepten-2-one, 6-methyl</td>
<td>1352</td>
<td>450.5</td>
<td>473.3</td>
<td>344.8</td>
<td>308.2</td>
<td>325.3</td>
<td>289.9</td>
<td>257.3</td>
<td>427.9</td>
<td>394.5</td>
</tr>
<tr>
<td>14</td>
<td>Octanoic acid, methyl ester</td>
<td>1399</td>
<td>37.9</td>
<td>117.7</td>
<td>92.9</td>
<td>29.8</td>
<td>96.1</td>
<td>29.8</td>
<td>nd</td>
<td>nd</td>
<td>8.3</td>
</tr>
<tr>
<td>15</td>
<td>Nonanal b</td>
<td>1408</td>
<td>390.2</td>
<td>171.8</td>
<td>131.3</td>
<td>65.8</td>
<td>38.6</td>
<td>49.2</td>
<td>113.6</td>
<td>170.5</td>
<td>98.4</td>
</tr>
<tr>
<td>16</td>
<td>Octanoic acid, ethyl ester</td>
<td>1444</td>
<td>88.5</td>
<td>364.1</td>
<td>420.6</td>
<td>87.0</td>
<td>62.4</td>
<td>34.1</td>
<td>42.1</td>
<td>56.5</td>
<td>38.8</td>
</tr>
<tr>
<td>17</td>
<td>Acetic acid b</td>
<td>1462</td>
<td>nd</td>
<td>202.8</td>
<td>187.6</td>
<td>nd</td>
<td>120.8</td>
<td>135.1</td>
<td>23.0</td>
<td>nd</td>
<td>155.9</td>
</tr>
<tr>
<td>18</td>
<td>2-furan-carboxaldehyde</td>
<td>1490</td>
<td>nd</td>
<td>nd</td>
<td>80.9</td>
<td>nd</td>
<td>62.2</td>
<td>96.6</td>
<td>26.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Caryophyllene c</td>
<td>1625</td>
<td>nd</td>
<td>nd</td>
<td>61.0</td>
<td>nd</td>
<td>124.7</td>
<td>nd</td>
<td>nd</td>
<td>110.9</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Decanoic acid, ethyl ester</td>
<td>1649</td>
<td>64.8</td>
<td>211.8</td>
<td>290.1</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
</tbody>
</table>

a. RI = Retention Index on HP-FFAP; b. Previously detected in studies with pink guava aroma (Steinhaus et al., 2009); c. Identified by comparison with reference standards; d. first number is temperature in Celsius and second number is amount of product in grams; e. Concentration (ug of internal standard=cinamamic acid, ethyl ester/ Kg of product); nd= not detected.
Table 8.4: Volatile compounds of guava pulp (*Psidium guajava* L.) obtained by hot air drying using HS-SPME and GC-MS analysis.

<table>
<thead>
<tr>
<th>No.</th>
<th>Compound</th>
<th>RI EXP&lt;sup&gt;a&lt;/sup&gt;</th>
<th>50-100&lt;sup&gt;d&lt;/sup&gt;</th>
<th>50-125&lt;sup&gt;d&lt;/sup&gt;</th>
<th>60-100&lt;sup&gt;d&lt;/sup&gt;</th>
<th>60-125&lt;sup&gt;d&lt;/sup&gt;</th>
<th>70-100&lt;sup&gt;d&lt;/sup&gt;</th>
<th>70-125&lt;sup&gt;d&lt;/sup&gt;</th>
<th>70-150&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Butanoic acid, ethyl ester&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>1044</td>
<td>34.0</td>
<td>55.8</td>
<td>37.4</td>
<td>nd</td>
<td>nd</td>
<td>180.8</td>
<td>217.4</td>
</tr>
<tr>
<td>6</td>
<td>Hexanal&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>1045</td>
<td>353.2</td>
<td>542.2</td>
<td>258.6</td>
<td>106.1</td>
<td>128.2</td>
<td>190.5</td>
<td>395.3</td>
</tr>
<tr>
<td>8</td>
<td>Hexanoic acid, methyl ester&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1194</td>
<td>24.8</td>
<td>45.5</td>
<td>31.7</td>
<td>nd</td>
<td>nd</td>
<td>51.3</td>
<td>nd</td>
</tr>
<tr>
<td>9</td>
<td>D-Limonene&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1204</td>
<td>47.9</td>
<td>109.5</td>
<td>118.6</td>
<td>84.5</td>
<td>119.4</td>
<td>58.4</td>
<td>nd</td>
</tr>
<tr>
<td>10</td>
<td>2-Hexenal, (E)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1216</td>
<td>40.8</td>
<td>nd</td>
<td>265.8</td>
<td>194.3</td>
<td>240.9</td>
<td>309.1</td>
<td>nd</td>
</tr>
<tr>
<td>12</td>
<td>Hexanoic acid, ethyl ester&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1241</td>
<td>466.6</td>
<td>574.5</td>
<td>341.2</td>
<td>375.1</td>
<td>335.6</td>
<td>474.3</td>
<td>361.5</td>
</tr>
<tr>
<td>13</td>
<td>Acetic acid, hexyl ester trans-2-(2-Pentenyl)furan</td>
<td>1281</td>
<td>166.9</td>
<td>243.2</td>
<td>174.9</td>
<td>52.4</td>
<td>182.3</td>
<td>72.4</td>
<td>1065.8</td>
</tr>
<tr>
<td>15</td>
<td>3-Hexen-1-ol, acetate, (Z)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1313</td>
<td>33.7</td>
<td>56.8</td>
<td>34.6</td>
<td>40.2</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>16</td>
<td>5-Hepten-2-one, 6-methyl-Octanoic acid, methyl ester</td>
<td>1317</td>
<td>1192.1</td>
<td>1745.7</td>
<td>1251.6</td>
<td>97.9</td>
<td>111</td>
<td>137.4</td>
<td>1065.8</td>
</tr>
<tr>
<td>18</td>
<td>Nonanal</td>
<td>1352</td>
<td>404.5</td>
<td>387.1</td>
<td>334.0</td>
<td>287.3</td>
<td>389.8</td>
<td>466.6</td>
<td>810.3</td>
</tr>
<tr>
<td>19</td>
<td>Furan, 3-(4-methyl-3-pentenyl)-Octanoic acid, ethyl ester</td>
<td>1399</td>
<td>64.6</td>
<td>79.1</td>
<td>53.9</td>
<td>34.4</td>
<td>29.6</td>
<td>48.4</td>
<td>119.4</td>
</tr>
<tr>
<td>21</td>
<td>Acetic acid</td>
<td>1408</td>
<td>72.2</td>
<td>62.1</td>
<td>52.6</td>
<td>71.8</td>
<td>87.8</td>
<td>76.3</td>
<td>125.1</td>
</tr>
<tr>
<td>22</td>
<td>1-Hexanol, 2-ethyl acetate</td>
<td>1434</td>
<td>37.8</td>
<td>65.2</td>
<td>39.1</td>
<td>nd</td>
<td>48.8</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>23</td>
<td>2-furan-carboxaldehyde</td>
<td>1444</td>
<td>319.6</td>
<td>343.8</td>
<td>210.6</td>
<td>187.9</td>
<td>170.9</td>
<td>212.8</td>
<td>142.7</td>
</tr>
<tr>
<td>24</td>
<td>Caryophyllene&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1462</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>142.2</td>
<td>213.0</td>
<td>235.0</td>
<td>254.1</td>
</tr>
<tr>
<td>25</td>
<td>Decanoic acid, ethyl ester&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1486</td>
<td>1716.6</td>
<td>2130.2</td>
<td>1480.7</td>
<td>nd</td>
<td>nd</td>
<td>541.4</td>
<td>336.7</td>
</tr>
<tr>
<td>26</td>
<td>Benzoic acid, ethyl ester&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>1490</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>44.6</td>
<td>nd</td>
<td>108.3</td>
<td>92.8</td>
</tr>
<tr>
<td>27</td>
<td>Citral&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1499</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>62.7</td>
<td>50.6</td>
<td>nd</td>
<td>95.7</td>
</tr>
<tr>
<td>28</td>
<td>trans-beta-Ionone&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1649</td>
<td>193.4</td>
<td>250.2</td>
<td>164.3</td>
<td>97.2</td>
<td>122.4</td>
<td>113.1</td>
<td>41.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1705</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>138.5</td>
<td>176.8</td>
<td>244.1</td>
<td>183.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1759</td>
<td>175.4</td>
<td>nd</td>
<td>102.7</td>
<td>73.3</td>
<td>117.1</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1974</td>
<td>235.8</td>
<td>221.4</td>
<td>51.9</td>
<td>72.8</td>
<td>79.5</td>
<td>nd</td>
<td>103.1</td>
</tr>
</tbody>
</table>

a. RI= retention index on HP-FFAP; b. Previously detected in studies with pink guava aroma (Steinhaus et al., 2009); c. Identified by comparison with reference standards; d. first number is temperature in Celsius and second number is amount of product in grams; e. Concentration (ug of internal standard=cinnamic acid, ethyl ester/ Kg of product); nd= not detected.

For both guava pulps and guava slices samples, the major volatile compounds are esters. However, in the guava pulp samples there are more terpenes while in the slices there are more aldehydes. When the drying temperature increases, the amount of esters decreases; while the amount of alcohol, ketone and acids are higher.

The volatile composition is similar to those established for aroma of Colombian fruits (Steinhaus et al., 2008; Steinhaus et al., 2009; Sinuco et al,
However important aroma compounds like 3-sulfanyl hexanol and 3-sulfanyl hexyl acetate are not extracted by HS-SPME (Cantillo et al., 2011). These results are in line with previous results for fresh fruit from France (Paniandy et al., 2000) where the aroma is mainly due to C6-aldehydes, while for fruits from Brazil (Carsek et al., 2006; Cardeal et al., 2005) esters and terpenes are the principal compound in HS.

Considering the relevance of mass and drying temperature in changing the volatile composition of guava pulps and slices, a correspondence analysis (CA) reveals that the variability can be explained into a 77.2% only for the first two dimensions. This result indicates that there is a significant variation in the drying temperature. Variations of samples at 50°C are due to 1-Hexanol, 2-ethyl-, acetate (A22), at 60°C to 2-Hexenal-(E) (A10) and at 70°C to Butanoic acid, ethyl ester (A5) and Acetic acid, hexyl ester (A13) (Figure 8.9).

![Figure 8.9: Correspondence Analysis (CA) of solids obtained from guava pulp. A50, A60, A70 (temperatures 50°C, 60°C and 70°C respectively); 100, 125, 150 (three different layer thicknesses corresponding to 100g, 125g and 150g of product. Triangle shaped points correspond to Table 8.4.](image)

PCA (Principal Component Analysis) was used to represent the data in two dimensions in order to differentiate each sample of the drying process. The first two principal components (PC) explained a variation of 67.9% of the volatile compounds in each treatment. PCA was suitable to differentiate pulp samples according to their spatial location. For the pulp samples, PCA shows clear differences between the drying temperatures. The solids obtained at
70°C are loaded positively in PC1 and PC2; as for powders, at 60°C results are loaded around zero in PC1 and negatively in PC2, and at 50°C loaded negatively in PC1 and positively in PC2 (Figure 8.10).

From the same Figure 8.10, it is possible to state that products obtained at 50°C are related to octanoic acid, ethyl ester (A20), trans-2-(2-pentenyl) furan (A14) and decanoic acid, ethyl ester (A25). At 60°C the difference can be due to 2-hexenal-(E) (A10) and at 70°C, nonanal (A18) and acetic acid (A21) show the main variations.

Figure 8.10: Principal Component Analysis (PCA) of solids obtained from guava pulp. A50, A60, A70 (temperatures 50°C, 60°C and 70°C respectively); 100, 125, 150 (three different layer thicknesses corresponding to 100g, 125g and 150g of product. Points A correspond to Table 8.4.

For the guava slices, it was not possible to find a correlation and variability effect because the variation with the two first components explains only by 60% (data not shown). It was also not possible to find significant differences between treatments.

In this way, HS-SPME provides information about volatile compounds behavior according to shape, mass and temperature in hot air drying of fresh guava. It is therefore possible to have products with similar volatile composition using the same drying temperatures even at different amount of guava pulps.

Shrinkage

Figure 8.11 shows SEM images of structural changes in the product surface for six states during convection drying of guava pulps at 60°C, from the initial
condition \( (t = 0 \text{ min}, \ X = 10.6 \ g/g) \) in image 1, until the end of the drying process \( (t = 570 \text{ min}, \ X = 0.02 \ g/g) \) in image 6. In image 1, a doughy structure is observed corresponding to the rubbery state. Moreover, we can see nodule formation and porosity in images 3, 4 and 5. In image 5 at 390 minutes and low moisture level \( (X = 0.72 \ g/g) \), there are more marked nodules and pores; at this point the transformation from rubbery to glassy state has already occurred. Image 6 at 570 minutes of drying time shows the material in the glassy state. At this low moisture point, the material becomes more rigid and shrinkage stops, generating this type of porous structure on the surface. The formation of parallel pores can be observed, which is typical for condition that no longer has greater shrinkage.

![Figure 8.11](image)

**Figure 8.11**: SEM images (60X) showing the shrinkage evolution during convective drying of guava pulps at drying temperature of 60°C.

An example of shrinkage and deformation observed during convective drying of guava pulp is presented in **Figure 8.12**. The diagram shows six contours that indicate the general deformation of the edge of the pulps during drying at 60°C. From the initial state (at \( t = 0 \text{ min} \)) with a surface area of 8611 mm² to the end of the process (at \( t = 435 \text{ min} \)) with a surface area of 4334 mm², there is a reduction of 50% in the surface area. In addition, a reduction of 41% in the average thickness was observed, from the initial to the final state of drying. Considering the contours in **Figure 8.12**, it can be seen that although shrinkage occurs from the beginning of the drying process, the contour
Cuervo-Andrade et al. - Drying process and Quality Evaluation of Guava

deflection appears at the final stages when moisture content is low (Ortiz, 2015).

Figure 8.12: Example of contours representing the evolution of the main edge deformation of guava pulps at the drying temperature of 60°C.

Guava pulps is a semisolid system and can be considered as a heterogeneous material consisting of a three-dimensional solid network or matrix usually holding large quantities of liquid phase (aqueous solution). When water is removed from the material, a pressure unbalance is produced between the inner and outer regions, generating contracting stresses that lead to material shrinkage or collapse, changes in shape and occasionally cracking of the product.

Shrinkage of food materials during drying process has, in general, a negative consequence on the quality of the dehydrated product. Changes in shape, loss of volume and increased hardness in most cases cause a negative impression to the consumer. Another important consequence of shrinkage is the decrease of rehydration capability of the dried product. For these reasons it is required to study the mechanisms that influence the shrinkage of each product in order to achieve the desired quality characteristics.

Considering the drying process of guava pulps by convective drying, there are several factors affecting the magnitude of shrinkage: volume of removed water, mobility of solid matrix, drying rate and processing conditions. In general, shrinkage of food materials increases with the volume of removed water and as more water is removed, the more contraction stresses are generated within the material (Mayor and Sereno, 2004).

Figure 8.13 shows the volume ratio of removed water ($V_w/V_o$) related to the fractional decrease in the sample volume ($V_o-V/V_o$) for convective drying of guava pulps at 60°C. The points at the diagonal represent that the ratio of
removed water which is the same as the fractional decrease in the sample volume. Considering the experimental data in Figure 8.13, it can be seen that, in general, the points are above the diagonal. This behavior can be explained by the decrease in the mobility of the solid matrix of the product. The mobility of the matrix is related to its constitutive mechanical behavior. The low mobility of the matrix, in this case, can be associated with its elasticity typical of a glassy state. In contrast, high mobility is associated with its viscoelasticity typical of a rubbery state.

Figure 8.13: Volume ratio of removed water \( (V_w) \) vs fractional decrease in the sample volume \( (V_o-V)/V_o) \) for convective drying of guava pulps.

Figure 8.14 shows the volume ratio \( (V/V_o) \) vs the moisture content \( (X/X_o) \) for convective drying of guava pulp at 60°C. The Figure 8.14 shows shrinkage evolution from high to low values of moisture content. At very low moisture contents, water could be removed with minimum product shrinking if the collapse of the cell structure is not complete, causing the occurrence of an air-filled porous network.
8.4 CONCLUSIONS

The model of Wang and Singh is the one that best describes the behaviour of the drying kinetics for the two conditions: guava pulp and slices within moisture content range between 19 to 90%. It was found that in the drying of guava pulps and slices the effect of temperature on the color was higher for the pulp sample of 150g at 50°C. This effect could have been caused by enzymatic actions that are more evident for the longest drying time at lower temperature. In the case of higher temperatures, color change could occur by non-enzymatic reactions.

Based on chemical analysis, it is possible to have products with similar volatile composition using the same drying temperatures even at different layer thicknesses of guava pulp. Shrinkage of foods during drying has an impact on the quality of the dried product. If the extension of shrinkage during the drying process is controlled, the quality of the dehydrated product may be improved. In the case of guava pulp, shrinkage is characterized by low mobility of the matrix typical of the elastic behavior associated with the glassy state. This observation is useful to adjust the drying process so as to avoid the early formation of a hard shell that hinders the posterior phases of dehydration. Similarly, when a posterior process requires rehydration, a damaged structure could be a problem to reach the required final product quality.
8.5 ACKNOWLEDGEMENT

The authors would like to thank the support of different laboratories: the laboratory of Nanotechnology at the Universidad Pontificia Bolivariana in Bucaramanga, Colombia, for the SEM images; the Laboratory of Precision Metrology at the Universidad Nacional de Colombia in Bogota for the characterization and dimensional metrology related to shrinkage; the laboratory of Flavor Chemistry Research Group at the Universidad Nacional de Colombia in Bogota for the GCMS analysis.

8.6 NOMENCLATURE

\( A \) area (m\(^2\))
\( T_h \) thickness (m)
\( T \) temperature (°C)
\( R_d \) drying ratio (g cm\(^{-2}\) min\(^{-1}\))
\( MR \) moisture ratio
\( Q \) heat load (J)
\( X \) moisture content, dry basis (g water / g dry solid)
\( X_c \) critical moisture content (g water/g dry solid)
\( X_o \) initial moisture content, dry basis (g water / g dry solid)
\( X_e \) equilibrium moisture content (g water / g dry solid)
\( V_w \) volume of removed water (m\(^3\))
\( V \) sample volume (m\(^3\))
\( V_0 \) initial sample volume (m\(^3\))
\( t \) drying time (min)
\( L^* \) lightness
\( b^*, a^* \) chromatic coordinates
\( \Delta E^* \) total color difference
\( C^* \) chroma, relative saturation
\( h^* \) hue angle, angle of the hue in the CIELab color wheel
\( R^2 \) coefficient of determination

HS-SPME Headspace-Solid Phase Micro Extraction
CIELAB color space is a CIELab cube color space
DVB/CAR/PDMS Divinyl benzene/Carboxen/Polydimethylsiloxane
GCMS Gas Chromatography-Mass Spectrometry
GC Gas Chromatography
MS Mass Spectrometry
PC Principal components

REFERENCES


Cuervo-Andrade, S. P. Quality oriented drying of Lemon Balm (*Melissa officinalis* L.); Max-Eyth-Gesellschaft Agrartechnik im VDI (VDI-MEG) 498, Witzenhausen,


Madioulia J.; Sghaiera J.; Lecomteb D.; Sammoudaa H. Determination of porosity change from shrinkage curves during drying of food material. Food and bioproducts processing 2012, 90, 43–51


Ministerio de Comercio Industria y Turismo (MCIT). Estudio de la cadena productiva de la Guayaba-Bocadillo en la Hoya del Río Suarez. Proyecto de desarrollo local y Comercio en Colombia (DELCO), 2011.


Steinhaus M.; Sinuco D.; Polster J.; Osorio C.; Schieberle P. Characterization of the aroma-active compounds in pink guava (Psidium guajava L.) by application of the aroma extract dilution analysis. J. Agric. Food. Chem. 2008, 56(11), 4120-4127
