Influences of Combined Microwave-Vacuum Frying on the Quality of Durian Chips

Chanoknate Thongcharoenpipat

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Chemical Engineering

Prince of Songkla University

2023

Thesis Title	Influences of combined microwave-vacuum frying on the quality of durian chips
Author	Miss Chanoknate Thongcharoenpipat
Major Program	Chemical Engineering

Major Advisor

....
(Assoc. Prof. Dr. Ram Yamsaengsung)

Examining Committee:

....Chairperson
(Assoc. Prof. Dr. Piyachat Wattanachai)

....Committee
(Assoc. Prof. Dr. Ram Yamsaengsung)

....Committee
(Assoc. Prof. Dr. Chayanoot Sangwichien)

....Committee
(Assoc. Prof. Dr. Pakamas Chetpattananondh)

....Committee
(Asst. Prof. Dr. Pornsiri Kaewpradit)

The Graduate School, Prince of Songkla University, has approved this thesis as partial fulfillment of the requirements for the Doctor of Philosophy Degree in Chemical Engineering.

....
(Asst. Prof. Dr. Thakerng Wongsirichot)
Acting Dean of Graduate School

This is to certify that the work here submitted is the result of the candidate's own investigations. Due acknowledgement has been made of any assistance received.

…..Signature
(Assoc. Prof. Dr. Ram Yamsaengsung)
Major Advisor

…..Signature
(Miss Chanoknate Thongcharoenpipat)
Candidate

I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

....Signature

(Miss Chanoknate Thongcharoenpipat)

Candidate

ชื่อวิทยานิพนธ์ การศึกษาอิทธิพลของการทอดสุญญากาศร่วมกับคลื่นไมโครเวฟที่มีต่อทุเรียนแผ่นกรอบ

ชื่อผู้เขียน นางสาวชนกเนตร ทองเจริญพิพัฒน์

สาขาวิชา วิศวกรรมเคมี

ปีการศึกษา 2565

บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อศึกษาอิทธิพลของกระบวนการต่อจลนศาสตร์การทอดของทุเรียนทอดกรอบสุญญากาศ นอกจากนี้ จุดประสงค์ของการวิจัยนี้ก็เพื่อหาสมการการอบแห้งชั้นบางที่เหมาะสมที่สุดสำหรับการทำนายจลนพลศาสตร์ของการทอดของผลิตภัณฑ์ โดยได้ทำการศึกษาเกี่ยวกับการทอดที่ความดันสัมบูรณ์ 8 kPa และอุณหภูมิการทอดที่ 90, 100, 110 และ 120°C นอกจากนี้ยังศึกษาอิทธิพลของระดับพลังงานไมโครเวฟ (400, 480, 560 และ 640W) และระดับการสุก (1 วัน 2 วัน 3 วัน และ 4 วันหลังการเก็บเกี่ยว) ดำเนินการทอดจนได้ความชื้นสุดท้ายของทุเรียนถึง 6.0% (w.b.) จากนั้นนำผลิตภัณฑ์ที่ผ่านการทอดมาวิเคราะห์ลักษณะทางกายภาพและคุณภาพทางประสาทสัมผัส คุณลักษณะเหล่านี้ถูกนำมาพิจารณาเมื่อกำหนดสภาวะที่เหมาะสมที่สุดสำหรับการทอดสุญญากาศร่วมกับคลื่นไมโครเวฟของผลิตภัณฑ์

จากการศึกษานี้ การทอดสุญญากาศร่วมกับคลื่นไมโครเวฟลดเวลาการทอดลงได้สูงถึง 20% เมื่อเทียบกับการทอดสุญญากาศปกติ ด้วยสัมประสิทธิ์การแพร่ยังผลสำหรับการทอดสุญญากาศปกติ การปรับสภาพล่วงหน้าก่อนการทอดแบบสุญญากาศ และการทอดสุญญากาศร่วมกับคลื่นไมโครเวฟ ที่อุณหภูมิ 110°C ให้ผลเป็น 4.59×10^{-09}, 5.62×10^{-09} และ 6.11×10^{-09} m^2 s^{-1} ตามลำดับ นอกจากนี้ แบบจำลองทางคณิตศาสตร์ทั้งแปดแบบจำลอง (Lewis, Page, Logarithmic, Demir et al., Midilli, Approximation of diffusion, Logistic และ Henderson และ Pabis) ที่ถูกใช้ทำนายเพื่ออธิบายการอบแห้งแบบชั้นบาง พบว่าแบบจำลอง Midilli สามารถทำนายพฤติกรรมการทอดของการทอดสุญญากาศปกติ การทอดของการปรับสภาพล่วงหน้าก่อนการทอดแบบสุญญากาศ และการทอดสุญญากาศร่วมกับคลื่นไมโครเวฟ โดยการทอดสุญญากาศร่วมกับคลื่นไมโครเวฟสามารถผลิตทุเรียนแผ่นกรอบที่มีการหดตัวน้อยลง มีความเหลืองมากขึ้น และมีความกรอบมากขึ้น (สอดคล้องกับโครงสร้างจุลภาคจากกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด)

นอกจากนี้ การทอดสุญญากาศร่วมกับคลื่นไมโครเวฟ ยังลดการดูดซึมน้ำมันลงถึง 10% ในขณะที่การทอดแบบสุญญากาศที่มีการปรับสภาพล่วงหน้า ให้ค่าการใช้พลังงานต่อหน่วยผลผลิตที่ต่ำที่สุด

ที่สภาวะอุณหภูมิการทอดที่ 110°C และความดันสัมบูรณ์ที่ 8 kPa การทอดสุญญากาศร่วมกับคลื่นไมโครเวฟที่ใช้กำลังไมโครเวฟสูงสุดจะใช้เวลาในการทอดเร็วที่สุด ค่าการใช้พลังงานต่อหน่วยผลผลิตต่ำสุด และมีโครงสร้างที่มีรูพรุนมากกว่าเมื่อเปรียบเทียบกับระดับกำลังไมโครเวฟที่ต่ำกว่า ยิ่งไปกว่านั้น ความสุกของทุเรียนทำให้ใช้เวลาในการทอดนานขึ้นโดยมีการหดตัวน้อยลงอย่างมีนัยสำคัญ การดูดซึมน้ำมันสูงขึ้น และสีเหลืองของทุเรียนมากขึ้นจากระดับความสุกวันที่ 3 เมื่อเทียบกับวันที่ 1 นอกจากนี้ ในทุเรียนที่สุกมากขึ้นเป็นผลให้ขนาดรูพรุนภายในและความกรอบของทุเรียนทอดกรอบเพิ่มขึ้น จากการประเมินทางประสาทสัมผัส ผู้ทดสอบชิมให้คะแนนทุเรียนแผ่นกรอบที่มีความสุกสูงกว่า ซึ่งบ่งชี้ว่าชอบของที่สุกแล้วมากกว่าทุเรียนทอดกรอบที่ยังไม่สุก สิ่งนี้ทำให้ทุเรียนสุกทอดสุญญากาศร่วมกับคลื่นไมโครเวฟและผลไม้สุกอื่น ๆ อาจเป็นทางเลือกที่เป็นไปได้สำหรับทดแทนผลไม้ทอดกรอบที่ยังไม่สุกและผลิตภัณฑ์ฟรีซดรายที่มีราคาแพงกว่า

Thesis title	Influences of combined microwave-vacuum frying on the quality of durian chips
Author	Miss Chanoknate Thongcharoenpipat
Major Program	Chemical Engineering
Academic Year	2022

ABSTRACT

This study aimed to determine the effects of process conditions on the drying kinetics of vacuum-fried durian chips. Additionally, the purpose of this research was to determine the most appropriate thin layer equation for predicting product drying kinetics. At an absolute chamber pressure of 8 kPa and frying temperatures of 90, 100, 110, and 120°C, studies on frying were conducted. The influence of microwave power levels (400, 480, 560, and 640W) and ripening levels (1 Day, 2 Days, 3 Days, and 4 Days after harvesting) at the optimal frying temperature was also investigated. The durian was fried until the final moisture content of durian reached 6.0% (w.b.). The fried products were then analyzed for the physical characteristics, as well as the sensory quality. These characteristics were taken into consideration when determining the optimal conditions for microwave-assisted vacuum frying (MWVF) of products.

According to this study, MWVF significantly reduced the frying time by 20% compared to VF ($P < 0.05$) with the effective moisture diffusivity for VF, pre-treatment before vacuum frying (P+VF) and MWVF at 110°C determined to be 4.59×10^{-09}, 5.62×10^{-09} and 6.11×10^{-09} $m^2 s^{-1}$, respectively. Additionally, eight mathematical models (Lewis, Page, Logarithmic, Demir et al., Midilli, Approximation of Diffusion, Logistic, and Henderson and Pabis) describing thin-layer drying were investigated. It was found that the Midilli model was considered adequate for describing the thin-layer drying behavior of VF, P+VF, and MWVF. MWVF produced chips with lower shrinkage, more yellowness and higher crispiness (consistent with the microstructure from scanning electron microscopy (SEM)). In addition, MWVF drastically decreased oil absorption by 10%, while P+VF yielded the lowest specific energy consumption (SEC).

MWVF with the highest microwave power produced the quickest frying time, the lowest SEC, and a more porous structure in comparison to those from lower power levels. These findings were obtained at 110°C and absolute pressure of 8 kPa. Moreover, the ripeness of durian led to longer frying times with significantly less shrinkage, higher oil absorption, and more yellowness for durians from Day 3 compared to Day 1. Furthermore, the more ripened durians produced a bigger internal pore size and crispier durian chips. From sensory evaluation, the taste panellists gave a higher rating for the durian chips with higher ripeness, indicating a preference for ripened products compared to conventionally fried un-ripened durian chips.

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to my thesis adviser Assoc. Prof. Dr. Ram Yamsaengsung for the continuous encouragement of my Ph.D. study and research, as well as for the compassion, motivation, enthusiasm, and extensive knowledge. His advice was helpful to me throughout the entire research and thesis-writing process.

Besides my advisor, I would like to thank the rest of my thesis committee: Assoc. Prof. Dr. Piyachat Wattanachai, Chairperson, Department of Chemical Engineering, Burapha University, whose worthy guidance and professional attitude is appreciable in completing this dissertation. I am also thankful to Assoc. Prof. Dr. Chayanoot Sangwichien, Assoc. Prof. Dr. Pakamas Chetpattananondh, and Asst. Prof. Dr. Pornsiri Kaewpradit, Department of Chemical Engineering, Prince of Songkla University for their encouragement, thoughtful comments, and challenging questions.

I thank financial support from the Graduate School Research Fund from the Prince of Songkla University and the Thailand Research Fund — Research and Researcher for Industries Fund (TRF — RRI). In addition, I am extremely thankful to all the staffs of Department of Chemical Engineering, Prince of Songkla University for their kind help and cooperation throughout my study period.

Finally, I deeply express my sincere gratitude to my family for their encouragement, support, and keen interest in my academic achievements.

Chanoknate Thongcharoenpipat

TABLE OF CONTENT

Page

TABLE OF CONTENT (CONTINUED)

TABLE OF CONTENT (CONTINUED)

TABLE OF CONTENT (CONTINUED)

Page

LIST OF TABLES

LIST OF TABLES (CONTINUED)

Page

LIST OF TABLES (CONTINUED)

LIST OF TABLES (CONTINUED)

Page

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

Page

LIST OF FIGURES (CONTINUED)

Page

CHAPTER 1

Introduction

1.1 Background and Rationale

In recent years, many food businesses have been pushed to produce fried products with lower oil content, as well as desirable texture and flavor. One of the most efficient options for food company in reducing oil uptake is vacuum frying (Su et al., 2016). By frying fruits and vegetables at reduced pressure (~ 8 kPa) and below the temperatures 160-180°C range, unacceptable chemical reactions, such as lipid oxidation can be diminished (Thongcharoenpipat and Yamsaengsung, 2021), and acrylamide formation and risk of cancer can be minimized (Banerjee and Kumar, 2017). Furthermore, many researchers have considered vacuum frying for improving the product appearance and texture, maintaining the fresh flavor and curtailing nutritional losses of vitamins in fried fruits, such as bananas (Yamsaengsung et al., 2011), potatoes (Su et al., 2016), and Chinese yam (Chitrakar et al., 2019). Moreover, in conjunction with freeze drying (FD), vacuum drying (VD), and vacuum frying (VF), the microwave assisted heating have been shown to reduce the drying time, being more efficient, and improving the product attributes (Su et al., 2017).

The study of Paengkanya et al. (2015) found that the pros of microwave vacuum drying (MWVC) include increasing the dehydration process, minimizing energy consumption of drying, and advancing the quality of durian chips, while Su et al. (2016) concluded that microwave assisted vacuum frying (MWVF) reduced oil absorption and could improve the qualities of fried fruits and vegetables. Moreover, physical pre-treatment prior to frying of the product, such as freezing could also be used to provide a desired product structure, while influencing the drying kinetics (Bai-Ngew et al., 2011). For example. Arévalo-Pinedo and Murr (2006) suggested from studying the kinetics of vacuum dried pumpkin that had been frozen and blanched prior to drying that the drying rate of the frozen sample was increased significantly compared to the sample pre-treated by blanching. They concluded that because the water molecules were already in an ice-crystal forms, they were able to be evaporated quicker than for those in blanching and no pre-treatments. Moreover, Bai-Ngew et al. (2011) found that pre-freezing of fresh durian helped to modify the microstructure of durian chips, while decreasing the hardness and improving the crispiness of the product.

Many investigations on the effect of ripening on the physicochemical properties of fried fruits have been studied. For banana chips (fried at atmospheric pressure at 180°C), Ammawath et al. (2001) suggested that the chips from Abu at 'green' and 'trace of yellow' stages showed better sensory scores for color, flavor, odor, texture, and overall acceptability the those obtained from Nangka variety at the same ripening stage. They concluded that although fresh bananas with higher starch content (green stage) produced crispier banana chips, the products also had higher oil content. On the contrary, Yamsaengsung et al. (2011) found that Day 2 (ripening at stage 6) vacuum fried (VF) banana chips (8 kPa and 110°C) had higher degree of thickness expansion and were more porous and crispier compared to less ripened banana (ripening at stage 5). They also deduced that the difference in physiological and chemical composition of fruits due to ripening can influence the textural quality of the product. In addition, Diamante (2008) found that for VF jackfruits, the ripened fruit had higher oil absorption, more yellowness, lower crispness, more sweetness and more aroma than half-ripened products.

Furthermore, with regards to the structural changes, Yamsaengsung et al. (2011) concluded that VF at higher temperature (above 110°C) resulted in less shrinkage, more thickness expansion, and harder products. In another study on VF of mango, Ayustaningwarno et al. (2020) reported that the un-ripened products had faster drying rate and higher hardness compared to ripened products at 110-120ºC. However, it was found that the oil content for ripened fried product was higher, while the color changes of un-ripened mango were more sensitive to frying temperature and time. Furthermore, when considering the nutritional and physicochemical quality of the products, the un-ripened VF mango was more favorable for commercial-quality snack food for health-conscious consumers. Recently, Thongcharoenpipat and Yamsaengsung (2021) found that MWVF resulted in a faster drying rate, and lower rate of oil absorption, while higher frying temperature helped minimize shrinkage of the products. Therefore, in order to gain more insights into the effects of MWVF, pre-treatment (P+VF) by freezing overnight at -18°C and ripening level on vacuum fried product, this research explored the drying kinetics, shrinkage, oil absorption, texture, microstructure, color, specific energy consumption (SEC), and acceptability of vacuum fried durian chips. This research could provide a high-quality alternative durian snack that is much more affordable than freeze-dried durian chips and healthier to consumer than the commercial un-ripened fried durian chips product.

1.2 Theoretical Background

1.2.1 Durian

Durian is distinguished by its huge size, intense odor, and thorn-covered husk. The fruit typically grows up to 30 centimeters (12 inches) in length and 15 centimeters (6 inches) in diameter, weighing one to three kilos (2 to 7 lb). Its form varies from oblong to round, the color of its husk from green to brown, and the color of its flesh from light yellow to red, as seen in Figure 1.1.

Figure 1.1 Durian Fruit (Swedishnomad, 2019; Lifehack, 2015).

The majority of cultivars have a common name and a code number that begins with the letter "D." As indicated in Figure 1.2, popular clones include Kop (D99), Chanee (D123), Berserah or Green Durian or Tuan Mek Hijau (D145), Kan Yao (D158), Mon Thong (D159), Kradum Thong, and D24 and D169, which have no common name. Each variety has its own particular flavor and aroma. In Thailand, there are about 200 varieties of *D. zibethinus*.

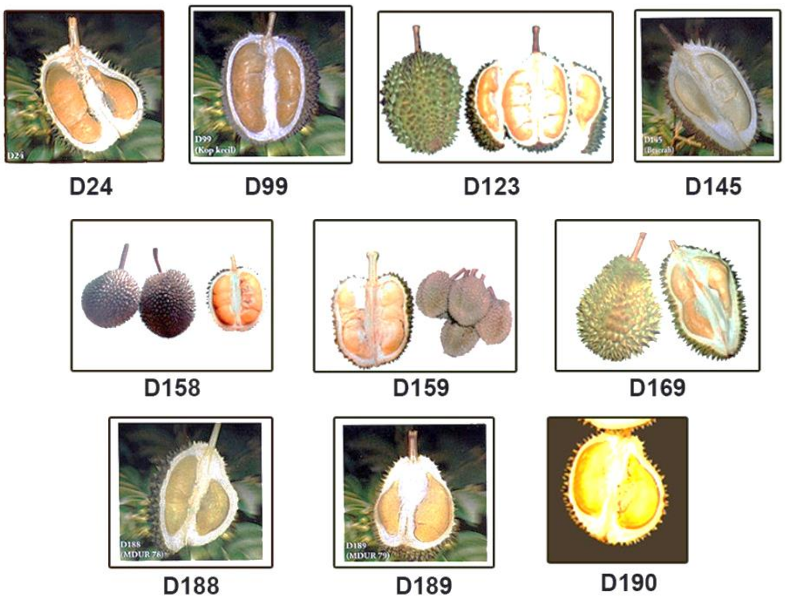


Figure 1.2 Different cultivars of durian (Durian Information - A Durian blog Devoted To "The King of Fruits", 2011).

When the husk of the durian fruit begins to break, it is ready to eat (Montagne, 2001). However, the optimal ripeness stage for enjoyment varies by region and species in Southeast Asia. Most cultivars of *D. zibethinus* are virtually always cut from the tree and kept to ripened while waiting to be sold, however, some species grow so tall that they can only be harvested once they have fallen to the ground. Some people in southern Thailand like durians when they are still young when the clusters of fruit inside the shell are crisp and mild in flavor. Fruit that is smooth and scented is preferred by certain people in northern Thailand. Most customers in Malaysia and Singapore like the fruit to be as ripe and sweet as possible, and they may even risk leaving the fruit to continue to ripen after the husk has broken apart. The flesh becomes richly creamy, mildly alcoholic (Davidson and Alan, 1999), with a strong scent and a complex flavor in this stage.

Durian (*Durio zibeththinus* Murr.) is one of the most popular tropical fruits in Southeast Asia and is widely claimed as the "King of Fruits". Due to its unique aromatic odor, specific taste, rich nutritional value as shown in Table 1.1, and high antioxidants, it is one of Thailand's top exported fruits, especially to China. In 2020 alone, Thailand harvest more than one million tons (OAE, 2021) with Montong (D159) being the most notable and harvested (Niponsak et al., 2020). During harvesting season, un-ripened durians are harvested and undergo deep-fat frying to produce durian chips in order to keep the market from over-flooding and the ripened durian price competitive. But since fried durian chips have a high oil content of around 30%, they may not be desirable to health-conscious consumers (Bai-Ngew et al., 2011). Moreover, in addition to ripened durians being produced as dessert snacks and coffee, they are also generally freeze-dried and sold commercially according to Figure 1.3 at a price up to three times higher than un-ripened fried durian chips due to their high energy consumption and high demand. Therefore, a less expensive process for ripened durian chips could meet demands and help alleviate the market surplus during the durian season.

Figure 1.3 Varieties product of Durian: (a) Durian cake, (b) Freeze-dried durian, (c) Durian coffee, (d) Durian ice-cream, (e) Durian wafer, and (f) Durian candy (Mothership, 2016; Stinkyspikes, 2011).

Table 1.1 Composition of durian (USDA, 2016).

Nutrient	Value per 100 g of edible portion (Recommended daily nutrient intakes)
Water	64.99 g
Energy	615 kJ (147 kcal)
Total lipid (Fat)	5.33 g
Protein	1.47 g
Carbohydrates, by difference	27.09 g
Fiber, total dietary	3.8 g
Potassium	436 mg (9%)
Phosphorus	39 mg (6%)
Iron	0.43 mg (3%)
Magnesium	30 mg (8%)
Manganese	0.325 mg (15%)
Calcium	6 mg (1%)
Zinc	0.28 mg (3%)
Vitamin A (equiv.)	44 IU
Vitamin B1 (Thiamin)	0.374 mg (33%)
Vitamin B2 (Riboflavin)	0.2 mg (17%)
Vitamin B3 (Niacin)	1.074 mg (7%)
Vitamin B5 (Pantothenic acid)	0.23 mg (5%)
Vitamin B6	0.316 mg (24%)
Vitamin B9 (Folate)	36 µg (9%)
Vitamin C	19.7 mg (24%)

µg = micrograms, mg = milligrams, IU = International units

1.2.2 During ripening

As a climacteric fruit, durian characteristic is greatly affected by ripening, including the physical properties, the presence of the bioactive compound, the microstructure of the fruit resulting from increased respiration rate, and autocatalytic ethylene production. Some changes include an increase in yellowness resulting from increasing carotenoids compounds, a change in the availability of antioxidants compounds, a stronger smell promoted by volatile sulfur compounds, and the softening of durian tissue due to the change in the amount of pectin inside the fruit (Arancibia-Avila et al., 2008; Yi et al., 2020). Moreover, starch is broken down into sugar and used as energy. Excess energy from the respiration process is released from the tissue by vaporization of water, which is then transpired from the fruit, resulting in weight loss (Siriboon and Banlusilp, 2004) which could affect the drying rate during the VF process.

The effect of ripeness, which directly correlates to the amount of sugar content, on the drying rate, shrinkage, and oil absorption of the durian chips are also investigated. A small degree of shrinkage is preferred as it relates to the overall appearance of the product, the microstructure nature of the product interior, and the hardness and crispiness of the product texture. An increase in sugar content and pectin formation could also decrease the rate of water desorption from the micropores of the product leading to an increase in frying time and longer exposure to oil diffusion into the product. In order to study these effects, samples were allowed to ripen for 1, 2, 3, and 4 days at a room temperature of 26±2°C and relative humidity (RH) of 45±10%. Day 1 corresponds to durians with completely green husk (the tip of the thorns covered in the rind is green and hard to clench between the tips) and flesh that is light yellow (Figure 1.4) and hard. Day 2 has similar characteristics to Day 1, but flesh that is slightly softer toward the interior. Day 3 durians have green-brown husk (the tip of the thorns covered in the rind starts to turn brown and easier to clench between the tips) and the flesh is darker yellow, with a firm exterior and soft interior. Day 4 durians have green-dark brown husk (the tips of the thorns are dark brown, easy to clench between the tips and distinct smell of durian has developed) and the flesh that is bright yellow and much softer exterior and interior.

Figure 1.4 Approximate color of durian at different ripeness.

Consumer preferences for ripeness make it difficult to make broad comments about what constitutes an "excellent" durian. A durian that falls from the tree continues to ripen for two to four days, but most people consider it overripe and unpleasant after five or six days (Morton, 1987), but some Thais boil it with palm sugar and serve it as durian (or thurian) guan (Gasik, 2014).

1.2.3 Theory of drying

The application of heat under controlled conditions to remove the majority of water by evaporation is known as drying. Drying has the primary goal of extending the shelf life of products by reducing water activity (a_w), which inhibits microbiological development. However, because the processing temperature is unlikely to be high enough to produce inactivation, caution should be taken while rehydrating the product. The type of material and the dehydration mechanism influence the drying mode and characteristics.

1.2.3.1 Drying mechanism

Drying is a mass transfer process that involves removing water or another solvent from a solid, semi-solid, or liquid through evaporation. For a limited time, an initial linear decline of the average product moisture content as a function of time, termed as a "constant drying rate period," may be seen in some materials with relatively high beginning moisture content. Throughout this time, the surface moisture outside individual particles is usually removed. The rate of heat transfer to the product being dried determines the drying rate during this period. As a result, the greatest effective drying rate is thought to be limited by heat transfer rate (Yamsaengsung et al., 2008; Junlakan, 2014). If the drying process is continued, the slope of the curve, or drying rate, gets steeper (falling rate period) and finally tends to be virtually horizontal over long periods at a time. When the product moisture content reaches "equilibrium moisture content," it is in dynamic equilibrium with the drying medium and remains constant. Water migration from the product interior to the surface is largely through molecular diffusion during the falling-rate period, i.e., the water flux is proportional to the moisture content gradient. This indicates that water transfers from higher-moisture-content areas to lower-moisture-content areas, a phenomenon explained by thermodynamics' Second law. Except in a well-designed freeze-drying process, when a significant amount of water is removed, the goods normally shrink and distort. The rate of removal of moisture or solvent from the inside of the material being dried influences the drying rate in the falling-rate period, which is referred to as "mass-transfer limited" (IRRI, 2009). As indicated in Table 1.2, the saturation vapor pressure of water related to the given temperature.

Table 1.2 Saturation vapor pressure of water referred to the given temperature (Wang, 2010).

T (ºC)	P (mmHg)	T (ºC)	P (mmHg)	T (ºC)	P (mmHg)	T (ºC)	P (mmHg)	T (ºC)	P (mmHg)
-10	2.1	14	12.0	38	49.7	62	163.8	86	450.9
-9	2.3	15	12.8	39	52.4	63	171.4	87	468.7
-8	2.5	16	13.6	40	55.3	64	179.3	88	487.1
-7	2.7	17	14.5	41	58.3	65	187.5	89	506.1
-6	2.9	18	15.5	42	61.5	66	196.1	90	525.8
-5	3.2	19	16.5	43	64.8	67	205.0	91	546.1
-4	3.4	20	17.5	44	68.3	68	214.2	92	567.0
-3	3.7	21	18.7	45	71.9	69	223.7	93	588.6
-2	4.0	22	19.8	46	75.7	70	233.7	94	610.9
-1	4.3	23	21.1	47	79.6	71	243.9	95	633.9
0	4.6	24	22.4	48	83.7	72	254.6	96	657.6
1	4.9	25	23.8	49	88.0	73	265.7	97	682.1
2	5.3	26	25.2	50	92.5	74	277.2	98	707.3
3	5.7	27	26.7	51	97.2	75	289.1	99	733.2
4	6.1	28	28.3	52	102.1	76	301.4	100	760.0
5	6.5	29	30.0	53	107.2	77	314.1	102	815.9
6	7.0	30	31.8	54	112.5	78	327.3	104	875.1
7	7.5	31	33.7	55	118.0	79	341.0	106	937.9
8	8.0	32	35.7	56	123.8	80	355.1	108	1004
9	8.6	33	37.7	57	129.8	81	369.7	110	1075
10	9.2	34	39.9	58	136.1	82	384.9	112	1149
11	9.8	35	42.2	59	142.6	83	400.6	114	1227
12	10.5	36	44.6	60	149.4	84	416.8		
13	11.2	37	47.1	61	156.4	85	433.6		

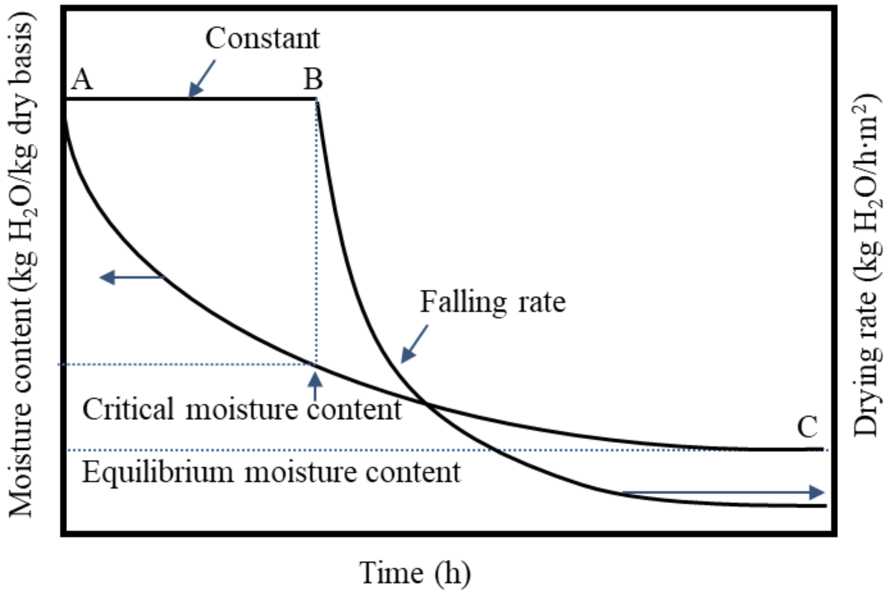


Figure 1.5 Typical drying rate curves. (Adapted from Luikov, 1966).

The drying rates of various biological materials will vary considerably, but a typical curve is depicted in Figure 1.5. When the biological material is placed inside the dryer, the surface heats up to the wet-bulb temperature for a short period of time. The drying process then begins along AB. Water is transported from the biological material's inside at the same rate that it evaporates from the surface. As seen by the drying curve, this is known as the constant rate period. The constant rate phase lasts until the critical moisture content (M_c) is reached. Drying starts to decline in the falling rate period at this time (B), as represented by line BC.

1.2.3.2 Drying in the constant rate period

The surface of the solid is initially highly wet throughout the constant rate drying period, and a continuous layer of water remains on the drying surface. This water is completely unbound, and it behaves as if the solid were not existent. Under a given air condition, the rate of evaporation is independent of the solid and is substantially the same as the rate from a free liquid surface (Mujumdar and Menon, 1995; Sriariyakul et al., 2016). Roughness of the solid surface may result in faster drying rates than a flat surface.

The following equation gives the equation for drying during the constant rate period:

$$\frac{dM}{dt} = \frac{h_c A (T_a - T_{wb})}{h_{fg}} \quad (1)$$

where: $\frac{dM}{dt}$ = drying rate, kg/h

h_c = convective heat transfer coefficient, kJ/h m^2 ^{o}C

A = surface area, m^2

T_a = drying air temperature, ^{o}C

T_{wb} = wet bulb temperature, ^{o}C

h_{fg} = latent heat of vaporization at T_{wb}, kJ/kg

1.2.3.3 Drying in the falling rate period

Water diffuses through the solid to the drying air as the evaporation plane moves toward the interior of the material being dried (Junlakan, 2014; Nathakaranakule et al., 2019). It describes a situation in which the surface can no longer provide enough free moisture to saturate the air in contact with it. The rate of drying under these conditions is highly influenced by the diffusion process by which moisture from within the material is transported to the surface. The falling rate period is frequently the longest period of a drying process, and in some biological materials when the initial moisture content is below the critical moisture content, it is the only section of the drying curve that can be seen.

1.2.3.4 Moisture content

Dry-basis (M_d) and wet-basis (W_b) are two ways to represent moisture content (M_w). The moisture content is expressed as a percentage of dry weight moisture. It is written as:

$$M_d = \left(\frac{m_w}{m_d}\right) \times 100 \quad (2)$$

The moisture content, expressed as a percentage of weight basis, can be written as:

$$M_w = \left(\frac{m_w}{m_w + m_d}\right) \times 100 \quad (3)$$

where: M_d = moisture content of matter, % dry-basis

M_w = moisture content of matter, % wet-basis

m_d = mass of dry matter, g

m_w = mass of water, g

1.2.3.5 Drying rate

The weight of a drying sample as a function of time is commonly used to measure drying kinetics in studies. Moisture ratio vs time, drying rate versus time, and average moisture content versus time are all examples of drying curves. Several theories on moisture migration's mechanism have been examined (Dadali et al, 2007; Shi et al., 2019). However, when it comes to drying food products, only capillary and moisture diffusion theories apply.

An effective drying model, which is made up of differential equations of heat and mass transport in the interior of the product and its interphase with the drying agent, can completely represent the drying process. Using any transport equation, knowledge of transport and material characteristics is required (Karathanos and Belessiotis, 1999; Junlakan, 2014). Moisture diffusivity, thermal conductivity, density, specific heat, and interphase heat and mass transfer coefficients are examples of such characteristics. In some of these cases, the drying constant is used instead of these attributes in the literature. This is a property's (Saeed et al., 2008) lumped parameter.

The drying rate can be expressed as:

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \quad (4)$$

where: M_t = moisture content at a specific time (g water/g dry base)

M_{t+dt} = moisture content at t+dt (g water/g dry base)

t = drying time (hr)

According to Hill and Pyke (1997), drying develops when there is a net flow of water out of the food product into the environment, causing the food to release its moisture content. They observed that the rate at which moisture diffuses or migrates from the inside to the outside air affects the drying rate. Nevertheless, according to Sriariyakul et al. (2016), the impacts of drying-air temperature and flow rate could be combined to provide an expression for drying rate that is expressed by the moisture decrease in percent per hour.

Saniso et al. (2019) agreed that another aspect involved in explaining the rate of water loss in food is the effective area over which water could be lost, and that a high surface area ensures quick transfer of moisture to the surface and the ease with which moisture is taken by the air current.

1.2.3.6 Drying Equation

1.2.3.6.1 Theoretical drying equation

Theoretical drying equation is based on moisture diffusion process as follows:

Moisture diffusion

Diffusion is the random molecular motion through which liquid is moved from one area of a solid to another. As a result, diffusing molecules are transported from a higher concentration to a lower concentration. Ordinary diffusion is the term for this phenomenon. Most known models of moisture loss and solid gain kinetics during the falling rate period are based on Fick's rule of diffusion under unstable state conditions (Salvatori et al., 1998). Fick's first law of diffusion establishes a linear relationship between a component's flux and its concentration gradient (Junlakan et al., 2016) by

$$F = -D\left(\frac{\partial C}{\partial x}\right) \quad (5)$$

where: F = rate of transfer per unit area of cross-section, kg/m^2

D = diffusion coefficient, m^2/s

C = concentration of diffusing substance, kg/m^3

x = distance, m

Effective moisture diffusivity

The transfer of matter from one stream to another requires mass transfer processes. Over the years, a large number of drying theories have been developed.

Molecular diffusion, liquid diffusion through solid pores, and other mechanisms are used to explain the moisture transfer process.

When many processes are present, and it is impossible to distinguish between these, the rate of moisture transport is represented by an effective diffusivity (D_{eff}), regardless of whether the mechanism is involved. Though not as theoretically sound as other methods, it is a highly practical and convenient way to explain moisture transfer. The following is how Fick's second law of diffusion can be used to derive the water transfer equation for solids drying under constant psychometric conditions:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \quad (6)$$

where: D_{eff} = effective diffusivity, m^2/s

M = local moisture content, decimal dry-basis

t = time, s

In generally, food drying occurs in two stages: a constant rate period and a falling rate period. A constant rate period follows a short heating time, followed by a falling rate period, which is the dominant time throughout the drying process. Effective moisture diffusion processes, which include liquid diffusion, vapor diffusion, and other conceivable mass transfer mechanisms, can be used to describe moisture transport within a hygroscopic material during the falling rate phase. "Effective moisture diffusivity" refers to water's overall mass transport property in food products (Dadali et al, 2007). Diffusivity, as indicated by Fick's diffusion equation, is thought to be the only physical process for transferring water to the surface during drying (Ozbek and Dadali, 2007). Leading to a shortage of knowledge about the mechanism of moisture movement during drying and the complexity of the process, effective moisture diffusion is used

(Afzal and Abe, 1998; Bai-Ngew et al., 2011a; Junlakan et al., 2016). It is affected by the material's composition, moisture content, temperature, and porosity.

In terms of diffusivity, Fick's law of diffusion was used to describe the transport of water inside the sample surface. The general solution moisture ratio can be calculated using an analytical technique with an initial condition and boundary conditions (Junlakan et al., 2016) as follows:

For infinite slab shape;

$$MR = \frac{8}{\pi^2}\sum_{p=0}^{\infty}\left[\frac{1}{(2p+1)^2}\right]\exp\left[-\frac{(2p+1)^2\pi^2 D\, t}{L^2}\right] \quad (7)$$

Considering only the first three terms;

$$MR = \frac{8}{\pi^2}\left[\exp\left(-\frac{\pi^2 D\, t}{L^2}\right)+\frac{1}{9}\exp\left(-\frac{9\pi^2 D\, t}{L^2}\right)+\frac{1}{25}\exp\left(-\frac{25\pi^2 D\, t}{L^2}\right)\right] \quad (8)$$

For cubic shape;

$$MR = \left(\frac{8}{\pi^2}\right)^3\sum_{p=0}^{\infty}\left[\frac{1}{(2p+1)^2}\right]^3\exp\left[-\frac{(2p+1)^2 3\pi^2 D\, t}{L^2}\right] \quad (9)$$

Considering only the first three terms;

$$MR = \left(\frac{8}{\pi^2}\right)^3\left[\exp\left(-\frac{3\pi^2 D\, t}{L^2}\right)+\frac{3}{9}\exp\left(-\frac{11\pi^2 D\, t}{L^2}\right)+\frac{3}{25}\exp\left(-\frac{27\pi^2 D\, t}{L^2}\right)\right] \quad (10)$$

For sphere shape;

$$MR = \frac{6}{\pi^2}\sum_{p=1}^{\infty}\left(\frac{1}{p^2}\right)\exp\left(-\frac{p^2\pi^2 D\, t}{9}\right) \quad (11)$$

Considering only the first three terms;

$$MR = \frac{6}{\pi^2}\left[\exp\left(-\frac{\pi^2 D\, t}{r_0^2}\right)+\frac{1}{4}\exp\left(-\frac{4\pi^2 D\, t}{r_0^2}\right)+\frac{1}{9}\exp\left(-\frac{9\pi^2 D\, t}{r_0^2}\right)\right] \quad (12)$$

For infinite cylinder shape;

$$MR = \left(\frac{8}{\pi^2}\right)\sum_{m=1}^{\infty}\frac{4}{\lambda_m^2}\exp\left(-\frac{\lambda_m^2 D\, t}{r_0^2}\right)\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{\pi^2(2n+1)^2 D\, t}{L^2}\right) \quad (13)$$

Considering only the first three terms;

$$\mathrm{MR} = \left(\frac{8}{\pi^2}\right)\left[\exp\left(\frac{-\pi^2 D\ \mathrm{t}}{\mathrm{L}^2}\right)+\frac{1}{9}\exp\left(\frac{-9\pi^2 D\ \mathrm{t}}{\mathrm{L}^2}\right)+\frac{1}{25}\exp\left(\frac{-25\pi^2 D\ \mathrm{t}}{\mathrm{L}^2}\right)\right]\times$$
$$4*\left[\frac{1}{\lambda_1^2}\exp\left\{\lambda_1^2\left(\frac{D\ \mathrm{t}}{r_0^2}\right)\right\}+\frac{1}{\lambda_2^2}\exp\left\{-\lambda_2^2\left(\frac{D\ \mathrm{t}}{r_0^2}\right)\right\}+\frac{1}{\lambda_3^2}\exp\left\{-\lambda_3^2\left(\frac{D\ \mathrm{t}}{r_0^2}\right)\right\}\right] \quad (14)$$

where: MR = the moisture ratio

D = the effective diffusion coefficient, m^2/s

L = dimension of sample, thickness, m

R = the radius of sample, m

t = drying time, s

λ_n = root of the Bessel function of the n^{th} kind of zero order

The effective diffusion coefficient (D) is conventionally described by the Arrhenius type equation as follows:

$$D = D_0 \exp\left[-\frac{\mathrm{E}}{\mathrm{RT}}\right] \quad (15)$$

where: D_0 = Arrhenius factor of the heterogeneous solid, m^2/h or m^2/s

E = the activated energy, kJ/mol K

R = universal gas constant, 8.314 kJ/kmol K

T_{abs} = absolute temperature, K

1.2.3.6.2 Semi-empirical drying equation

A semi-empirical drying model is generally developed by assuming that the difference between the moisture grain and equilibrium moisture affects the drying rate under the drying condition. This assumption is comparable to Newton's cooling law, which is as follows:

$$\frac{\mathrm{dM}}{\mathrm{dt}} = -\mathrm{k}\left(\mathrm{M}-\mathrm{M_{eq}}\right) \quad (16)$$

when initial condition is $M(0) = M_{in}$, the following equation is obtained:

$$MR = \exp(-kt) \quad (17)$$

where: k = drying constant, h^{-1}

1.2.3.6.3 Empirical drying equation

The study of the drying behavior of different materials has stimulated the interest of various researchers during the last 60 years, for both theoretical and practical considerations. Many mathematical models have been applied to represent the drying process in research on the drying behavior of various agricultural production, with thin-layer drying models being the most prevalent (Mohammadi et al., 2008). Parti (1993) claims that mathematical models that describe grain and food drying procedures can also provide temperature and moisture information.

Theoretical, semi-theoretical, and empirical models are the three main types of thin-layer drying equations and used to characterize the drying kinetics of biological material for the purpose of predicting the frying time required to achieve the desired moisture content, scale up production, or even design the equipment. Jayas et al. (1991) provide a thorough analysis of these equations. Semi-theoretical models are generated from theoretical models (Fick's second law), but they are simplified and sometimes supplemented with empirical coefficients to enhance curve fitting. A direct link between moisture content and drying time is determined in empirical models, and the parameters associated with it have no physical meaning.

Lewis (1921), referenced by Jayas et al. (1991), the law of heat transfer from a body immersed in a cold fluid could be used to compare the moisture transfer from agricultural products. By comparing this occurrence with Newton's cooling law.

Lewis also offered out an equation that was based on the assumption that the rate of moisture content is proportional to the difference between the moisture content and the equilibrium moisture content of the material.

The internal resistance to moisture movement and consequent moisture gradients within the material are assumed to be negligible in Newton's law of cooling. It solely takes into consideration surface resistance. The equation 16's solution is referred to as the Lewis, Newton, Simple, or Exponential model whereas if boundary condition is assumed to be M = M_{in} at t=0 (Ertekin and Ziya Firat, 2015).

$$MR = \frac{M_t - M_e}{M_{in} - M_e} = \exp(-kt) \tag{18}$$

where: MR = moisture ratio

M_t = moisture content at time, t (% w.b.)

M_e = equilibrium moisture content (% w.b.)

M_{in} = initial moisture content (% w.b.)

K = drying constant determined from the experimental data (1/h)

T = time (h)

The equation 18, however, cannot describe the drying rate accurately throughout the drying period (Jayas et al., 1991). The modified drying equations were obtained by Henderson and Pabis (1961) which is the first term of a general series solution of Fick's second law, with another constant added:

$$MR = a \quad \exp(-kt) \tag{19}$$

where: a = empirical drying constant

k = empirical drying constant (1/h)

By adding a dimensionless empirical constant (n) to the time term, this model empirically improves upon Lewis model (Equation 18) by addressing its shortcomings. This parameter modifies the time, and the model in this instance provides better results for the prediction of moisture loss. Hence, Page (1949) suggested equation 20 as a drying model.

$$\mathrm{MR} = \exp(-\mathrm{kt}^{n}) \tag{20}$$

where: n = empirical drying constant

k = empirical drying constant (1/h)

$$\mathrm{MR} = a\exp(-k(\mathrm{tn})) + bt \tag{21}$$

where: a,b,n = empirical drying constant

k = empirical drying constant (1/h)

Equation 21 is a variation of the Midilli drying equation (Midilli et al., 2003), which describes the moisture ratio as a function of drying time in a form similar to the Henderson and Pabis model with the addition of an empirical term to "t".

$$\mathrm{MR} = a\exp(-\mathrm{kt}) + (1-a)\,exp(-gt) \tag{22}$$

$$\mathrm{MR} = a\exp(-\mathrm{kt}) + (1-a)\,exp(-kbt) \tag{23}$$

where: a, b = empirical drying constant

k, g = empirical drying constant (1/h)

While the equation 23 known as Approximation of diffusion After rearrangement of Verma et al. model by separating the drying constant term “k” from “g,” the new model is obtained. Additionally, Logistic model (Alibas, 2014) was proposed as the empirical model to describe the moisture ratio as a function of drying time of agricultural product as following equation.

$$\mathrm{MR} = a/\left(1 + \exp(\mathrm{kt})\right) \tag{24}$$

Equation (25) is the general form of a two-term model that uses the first two terms of Fick's second law's general series solution.

$$\mathrm{MR = A \quad exp(-Bt)+C \quad exp(-D\ t)} \tag{25}$$

where: A, C = empirical drying constants

B, D = empirical drying constants (1/h)

Doymaz (2004) adjusted Equation 25 to the thin-layer drying kinetics of white mulberry. In the same study, he used a modified version of the Page equation (Equation 20) but found that the Logarithmic model (Equation 26) best characterized the drying process.

$$\mathrm{MR=a \quad exp(-kt)+c} \tag{26}$$

where: a, c = empirical drying constants

k = empirical drying constant (1/h)

While Demir et al. (2007) proposed equation 27 as a new model by using curve fitting procedure similar to Page, Logaritmic and Midilli models, with another constant added:

$$\mathrm{MR} = a \quad \exp(-\mathrm{kt})^{n} + c \tag{27}$$

where: a, c, and n = empirical drying constant

k = empirical drying constant (1/h)

1.2.3.7 Goodness-of fit statistics for thin-layer drying models

Statistical measurements are used to evaluate and compare thin-layer drying models. As a result, the fitted models' quality is determined. The following are some examples of these measures:

1.2.3.7.1 Root mean square error (RMSE)

It represents the data's volatility. As a criterion for quality of fit, lower values of root mean square error are used:

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}})^2\right]^{1/2} \tag{28}$$

1.2.3.7.2 Mean sum of squares of errors (MSE) or (χ^2)

The difference between the experimental and predicted moisture content is the mean square of the deviations. The term "reduced chi square" (χ^2) is defined as follows:

$$\chi^2 = \left[\frac{\sum_{i=1}^{n}\left(\mathrm{MR}_{\mathrm{pre,i}} - \mathrm{MR}_{\mathrm{exp,i}}\right)^2}{N-Z}\right] \tag{29}$$

where: $\mathrm{MR}_{\mathrm{exp,i}}$ = the ith experimental moisture ratio

$\mathrm{MR}_{\mathrm{pre,i}}$ = the ith predicted model moisture ratio

N = the number of sampling times

z = the number of constants in the drying model.

1.2.3.7.3 Coefficient of determination (R^2)

This is the ratio of the regression sum of squares (*SSR*) to the total sum of squares (*SST*), which indicates how much variance in the dependent variable the model accounts for. It assesses the model's ability to fit the data. Various authors have used it to evaluate drying models. The quality of fit for the models is determined by R^2 values that are higher. The following formula may be used to compute the *SSE* and *SST*:

Regression sum of squares:

$$SSR = \sum_{i=1}^{N} (\hat{y}_i - \bar{y})^2 \tag{30}$$

$$SST = \sum_{i=1}^{N} (y_i - \bar{y})^2 \tag{31}$$

$$R^2 = \frac{\sum_{i=1}^{N} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{N} (y_i - \bar{y})^2} \tag{32}$$

$$SSE = \sum_{i=1}^{N} (y_i - \hat{y}_i)^2 = SST - SSR \tag{33}$$

where: *SSE* = the reduced sum of square error

y_i = the ith experimental value

$\bar{y}$ = the average of experimental value

$\hat{y}_i$ = the ith predicted model value

1.2.3.7.4 The standard error of estimate (*SEE*)

It estimates the dispersion of measured data around the regression line and shows a model's fitting ability in relation to the number of data points (Sun, 1999).

$$SEE = \sqrt{\frac{\sum_{i=1}^{N} (\mathrm{MR}_{\mathrm{exp,\,i}} - \mathrm{MR}_{\mathrm{pre,i}})^2}{df}} \tag{34}$$

where: *df* = degree of freedom of regression model

1.2.4 Quality of dried foods and deteriorative reactions during drying

According to United Nations Industrial Development Organization (2012), Dried food quality is determined by changes that occur during preparation and storage. Modifications to the physical structure are included in some of these alterations. Texture, rehydrability, and appearance are all affected by these changes. Chemical reactions cause other changes, but physical structure influences them as well, notably through impacts on the diffusivity of reactants and reaction products.

Engineering and quality attributes are the two key areas of dried product properties that are commonly studied. Effective moisture diffusivity, effective thermal conductivity, drying kinetics, specific heat, and equilibrium moisture content are all engineering characteristics of dried materials. There are many attributes associated with product quality. These qualities are required for determining and characterizing the quality of dried products and are divided into the following categories:

- Structural properties: density, porosity, pore size, specific volume, and others.

- Textural properties: compression test, stress relaxation test, tensile test, and others.

- Nutritional characteristics: vitamins, proteins and others.

- Sensory properties: aroma, taste, flavor and others.

-Thermal properties: state of product; glassy, crystalline, rubbery, and others.

- Rehydration properties: rehydration rate, rehydration capacity.

- Optical properties: color, appearance, and others.

The quality of dehydrated foods has received considerable attention in recent decades. The quality of dehydrated materials appears to be influenced by the drying method used as well as the physical-chemical changes that occur throughout the drying process. The drying constant, color, texture, density, porosity, and sorption properties of materials are all affected by the drying technique and process conditions.

The rising need for efficient, high-quality, and convenient products at a low cost has resulted in the use of a variety of drying processes in practice. The parameters that determine drying quality have been briefly stated in Table 1.3.

Table 1.3 Factors that affect the drying of food (Heldman, 1992).

Physical	Chemical	Nutritional
Rehydration Solubility Texture Aroma loss	Browning reactions Lipid oxidation Color degradation	Vitamin deterioration Protein loss Microbial survival

Food products degrade at different rates depending on the food type, content, formulation, packaging, and storage system. Deterioration has the potential to occur at any point between the procurement of raw materials and the final consumption of a final product, and it may be increased or reduced at any of these points. As a result, effective preservation methods for food and dairy products are generally multi-component, relying on more than one aspect. The principal degrading responses, which are the primary preservation goals, are well-known and limited (Table 1.4). Some are mainly physical in the mechanism of action, whereas others are chemical, enzymatic, or microbiological. When preservation fails and these reactions become uncontrollable, the consequences are numerous. These might range from slight yet undesirable changes in color or flavor to a change in texture inside the food. The most substantial forms of deterioration, on the other hand, are those associated with the presence or multiplication of microorganisms, and these range from undesirable spoilage to the transmission of life-threatening diseases caused by the most dangerous of food-poisoning microorganisms, such as Clostridium botulinum, Salmonella, enteropathogenic Escherichia coli, and Listeria monocytogenes.

Table 1.4 Reactions that Cause Food to Deteriorate (Gould, 1995).

Basis of reaction	Example and consequence
Physical	- Moisture movement, causing drying and toughening of texture, hydration and softening of texture, aggregation
Chemical	- Oxidation, causing oxidative rancidity, loss of color
	- Maillard reactions, causing discoloration, change in texture
Microbial	- Growth of toxigenic organisms, causing food poisoning
	- Growth of spoilage organisms, causing quality deterioration
	- Presence of infectious organisms, causing food poisoning
Enzymatic	- Lipoxygenase, causing oxidative rancidity
	- Lipase, causing lipolytic rancidity
	- Polyphenol oxidase, causing enzymic browning
	- Protease, causing gelation and flavor and texture changes

Quality losses can occur as a result of reactions that occur during drying, notably nutritional losses and other deterioration induced by browning reactions. Browning reactions and nutrient losses are two types of responses that occur during drying. Furthermore, structural changes occur, affecting the quality of dried fruits and vegetables.

1.2.5 Changes in chemical properties that occur during food drying

1.2.5.1 Browning reactions

According to United Nations Industrial Development Organization (2012), Browning reactions, which are among the most significant reactions in food during processing and storage, are an interesting study issue due to their consequences for food stability and technology, as well as nutrition and health. They can include a variety of substances and follow a variety of chemical processes. Browning reactions in foods are common and become visible when food ingredients are exposed to processing or mechanical harm. They are significant in terms of changing the appearance, flavor, and nutritional value. Browning is considered to be acceptable if it improves the look and flavor of a food product in terms of tradition and customer acceptability, as in the examples of coffee, maple syrup, beer, and toasting bread. Browning, on the other hand, is undesirable in many other situations, such as fruits, vegetables, frozen and dried products, since it results in off-flavors and colors. As a result, understanding the processes and techniques of suppression of browning reactions is critical. Another notable negative impact of browning is a reduction in the nutritional content of the food product.

The rate of browning reactions is affected by the drying temperature, the pH and moisture content of the product, the heat treatment duration, and the concentration and character of the reactants. The rate increases as the temperature rises, and the rate rises quicker in systems with a high sugar concentration. Dilution causes a drop in response rate over 30% moisture content, whereas the intrinsic capacity of sugars to lower water activity causes a decrease below 30% moisture level.

Browning reactions impact color, reduce nutritional value and solubility, produce off-flavors, and cause textural changes. Browning may be classified into two types: enzymatic and non-enzymatic (Maillard reactions, caramelization, and ascorbic acid oxidation). This color change is usually undesirable but knowing the sort of response involved makes it easier to develop methods for controlling it.

(1) Enzymatic Browning

A set of enzymes known as "phenolase" causes browning in many fruits and vegetables, such as potatoes, apples, and bananas. The color of fruits and vegetables changes when the tissue is damaged, sliced, peeled, infected, or subjected to any variety of abnormal conditions. The conversion of phenolic chemicals to brown melanin causes the damaged tissue to darken quickly when exposed to air. phenoloxidase, cresolase, dopa oxidase, catecholase, tyrosinase, polyphenoloxidase, potato oxidase, sweet potato oxidase, and phenolase complex are all members of this enzyme system.

Phenolase can be found in a wide range of plants, including roots, citrus fruits, plums, bananas, peaches, pears, melons, olives, tea, mushrooms, and more. It has a molecular weight of Paper 31- PAGE 4/18, 128.000 and a copper content of 0.2 percent, which means that each enzyme molecule contains four Cu molecules. Cupper is present in the cuprous form in the freshly created enzyme, but as it ages, it progressively oxidizes to the cupric form. As a consequence, there is no loss of activity as a result of this change. Phenolase is colorless in its purest form. At a neutral pH, concentrated phenolase solutions are the most stable. However, heating the enzyme for a brief time at 60°C inactivates it. H_2S, KCN, and other chemicals that form stable compounds with copper also inhibit phenolase.

Many naturally occurring o-diphenolic compounds in plants can be oxidized by phenolase. The mechanism of phenolase's action on o-diphenolic compounds is really rather complicated. The action of phenolase is considered to be dependent on the conversion of copper from the cupric to the cuprous state, because copper is the prosthetic group of the enzyme. Simply put, phenolase catalyzes the oxidation of colorless phenolic molecules into red to brown o-quinones. O-quinones are the pigments that give cut fruits and vegetables their brown color. Highly collared complexes arise when they react with amino acid derivatives.

The presence of phenolase, its copper prosthetic group, and oxygen is required for the initial reaction, which involves the conversion of a phenolic molecule to its equivalent quinone. This can be used to control or prevent food browning caused by enzymes. During the dehydration process, any damage to the plant tissue, whether caused by heat or improper handling procedures, might activate phenolase.

Enzymatic browning of foods is generally unfavorable since it affects the food's acceptability for two reasons: (1) the undesirable development of off-color and (2) the production of off-flavors.

Control Methods of Enzymatic Browning

(I) Heat

Heat applied to the food product at a high temperature over a longer length of time inactivates phenolase and any other enzymes present. The usage of heat can cause a number of problems. The fruit or vegetable becomes overdone, resulting in unpleasant textural changes and the formation of off-flavors. Such issues might arise during the processing of pre-peeled potatoes, apples, pears, and peaches.

When it comes to heat-treatment of foods, temperature and time are intimately connected. These parameters are affected by the quantity of enzyme present. It is also critical to carefully manage the heating duration at high temperatures in order to inactivate the enzymes while preventing major changes in flavor and texture. A balance should be maintained between each raw ingredient and the desired food result.

(II) Sulphur dioxide and sulphites

Sulfur dioxide and sulphites, commonly sodium sulphate, sodium bisulphate, and sodium metabisulphate, are chemical phenolase inhibitors that have been applied in the food business a long time. It can be used as a gaseous sulphur dioxide or as dilute aqueous sulphite solutions. The gas will permeate the fruit or vegetable faster, but sulphite solutions are easier to manage, such as in the form of a dip in the processing plant or as a spray. The usage of sulphur dioxide or sulphites has both advantages and disadvantages. They can be used in cases where heat would cause undesired textural changes and the formation of off-flavors. When applying SO_2, the inside atmosphere of the product must be properly considered. Apple slices, for example, have a significant quantity of oxygen in the interior tissue, which can produce browning. In order to successfully control browning, SO_2 must infiltrate the whole slice. They contain antibacterial characteristics and aid in the preservation of vitamin C. However, their usage in food products may result in an unpleasant flavor and odor, as well as bleaching the natural color of the food. At high concentrations, it is toxic and may be identified organoleptically. The unfavorable, damaging impact of sulphur dioxide or sulphites on vitamin B or thiamine is perhaps the most important consequence of using them in products. Despite these disadvantages, this class of phenolase inhibitors is frequently employed in food processing, owing mostly to its efficacy and inexpensive cost.

(III) Acids

This is a commonly used approach for enzymatic browning control. Citric, malic, phosphoric, and ascorbic acids are among the acids used because they exist naturally in tissues. Their main effect is to reduce tissue pH and hence slow the rate of enzymatic browning. Phenolase has an optimal pH range of 6-7, and beyond that, there is essentially little enzymatic activity.

Citric acid has long been used as a chemical inhibitor of enzymatic browning, often in combination with ascorbic acid or sodium bisulphite. Prior to processing, cut fruit, such as peaches, is frequently soaked in dilute solutions of these acids. Citric acid inhibits phenolase in two ways: it lowers the pH of the medium and it chelates with the copper moiety of the enzyme.

Ascorbic acid is a significantly more effective inhibitor of phenolase. Its vitamin content is also well-known. It has no detectable flavor at the concentrations used, and it has little corrosive effect on metals. Ascorbic acid converts the o-quinones produced by phenolase to the original o-dihydroxphnolic compounds, preventing the development of brown compounds.

(IV) Dehydration in sugar

The fruit is reduced to 50% of its original weight by osmosis in sugar or syrup, which partially dehydrates the fruit. After being drained, the fruit is either further frozen or dried in an air or vacuum drier. Through full dehydration, the sugar or syrup prevents enzymatic browning. In addition, it has a flavor-protecting function.

(2) Non-enzymatic browning

Changes in the structure of derivative fruit products occur during the production process, modifying the color and final appearance of the product. Although most non-enzymatic browning in food materials is undesirable because it implies that the product's flavor and appearance have deteriorated, browning in other products is perfectly acceptable. Browning of baked products during baking, beer, molasses, coffee, and alternative cereal drinks, various breakfast foods, and roasting and other forms of heat preparation of meat are all examples of this. Brown colors that develop in most other products, on the other hand, are undesirable, and strategies to minimize or prevent such changes are in use.

There are three different types of non-enzymatic reactions: (I) Caramelization, (II) Maillard reaction, (III) Ascorbic acid oxidation.

(I) Caramelization

This is an example of non-enzymatic browning, in which sugars are degraded without the presence of amino acids or proteins. Caramelization happens when sugars are heated under anhydrous circumstances or exposed to a high concentration of dilute acid, resulting in the creation of anhydrous sugars.

Commercially available caramels are manufactured from glucose syrups, however caramelization is mainly the consequence of processes that occur when sucrose is cooked. This process (at 200°C) has three steps, during which water is lost and isosacchrosan and later additional anhydrides are generated. The first stage begins with the melting of sucrose, which is followed by 35 minutes of foaming. Each molecule of sucrose loses one molecule of water during this time. After that, the foaming stops. A second stage of foaming begins shortly after, lasting 55 minutes.

Approximately 9% of the water is lost during this stage, and the chemical generated is caramelan, a pigment having an average formula of $C_{24}H_{36}O_{18}$. Caramelan melts at 138°C, is bitter, and is soluble in water and ethanol. During the third stage of foaming, which begins after about 55 minutes, the color caramelen is formed. This pigment's formula is $C_{36}H_{50}O_{25}$. Caramelen is water soluble and melts around 154°C.

The major downside of this reaction is the potential for the development of unpleasant, burnt, and bitter compounds if the reaction is allowed to run unchecked. Bisulphites, which react with sugar to reduce the concentration of aldehydic form, can slow down this process.

(II) The Maillard reaction

The Maillard reaction has assisted in the improvement of the look and flavor of foods for as long as food has been cooked. Because the Maillard reaction is linked to aroma, taste, and color, it has been a major and substantial difficulty in the food business, especially in traditional procedures like coffee and cocoa bean roasting, bread and cake baking, cereal toasting, and meat cooking. Furthermore, a wide range of reaction products are generated during the Maillard reaction, many of which are important for dietary nutrition. This can be limited by decreased digestibility and the potential formation of toxic and mutagenic compounds, but it can also be aided by the synthesis of antioxidative materials.

The chemistry of the Maillard process is quite complicated. It refers to a network of reactions rather than a single reaction route. Controlling the Maillard process is notoriously difficult. Food processing variables are influenced by a variety of elements involved in the preparation of food.

The Maillard reaction was named after Louis Maillard, a French scientist who detected the development of dark pigments called melanoidins when a solution of glucose and glycine was heated.

The Maillard reaction occurs when amino acids and proteins interact with sugars. Because a free carbonyl group is required for this combination, the carbohydrate must be a reducing sugar. Melanoidins, which are brown pigments, are the final outcome. There are three phases to the response mechanism:

(i) Initial phase (colorless)

a. sugar-amine condensation

b. Amadori rearrangement

(ii) Intermediate phase (colorless to yellow)

c. sugar dehydration

d. sugar fragmentation

e. amino acid degradation

(iii) Final phase (highly colored)

f. aldol condensation

g. aldehyde-amine polymerisation, formation of heterocyclic nitrogen compounds.

The carbonylamino reaction may occur in both acidic and alkaline settings, but it prefers the latter. A rise in pH has been linked to an increase in reaction rate in many studies. As a result of the link between reaction rate and pH, foods with a high acidity, such as pickles, would be less sensitive to this reaction.

The most important chemical compounds generated in non-enzymatic browning processes are furfural and hydroxymethylfurfural (HMF). The HMF content is significant since it indicates the degree of heating of the processed products.

It has been demonstrated that buffers actually accelerate the browning process for sugar amino acid systems in non-enzymatic browning because of their impact on the ionic environment in which the reaction takes place. A number of research processes have shown that this reaction is temperature dependent, with higher rates observed as the temperature rises. In aqueous solution, this reaction progresses rapidly, but total dehydration of the reactants causes the reaction to stop.

Reducing sugars are essential for this reaction because they provide the carbonyl groups required for interaction with the free x-amino groups. The reaction can occur in the presence of reducing disaccharides, such as maltose and lactose, and is not limited to monosaccharides. Non-reducing sugars, on the other hand, cannot participate until the glycosidic link is severed, releasing the reaction's constituent reducing monosaccharides. Aldopentoses appear to have a higher order of reactivity than aldohexoses, but reducing disaccharides have much lower activity.

(III) Ascorbic acid oxidation

Another process, involving ascorbic acid, appears to be at work during the discolouration of dried vegetables. The synthesis of dehydroascorbic acid and diketogluconic acids from ascorbic acid is considered to happen during the final stages of the drying process, and these acids are capable of nonenzymatically reacting with free amino acids, resulting in the red to brown coloring. Strecker degradation may be involved in this reaction.

(IV) Inhibition of non-enzymatic browning

The production of colored complexes in food can be influenced by a number of factors. pH, temperature, moisture content, time, concentration, and the composition of the reactants are only a few of characteristics.

As the temperature rises, the rate of browning accelerates. Because these reactions have a high temperature coefficient, reducing the temperature of food products during storage can assist to decrease these processes.

Dehydrating techniques can reduce the moisture content, which can prohibit moisture-dependent processes from performing at optimum best. In order to carry out these operations, one must first ensure that the dehydrated product is suitable for sale in that form, and that it is packaged properly to prevent moisture absorption during storage.

Lowering the pH could give a suitable form of control if this form of browning is present, because the Maillard process is often preferred at more alkaline conditions.

By utilizing an inert gas to exclude oxygen, gas packing is incredibly beneficial. This decreases the probability of lipid oxidation, which might result in reduced molecules capable of interacting with amino acids. While the absence of oxygen does not appear to influence the initial carbonylamino reaction, it is expected to affect later reactions in the browning process.

Chemical inhibitors have proven effective in suppressing browning processes in a range of foods during manufacture and storage. Sulphites, bisulphites, thiols, and calcium salts are among the most commonly used.

Sulphites have been shown to be effective at controlling a variety of browning processes. By complexing with the reducing group of D-glucose and ascorbic acid, bisulphites prevent them from being converted to S-hydroxymethyl-furfural and furfural, respectively. As a result, furfural formation is blocked, preventing the generation of colorful pigments. They can also prevent the carbonyl group of the reducing sugars from reacting with the carbonylamino.

Browning has been related to calcium chloride, which has been suggested as a potential inhibitor. Its inhibitory effect is due to the chelating of calcium with the amino acids.

Although the various inhibitors suggested can prevent browning to variable degrees, it is important to keep in consideration that the nutritional content of the foods may have been greatly lowered. The carbonylamino reaction, for example, might have rendered the amino acids inaccessible during the initial stages of the Maillard reaction, even when no browning is visible. However, determining that this is the stage that is prevented is extremely complicated.

1.2.5.2 Lipid oxidation

In many foods, especially dry foods, lipid oxidation causes rancidity, taste development, and the loss of fat-soluble vitamins and pigments. Moisture content, type of substrate (fatty acid), amount of reaction, oxygen content, temperature, presence of metals, presence of natural antioxidants, enzyme activity, UV light, protein content, free amino acid content, and other chemical processes all impact oxidation rate.

Oxidation can be reduced by removing oxygen from foods, but the oxygen content must be very low to have an impact. The effect of oxygen on lipid oxidation is also influenced by the porosity of the product. Because of their high porosity, freeze-dried foods are more sensitive to oxygen. Due to shrinking, air-dried foods have a smaller surface area and are less damaged by oxygen. To reduce lipid oxidation, the literature recommends lowering the oxygen level during processing and storage, as well as adding antioxidants and sequestrates.

1.2.5.3 Color loss

The color of food is determined by the conditions in which it is viewed as well as the food's ability to reflect, scatter, absorb, or transmit visible light. Drying influences the reflectance and color of food by changing its surface properties. Green leaves, as well as red and yellow vegetables, contain carotenoids, which are fat-soluble pigments. Heat and oxidation during drying create chemical changes in carotenoid and chlorophyll pigments. Longer drying durations and higher drying temperatures result in more pigment loss in general. Browning occurs during storage due to oxidation and residual enzyme activity. Improved blanching techniques and ascorbic acid or sulphur dioxide treatment of fruits prevent this. According to several research, the majority of carotenoid degradation happens during storage rather than as a result of dehydration. Temperature and moisture increased, and pigment retention in dried foods reduced. The beet pigments were found to be the most stable in powders, next in slices, and finally in solution.

All higher plants' natural green pigment is a combination of chlorophyll a and chlorophyll b. The retention of magnesium in pigment molecules is directly related to the retention of chlorophyll's inherent greenness. Chlorophyll is transformed to pheophytin by losing part of its magnesium under moist heating conditions. Instead of a grass green, the color changes to an olive green.

During the traditional drying of fruits, amino acids and reducing sugars interact (Maillard reaction). Sulphuring the fruits prevents enzymatic browning and delays the Maillard process.

There are several different approaches to color analysis. The RGB (red, green, blue), LAB (lightness, redness-greenness, yellowness-blueness), and XYZ scales are the most often used systems for analyzing color into three factors, allowing any composite color to be simply measured by a set of three numbers.

1.2.5.4 Change in oil during frying

According to Sahin and Sumnu (2009), the food to be fried, the oil used, and the process characteristics, particularly temperature and frying time, all have a factor in the frying process.

Deep-frying exposes the oil to high temperatures in the air and moisture on a continuous or repeated basis. During this period, a variety of chemical processes, such as oxidation and hydrolysis, as well as changes owing to heat degradation, take place. As these processes progress, the oil's functional, sensory, and nutritional quality deteriorates, and it may finally become impossible to create high-quality fried foods, forcing the frying oil to be discarded. The chemical processes that occur during deep oil frying differ from those that occur when the oil is heated constantly, according to Chang et al. (1978) and Landers and Rathman (1981). As a result, responses seen in research involving oils heated in air with or without agitation may not be representative of those observed in common intermittent frying conditions.

There are two types of decomposition products that occur during frying: volatile and non-volatile compounds.

1.2.5.4.1 Volatile decomposition products

Aldehydes, ketones, alcohols, acids, esters, hydrocarbons, lactones, and aromatic compounds are examples of volatile decomposition products (VDP).

The steam generated during frying removes the majority of the VDPs from the frying medium (Stevenson et al., 1984). However, according to Chang et al. (1978), some of these compounds are retained in fried food and absorbed by the deep-frying operator, potentially affecting the health of these persons.

1.2.5.4.2 Non-volatile decomposition products

The second kind of product created during deep-frying is non-volatile decomposition products (NVDP). The unsaturated fatty acids in the frying medium are thermally oxidized and polymerized, which leads to the production. This is concerning because these compounds not only remain in the frying oil, promoting further deterioration, but they are also absorbed by fried food and so consumed.

According to Paradis and Nawar (1981), compounds with a larger molecular weight accumulate steadily and have low volatility, making these more reliable indicators of oil usage. Physical changes in the frying oil (e.g., increased viscosity, color, and foaming) as well as chemical changes (e.g., increased free fatty acids (FFAs), carbonyl value, hydroxyl content, saponi cation value, and decrease in unsaturation; and decrease in unsaturation) cause an increase in the formation of high molecular weight products.

These variations in the quality of frying oil are caused by a variety of reactions. The solubilization of colorful chemicals and fatty components in the fried food may change the color of the frying medium and the nature of the oil's composition.

Hydroperoxides can be degraded in three ways: (a) fission, which produces alcohols, aldehydes, acids, and hydrocarbons, as well as contributing to the darkening of frying oils (due to α-, α-, and α-, α′- unsaturated carbonyl compounds) and flavor changes; (b) dehydration, which produces ketones; and (c) free-radical formation of dimers and trimers, which leads to poly The rate at which viscosity rises corresponds to the rate at which polymers are formed. According to Artman (1969), the oil's UV absorption rises due to the conjugation of double bonds and the buildup of oxygenated products. The oil's iodine value may rise in the early stages of thermal oxidation due to the production of new unsaturated connections, but it will reduce as the double bonds are consumed in different processes.

During the frying process, unsaturated fatty acids are most impacted (Gupta, 2005). The degree of unsaturation of the fatty acids present is typically related to the rate of oxidation. As a result, linolenic acid (which has three double bonds) is much more vulnerable than oleic acid (one double bond). Hydrolysis occurs when moisture in fried foods is present, resulting in the creation of FFAs, monoglycerides, diglycerides, and glycerol. FFAs can also be generated during oxidation as a result of double bond breaking and oxidation.

Moisture also helps to remove peroxides, flavors, and smells that would otherwise develop in the frying oil by creating a "steam blanket effect" over the fryer, decreasing contact with air and helping to remove peroxides, flavors, and aromas that would otherwise accumulate in the frying oil.

Heat accelerates the formation of dimers and cyclic compounds through polymerization, which results in the final kind of change in the quality of frying oil. The compounds that result from this process are large molecules formed by carbon-to-carbon and/or carbon-to-oxygen-to-carbon bridges between several fatty acids, increasing the concentration of polar compounds, despite the fact that the mechanisms are complex and incompletely understood.

Increases in these chemicals cause oil viscosity, foaming, "gum" deposition, and color darkening to rise.

The effect of Maillard reaction products migrating to the frying medium on the oil's oxidative stability is one issue of particular interest. Several studies have demonstrated that Maillard products have antioxidant activity in model systems and foods, however there has been little research on frying oils. The oxidative stability index of high oleic high palmitic sunflower oil, as evaluated by the Rancimat device at 120°C, rose significantly following discontinuous frying of almonds, peanuts, and sunflower seeds, according to recent research. According to Marmesat et al. (2005), Maillard products may contribute to the frying oil's increased stability.

The interaction of lipid oxidation products with amines, amino acids, and proteins in frying oil can result in non-enzymatic browning (Zamora and Hidalgo, 2005).

Another mechanism based on the interaction of epoxyalkenals with protein amino groups has been proposed to explain the production of polypyrrolic polymers that contribute to non-enzymatic browning and the synthesis of volatile heterocyclic. Although epoxides have been found to be one of the principal functional groups discovered in thermoxidized and used frying oils (Velasco et al., 2004), epoxyalkenals have not been reported to occur at frying temperatures, therefore their contribution to non-enzymatic browning of fried foods is undefined.

The majority of non-enzymatic browning studies has been performed in model systems, therefore the extent of processes involving lipid oxidation products and the Maillard reaction in real frying conditions is uncertain. This is because to the fact that the reaction products are difficult to remove macromolecules, and the large number of substances involved makes analysis challenging. These two chemical pathways are also impacted by one another, link reaction intermediates, and produce comparable products. In a recent assessment of the subject, it was recommended that the two reactions are so interrelated that they should be evaluated at the same period (Zamora and Hidalgo, 2005).

The oil's state of oxidation appears to perform a vital role in the browning that occurs during frying, however this function is attributed to a physical process caused by the interfacial activity of lipid oxidation chemicals. Because oxidation products are found at the oil–food interface, there is more contact between the two phases and, as a result, better heat transmission, which aids browning. Blumenthal's theory is based on this, as stated above.

1.2.6 Physical changes that occur during frying (Sahin and Sumnu, 2009)

1.2.6.1 Shrinkage

The change in dimensions and size of the fried product is referred to as shrinkage. During the frying process, the thickness of the potatoes decreased dramatically (Costa et al., 1997). The rate of shrinkage rose with frying temperature and reduced with potato thickness, but temperature had no effect on the final volume. Except for very low moisture content, volume fell mostly due to water loss, and hence potato density did not change significantly. Because of oil absorption and the buildup of entrapped water vapor, volume increased at the conclusion of frying (especially for small samples and high frying temperatures). Oil absorption and water loss increased as oil temperature raised and sample thickness dropped in French fries. During the frying process, there was very little shrinkage. Specific volume dropped as oil temperature increased and sample thickness decreased (Krokida et al., 2000).

Tortilla chips are one of the most widely consumed masa-based snacks. The majority of the shrinkage of tortilla chips happened within the first 5 seconds of frying in fresh soybean oil at 190°C for 60 seconds (Kawas and Moreira, 2001). Because of the crust development, chip thickness grew by around 40%, and vapor production caused some bubbles to form on the surface. During frying, the crust thickness rose nonlinearly as the moisture content decreased. At the completion of the frying process, tortilla chips shrank by around 9% in diameter, expanded by 10% in thickness, and puffed by 100%. Due to the decrease in bulk density driven by water loss, the chips became more porous (pore size increased in number and size) at the end of the frying process. As the frying time increased, the pore size distribution became more regular, and the number of big pores increased, filling out the whole structure of the chips in a normal distribution. When the shrinking stopped, puffing began (Yamsaengsung and Moreira, 2002b). The amount of pressure that could be released from the core area was limited by the formation of a crust on the chip's outer layer. Puffing began at a moisture content of around 10% on a wet basis (w.b.) and proceeded until about 2%.

1.2.6.2 Volume, density, and porosity

Because porosity and volume are intimately connected to mechanical characteristics and microstructure, they are essential physical properties of raw and fried vegetables. The violent development of bubbles in material tissue during frying results in a structure with varying porosity over time that is influenced by operational settings. Food geometry, drying technique, and drying conditions all influence shrinkage and deformation.

Porosity (φ), commonly known as the volume fraction of air or void fraction in a sample, is calculated as follows:

$$\varphi = 1\text{-}\frac{\rho_b}{\rho_s} = 1\text{-}\frac{V_s}{V_b} \qquad (35)$$

where: ρ_s = the solid density

ρ_b = the total density and defined as the material mass divided by the total material volume.

The total volume of irregular forms (such as those produced during frying of potatoes and tortillas) could be measured by volumetric displacement using 100 µm diameter glass beads.

The mass of a quantity of matter per unit volume of the same quantity is named density. Although density is a basic measure that is extensively used in food process analysis, it can be perplexing since density is defined differently from different individuals. The true, skeleton, or solid density, also known as "absolute" or "particle" density, refers to the density determined on the basis of the volume, omitting any pores and interparticle spaces that may be present. The apparent density (envelope density) is determined using the volume, which includes pores but does not include interparticle spaces. To put it another way, apparent density determines the number of blind and non-interconnected pores in a sample while excluding open, interconnected, and interparticle pore spaces. The bulk density is determined by measuring the volume of the pores and interparticle spaces. The problem in understanding density terms presented in various study papers derives from the difficulty in precisely quantifying pores and interparticle spaces in materials.

Shrinkage changes the density and porosity of fried foods, which affects vegetable transport qualities including thermal and mass diffusivity. Roughness is a physical property that has a big impact on processes that are about food surfaces. Oil uptake in fried foods is a good example, as it is essentially a surface phenomenon. To calculate roughness in fried potatoes, some researchers employed fractal geometry, while others used statistical approaches (Bouchon and Pyle, 2004; Pedreschi et al., 2000).

Pinthus et al. (1992) reported that the crust porosity of fried reformed potato products reduced during the frying process, and that lower gel strengths had a massive effect. After changing subfreezing storage conditions, Pinthus et al. (1995) found that the porosity of a restructured potato product varied from 0.089 to 0.168. Oil absorption during frying and porosity before frying were shown to have a linear relationship. During frying, particle density rose, bulk density dropped, and porosity increased significantly. After a short duration, oil absorption was shown to be linearly proportional to the porosity of the fried product. To characterize the mechanics of oil absorption, a new term was invented: "net porosity," which excludes the empty volume occupied by oil. The effects of frying conditions on the shrinkage and porosity of fried potatoes were investigated by Krokida et al. (2000). During frying, apparent density, true density, specific volume, and internal porosity were examined and shown to have a significant impact on moisture loss and oil uptake. The porosity of French fries rises with the temperature of the oil and the thickness of the sample and is higher for foods fried in hydrogenated oil. Moreira et al. (1997) found that tortilla chips produced from finely powdered masa puff up excessively, resulting in more oil absorption and reduced porosity, whereas tortilla chips made from coarse particles had the least oil content and no puffing.

1.2.6.3 Texture

Texture is a sensory perception that can be perceived, described, and quantified by humans. It's commonly related with mechanical, geometrical, and auditory factors and is defined as a multi-parameter characteristic. Szczesniak (1963) offered the recognized definition of texture, which states that "texture is the sensory and functional expression of the structural and mechanical qualities of foods, as determined by the senses of visual, hearing, feeling, and kinesthetic." The structural qualities of food define texture. In especially for fruits and vegetables, perceived texture and physical structure interact in factors are variables.

Textural changes in raw tissues during frying are the results of a variety of physical, chemical, and structural changes, as well as heat and mass transfer with chemical reactions. The gelatinization of starch after heating might have a significant impact on texture in products with a high starch content, such as potatoes. Raw vegetables are fried, causing significant changes in the microstructure, which affect the final physical and sensory qualities. It's important to understand how the texture of vegetable tissue changes during the frying process. In battered and breaded foods, texture is also a significant physical quality. The final surface coating of battered or breaded products is formed by frying a crisp, continuous, and uniform layer over the food substrate. The appeal of fried food is mostly due to the crispiness of the coatings (Mellema, 2003).

Studies on the fundamental mechanical characteristics of fried potatoes can help quantify changes in structural factors including crispness and hardness, which are essential for fried potato processing units (Ross and Scanlon, 2004). To quantify the texture of some foods (e.g., fried potatoes), several procedures (both subjective and objective) have been used. In a puncture test on potato chips, Bourne et al. (1966) determined the initial slopes of the force–deformation curve. The maximum breaking force varied greatly, whereas the initial slope was more consistent. This parameter was suggested as a way to quantify sharpness. The texture of fried potatoes is affected by solids distribution, oil spots/pockets, and crust frying patterns (e.g., whether potato samples are cooked over a layer of hot oil or are partially or totally immersed). Despite its variability, the puncture test provides excellent discrimination between the mechanical qualities of the crust and, since it is less sensitive to the cross-sectional geometry of the product, it can be used for products of various sizes and forms. To evaluate the texture of potato chips, Segnini et al. (1999) designed a puncture test with three support points. This method produced fewer variations in analytic data and allowed for the linkage between texture and moisture content. A puncture test was devised by Pedreschi et al. (2001) to determine *in situ* textural changes in potato strips during frying. This test allowed for the testing of potato strips at various positions and frying times inside the hot oil, avoiding the chilling process that occurs when the strips are taken from the fryer and may impact their mechanical qualities.

Vegetable tissue texture deterioration after frying shows an initial softness followed by a hardening of the tissue. According to Pedreschi and Moyano (2005), a model with the sum of two terms has been given, the first for softening with first-order kinetics and the second for hardening, which depends on the square of time in the case of potato chips and linearly on time in the case of French fries (Pedreschi et al., 2001). Increased frying temperatures enhanced core frying and crust hardening, resulting in thicker crusted French fries. In the case of potato chips, frying revealed an early stage in which the potato tissue softened and became cooked, followed by a later stage in which crust development began and gradually solidified. The texture qualities of potato chips and French fries are heavily influenced by the processing conditions (Pedreschi and Moyano, 2005).

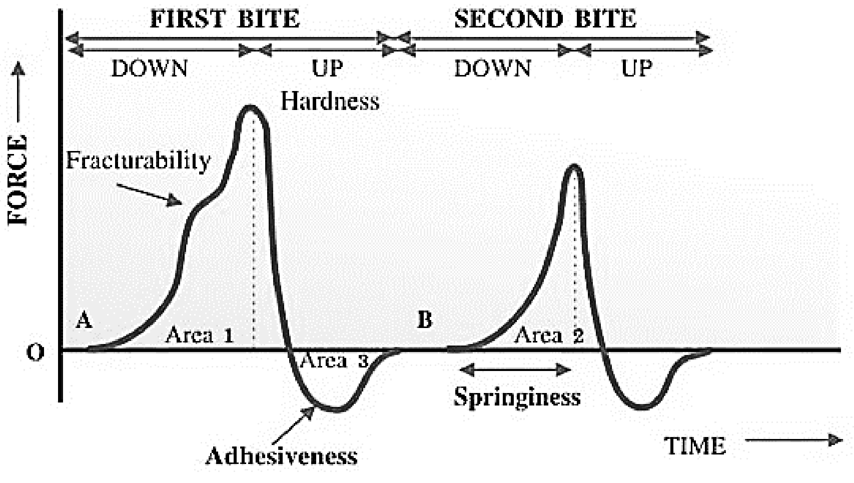


Figure 1.6 Texture Profile Analysis graph (Food Network Solutions, 2006).

Texture profile analysis is a test using a flat plate probe whose diameter is larger than the material size. The test is to apply the compression test twice to a standard-size food sample, simulating the use of teeth to grind food. The texture profile analysis method is applied to measure the texture of many foods in the ready-to-eat state, including meat and meat products such as ham, sausage, cheese, vegetables, fruits, tofu, and jelly because the quality is related to the Sensory evaluation. The test results are graphed between force (N) and time or deformation (see Figure 1.6). The test, called the TPA curve, can be used to find a variety of parameters that describe the texture of food.

1.2.6.4 Color

Color is the most important visual property in the perception of product quality among the several groups of physical attributes of foods and foodstuffs. Consumers' initial quality characteristics are the appearance and color of the food surface, which are key in product approval even before it reaches the mouth. Because color corresponds strongly with physical, chemical, and sensory evaluations of food quality, consumers prefer to link color with flavor, safety, storage duration, nutrition, and level of satisfaction.

Color development in fried potatoes occurs only when sufficient drying has happened and is dependent on the drying rate and heat transfer coefficient at different stages of frying. The color of the fried products is predicted to be affected by process factors such as time, oil temperature, and raw material pretreatments, where L, a, and b are the lightness, redness and yellowness (Figure 1.7) of the sample, respectively. The Maillard process causes color variations in fried potatoes, which is influenced by the amount of reducing sugars (mostly D-glucose) and amino acids or proteins on the surface, as well as surface temperature and frying time. Browning is usually a zero-order process at temperatures below 60°C. A plot of brown pigment against time will curve upwards at increasing temperatures, as in a first-order process

(Hutchings, 1994). Because a deep-fat frying process normally has a comparatively short period with a surface temperature of 60°C, a first-order kinetics study for browning during frying is predicted.

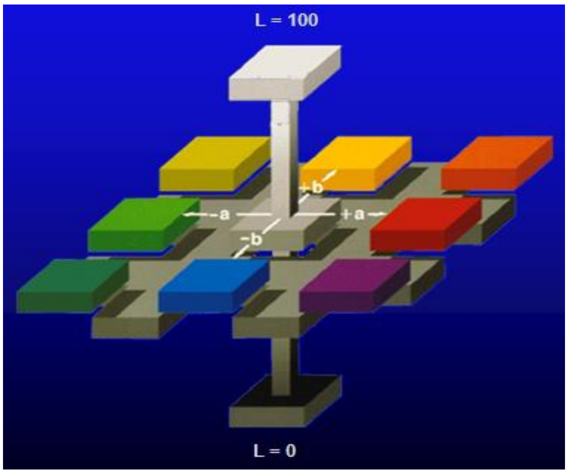


Figure 1.7 L, a, b color scale chart (Hunterlab, 1995).

Three color characteristics of donuts (L, a, b) were found to be substantially related with frying time, with rising redness (a) and decreasing lightness (L) as a function of time (Velez-Ruiz and Sosa-Morales, 2003).

The frying temperature influenced the color of fried onion rings (Ling et al. 1998). Onions rings fried at 190°C showed lower L (lower lightness), greater "a" (higher redness), and lower "b" (lower yellowness) values than onion rings fried at 170°C. At increasing temperatures, the rate of non-enzymatic browning (Maillard) reactions between proteins and reducing sugars increased, resulting in these color changes. Likewise, raising the frying temperature decreased L, raised "a," and decreased "b" in coated chicken thighs and breasts (Waimaleongora-Ek and Chen, 1983). With increasing frying time, coated chicken portions showed similar color changes. The positive "a" value (redness) of onion rings rose with frying time as well, whereas L and "b" did not change much.

1.2.6.5 Oil uptake

As a result of the different absorption mechanisms, Bouchon et al. (2003) identified three oil fractions: (i) structural oil, which is the oil that is absorbed during frying; (ii) penetrated surface oil, which is the oil that is suctioned into the food during cooling after removal from the fryer; and (iii) surface oil, which is the oil that remains on the surface as shown in Figure 1.8.

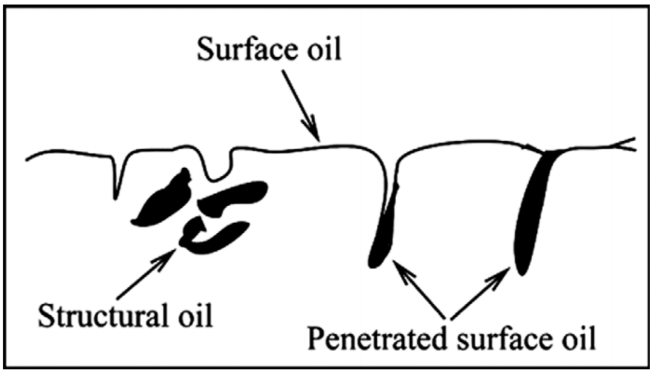


Figure 1.8 Three oil fractions in fried food (Lumanlan et al., 2019).

The thermal and physical–chemical characteristics of the food and oil, as well as the food geometry and oil temperature, all impact heat and mass transfer during frying. Most of the oil on the fried piece surface does not penetrate during frying; it adheres to the piece surface at the end of frying, and a large proportion of it penetrates into the microstructure of the food after frying. Bouchon (2002) and Yamsaengsung and Moreira (2002a) published a comprehensive review of the many mathematical models created to understand frying food transport phenomena. In the modeling of frying transport processes, only a few researchers have included crust formation as a moving boundary problem (Bouchon 2002; Farkas et al., 1996). Few researchers, on the other hand, have included post-frying oil absorption in mass transfer.

The degree of degradation of the frying oil, temperature, pressure, and frying time, food geometry, chemical composition of the raw food, pre-treatments, surface roughness, and porosity of the food to be fried are some of the main factors that affect oil absorption in fried products. At higher frying temperatures, oil absorption generally reduces. Vacuum frying reduces the amount of oil in fried potato and apple slices (Granda et al., 2004; Mariscal and Bouchon, 2008). Recent study has attempted into using the microwave to fry potatoes (Oztop et al., 2007) and battered and breaded chicken (Barutcu et al., 2007). In comparison to traditional deep-fat frying, oil absorption was reduced in microwave fried potatoes, while oil content was greater in microwave fried chicken fingers.

1.2.7 Changes in nutrition that occur as a result of food drying

1.2.7.1 Nutrient losses

According to United Nations Industrial Development Organization (2012), when food is dried, it loses moisture, resulting in an increase in the concentration of nutrients in the residual bulk. Dried foods have more protein, fat, and carbohydrate content per unit weight than the fresh counterparts. Wide variations in preparation techniques, drying temperature and time, and storage conditions cause large variances in published statistics on the nutritional content of dried foods. In the case of fruits and vegetables, loss caused during preparation commonly exceed those incurred throughout the drying process. Partially oxidized water-soluble vitamins are to be expected. During blanching and enzyme inactivation, water-soluble vitamins are reduced. Some vitamins (for example, riboflavin) become supersaturated and precipitate out of solution as the drying process progresses. As a result, losses are low

(Table 1.5). Others, such as ascorbic acid, are soluble until the food's moisture content is very low, then react with solutes at a faster rate as drying progresses. High temperatures and high moisture content are both harmful to ascorbic acid. The greatest rate of ascorbic acid breakdown occurs at specified (critical) moisture levels, according to several research. The critical water content appears to change depending on the dried product and/or the dehydration procedure. To minimize excessive losses, short drying times, low temperatures, and low moisture and oxygen levels during storage are required. Since ascorbic acid is most heat sensitive at high moisture content, the product should be dried at a low starting temperature to enhance ascorbic acid retention. As the drying process advances, the temperature can be raised, and ascorbic acid becomes more stable as the moisture content decreases. Although thiamin is heat sensitive, other water-soluble vitamins are more resistant to heat and oxidation, and drying losses rarely surpass 5%–10%.

Sun-dried, dehydrated, or a mix of the two methods can be used to prepare fruits. Carotene concentration decreases as a result of sun drying. Dehydration, particularly spray drying, can cause this vitamin to be lost. Sun-dried fruits lose a significant amount of vitamin C. Fruits that have been frozen dried retain more vitamin C and other minerals. Dehydrated meals retain vitamins better than sun-dried foods in nearly every way.

Vegetable tissues that have been dried artificially or in the sun tend to lose nutrients in the same sequence as fruits. If vegetables are processed without enzyme inactivation, the carotene concentration can be reduced by as much as 80%. The best commercial processes will allow for drying with losses of less than 5% carotene. In blanched tissues, thiamin concentration is expected to be reduced by 15%, but unblanched tissues may lose three-quarters of this vitamin. When it comes to ascorbic acid, quick drying retains more than gradual drying. In general, slow sun drying processes decrease the vitamin C content of vegetable tissue. In any case, the vitamin potency will deteriorate as the dry food is stored.

The amount of vitamins maintained in milk products is determined by the nutritional content of the raw milk and the technique of processing. Drum-dried and spray-dried milk both preserve high levels of vitamin A. Dry milk that has been vacuum packed retains a high level of vitamin A. Spray and drum drying also cause thiamin losses, however these are on a much lower scale than fruit and vegetable drying. With riboflavin, similar results are found. During the drying of milk, ascorbic acid is lost. Vitamin C is heat and oxidation sensitive, thus it may be completely lost during the drying process. Ascorbic acid levels may be preserved in the same order of magnitude as fresh raw milk with proper processing, vacuum drying, and freeze-drying. Milk's vitamin D concentration is often reduced when it is dried. Prior to drying, fluid milk should be supplemented with vitamin D. Other vitamins, such pyridoxine and niacin, are not significantly depleted.

Dried meat usually has a lower nutritional content than fresh meat. During processing, thiamin is lost, with higher losses at higher drying temperatures. Dried meat loses the most of its vitamin C. Riboflavin and niacin losses are low.

Oil-soluble nutrients (such as important fatty acids and vitamins A, D, E, and K) are largely found in the food's dry matter, therefore they are not concentrated after drying. Heavy metal catalysts that enhance the oxidation of unsaturated nutrients, on the other hand, use water as a solvent. The catalysts develop more reactive when water is removed, and the rate of oxidation increases. Interaction with the peroxides generated by fat oxidation causes fat-soluble vitamins to be lost. Low oxygen concentrations, storage temperatures, and the absence of light all help to prevent losses during storage.

Table 1.5 Vitamin loss in a variety of dried foods (Fellows, 1988).

Food	Loss (%)						
	Vitamin A	Thiamin	Vitamin B_2	Niacin	Vitamin C	Folic acid	Biotin
Fruits[a]	6	55	-	10	56		
Vegetables[b]	5	<10	<10	-	-	-	-
Whole milk (spray-dried)	-	-	-	-	15	10	10
Whole milk (drum-dried)	-	-	-	-	30	10	10
Fig (sun-dried)	-	48	42	37	-	-	-
Pork	-	50-70	-	-	-	-	-

[a] Fruits are from fresh apple, apricot, peach, and prunes that have been lost.

[b] Peas, corn, cabbage, and beans are among the vegetables that have suffered losses (drying stage only)

(I) The Effects of Drying on Protein

The biological value of dried protein is determined by the drying technique. Long-term exposure to high temperatures can degrade the protein's nutritional value. Protein digestibility could be improved by low-temperature treatments compared to native material. During drum drying, milk proteins are partly denaturated, resulting in decreased milk powder solubility, aggregation, and loss of clotting ability. The biological value of milk protein is reduced by Maillard reactions between lysine and lactose at high storage temperatures and moisture contents above around 5%. Lysine is heat-sensitive, and losses in whole milk vary from 3–10% when spray dried to 5–40% when drum dried.

(II) The effect of drying on fats

In dried foods, rancidity is a major concern. Fats are more easily oxidized at higher temperatures than at dehydration's low temperatures. Antioxidant protection of lipids is an effective control.

(III) The effect of drying on carbohydrates

Fruits are generally high in carbohydrates but low in protein and fat. Carbohydrates are the main cause of fruit degradation. Enzymatic browning or caramelization processes can cause discoloration. In the latter case, the interaction of organic acids with reducing sugars results in discoloration, which is visible as browning. Browning can be controlled by injecting sulphur dioxide into tissues. Enzyme toxicity and antioxidant power are the mechanisms at action. Low moisture content is required for this treatment to be effective. Carbohydrate degradation is particularly noticeable in dried fruit and vegetable tissues. Unless the tissues are preserved with sulphates or other appropriate chemicals, slow sun drying allows significant damage. The least expensive approach of achieving such protection is to burn sulphur before drying.

1.2.7.2 Microbiological quality

Since microorganisms are extensively distributed throughout nature and foodstuffs come into touch with soil and dust at some point, microorganisms are expected to be active anytime conditions permit. The limiting of moisture for growth is one clear strategy of control. Moisture is required by living tissues. The quantity of moisture in food determines which microorganisms can grow. Reducing a product's water activity below 0.85 inhibits it from growing, but it doesn't make it sterile. Although the heat of the drying process reduces the numbers, the survival of food-spoilage organisms in the reconstituted food may cause difficulties. Controlling microorganisms during processing is based mainly on fairly basic recommendations. Even while modest drying temperatures are better for keeping organoleptic qualities, the greatest feasible drying temperatures should be employed to optimize thermal death. The maximum permitted moisture content is limited when a process is adjusted for other quality variables.

When it comes to drying, sodium chloride is widely used. Salt is effective for preventing microbial development during the drying and dehydration of meat and fish in the sun.

Starting with high-quality, low-contamination foods, pasteurizing the material prior to drying, processing in clean facilities, and storing dried foods in conditions that protect them from dust, insects, rodents, and other animals is the most effective management.

1.2.7.3 Storage stability

The organoleptic, physical, and chemical changes that occur in dried fruit and vegetables during storage, as well as the rates at which these changes occur, are discussed when addressing storage stability. The main forms of degradation of dried fruits and vegetables in storage are darkening and loss of taste.

(1) Major variables impacting storage stability include sulphur dioxide content, storage temperature, light, packing material, moisture content, antimicrobial treatment, and trace elements. Only free sulphite is useful in preventing pigment materials from forming. The loss of sulphur dioxide during storage influences the dried product's practical shelf life in terms of deterioration due to non-enzymatic browning. Residual sulphites are required for storage at semitropical or summer temperatures to avoid darkening and taste bittering, as well as to make the dried fruit a less attractive medium for microorganism development. During storage, sulphur dioxide helps in the preservation of a light, natural color. The rate of darkening during storage is inversely related to the amount of sulphur dioxide present. As a result, every situation that promotes sulphur dioxide loss also enhances product darkening. The addition of an oxygen scavenger pouch to the sealed, packed sulphured dried fruit is one approach to prevent sulphite loss and so discoloration.

(2) The storage temperature is critical in terms of quality preservation. To enhance storage life, dried fruits and vegetables should be stored at relatively low temperatures. Temperature has a significant impact on the loss of sulphur dioxide from the dried product during storage. A -6.67°C rise in temperature increases the rate of sulphur dioxide leakage by around thrice. Furthermore, when temperatures rise, the rate of change in taste accelerates.

(3) Light has a negative impact on quality during storage. It reduces carotene concentration, increases the rate and amount of sulphur dioxide loss, and therefore accelerates darkening. It also has an impact on riboflavin content.

(4) The packing material used and the package environment are also crucial factors in terms of storage stability. The type of packaging chosen depends on

the anticipated storage conditions. Packaging can be done by using a vacuum, nitrogen, or atmospheric pressure.

(5) Dried foods have a moisture content of less than 20% and a water activity of 0.7 or less. They are tough and firm, with a high resistance to microbial degradation. Some products have critical water activity below which browning is reduced. Storage stability improves as moisture content decreases. However, it has been noted that the highest rate of degradation of dried fruits occurs at a moisture level of 5–8 percent.

(6) During storage, dried fruits and vegetables must be protected from animals and insects. Fumigation is commonly used to keep insects away during storage and before packing. In addition to fumigation, antimycotic chemicals (fungistats) are used to prevent mold formation in most prunes and figs at 30–35 percent moisture. To prevent melting, sorbic acid and sorbate salts are used as dips or sprays; sulphur dioxide or sulphite salts are used to preserve fruits from color changes and browning when drying, as well as to repel insects. The most effective is the potassium sorbate dip. The efficacy is determined by the product's pH.

(7) Some salts and metals are harmful to the nutritious value, taste, and storage quality of food. These trace elements may be introduced into raw materials during washing or pre-treatment. Calcium firms the texture; iron and copper react with tannins to cause blackening and may increase ascorbic acid breakdown. Bitterness is imparted by sodium, magnesium, and calcium sulphates. Certain zinc, cadmium, and chromium salts are hazardous.

1.2.8 The cause of dried food degradation (TPUB, 2007)

1.2.8.1 Temperature

Temperature will have a considerable impact on the rate of degradation (Table 1.6). One may use a chemical rule (van't Hoff's rule) to determine the rate at which the degradation change will occur. In essence, the rule states that the rate of a chemical reaction doubles for every 10°C rise in temperature. When applied to chemical processes that occur in foods, this rule will suffice. Using this general rule, one can state that for every 10°C rise in a food's storage temperature, the shelf life is cut in half since the rate of deterioration chemical reaction doubles. Peroxide decomposition is extremely slow at low temperatures, relatively quick at high temperatures.

1.2.8.2 Light

The changing of color in many foods may be caused by light, which is another type of physical change that affects food degradation. Some vitamins, such as riboflavin, vitamin A, and vitamin C, are destroyed by light (Table 1.6).

1.2.8.3 Relative humidity

Excessive moisture causes gross changes in foods, which are a common occurrence. This type of degradation is most common in dried, dehydrated, and freeze-dried foods. These foods are particularly hygroscopic (absorb and retain moisture rapidly); if not correctly packed, the product will become lumpy or caked whether there is an excessive amount of moisture present. Other types of degradation, such as bacterial growth and chemical processes like oxidation, may occur as a result of this situation.

1.2.8.4 Oxygen

The breakdown of peroxides causes oxidative rancidity. The oxidation of unsaturated lipids produces peroxides. Aldehydes, ketones, and hydrocarbons are some of the by products of peroxide decomposition. These aid in the production of oxidative rancidity's tastes and smells.

(1) Abnormal characteristics.

A product that has experienced oxidative rancidity will have an unnatural (rancid) taste as well as a paintlike or acrid (burning) odor. This deterioration process usually does not impact the color of a food product.

(2) Unsaturated fatty acids.

Oxidative rancidity affects all foods containing unsaturated fatty acids (UFA).

(I) Three factors influence the rates of development and intensity of unpleasantness caused. These are the lipid components' composition, the placement in the food, and the storage conditions. High amounts of UFA, especially acids with three or more double bonds, and exposure to air at high temperatures cause extreme rancidity to develop quickly.

(II) Peroxide decomposition is exceedingly slow at low temperatures, but quick at high temperatures.

Table 1.6 Semi-perishables, major mechanisms of degradation.

Semi-perishables	Mode of deterioration	Critical environmental factors
Canned fruits and vegetables	Loss of flavor, texture, color, nutrients	Temperature
Fried snack Foods	Rancidity, loss of crispness, breakage	Oxygen, light, temperature, relative humidity, physical handling
Breakfast cereals	Rancidity, loss of crispness, nutrient loss, breakage	Relative humidity, temperature, rough handling
Pasta	Texture changes, staling, vitamin, protein quality loss, breakage	Relative humidity, temperature, light, oxygen, rough handling
Dehydrated foods	Browning, rancidity, loss of color, loss of texture, loss of nutrients	Relative humidity, temperature, light, oxygen
Tea	Loss of flavor, absorption of foreign odor	Oxygen, temperature, light, relative humidity
Non-fat dried milk	Flavor deterioration, loss of solubilization, caking, nutrient loss	Relative humidity, temperature

1.2.9 Vacuum fryer

Vacuum fryers are used to fry fruits and vegetables. It is essential to keep the original color of the product while allowing for little browning. These fryers typically have a low output capacity. Batch vacuum fryers are commonly used. Continuous vacuum fryers are challenging to construct and maintain. They are also quite costly and are rarely produced.

Vacuum batch fryers offer various distinguishing characteristics. The fryer operates at a pressure of ≤100 mmHg and at a temperature of approximately 121.1°C. At this temperature, the food dehydrates mainly to the vacuum. The oil in vacuum frying is heated by an external oil heater. Food is arranged in a basket. The basket is put in the vacuum chamber above the surface of the oil. The vacuum frying chamber door is closed, closed, and vacuum is provided. When the vacuum in the chamber reaches 100 mmHg pressure, the basket is dropped into the heated oil at a temperature of around 121.1°C. When the material is submerged in the oil, the temperature instantly decreases. The oil is constantly circulated through an external heater. When the product's moisture content reaches a predetermined level, the oil regains its temperature. The vacuum in the fryer is gently broken after frying. To prevent the oil from oxidation, this is best achieved with nitrogen rather than air. The frying chamber door is opened, and the product basket is removed. The surplus oil is drained, and the product is cooled before it is packaged.

Vacuum frying is performed at pressures lower than atmospheric, which decreases the boiling temperatures of the oil and moisture in the foods. As a result, frying can be conducted at lower temperatures. In Europe, vacuum fryers are used to make French fries because they can reach the required moisture content without significantly browning the product (Moreira et al., 1999).

Due to lower temperatures and the absence of air during the process, vacuum frying has various advantages, such as less oil absorption and the preservation of the product's natural color and flavor, as well as the preservation of oil quality for longer periods of time (Shyu et al., 2005). However, because vacuum frying is often performed in closed units, it suffers from the drawbacks associated with batch procedures. Continuous vacuum fryers are also available, but they are prohibitively expensive (Gupta et al., 2004).

1.2.10 Microwave energy (FDA, 2016).

Microwaves are a type of "electromagnetic" radiation, which means that are waves of electrical and magnetic energy flowing across space at the same time. Electromagnetic radiation has a wide range of wavelengths, ranging from very long radio waves to very short gamma rays. Only a small fraction of this spectrum, known as visible light, can be detected by the human eye. A radio detects a particular part of the spectrum, while X-ray equipment detects yet another.

Non-ionizing radiation includes visible light, microwaves, and radio frequency (RF) waves. The energy of non-ionizing radiation is insufficient to push electrons out of atoms. Ionizing radiation includes X-rays. Ionizing radiation can cause harm to organic matter cells by altering atoms and molecules. Microwaves are used in the manufacturing industry to dry and cure plywood, cure rubber and resins, rise bread and doughnuts, and cook potato chips. Microwave energy is most often used by consumers in microwave ovens. Microwaves can be employed in cooking because they are reflected by metal, travel through glass, paper, plastic, and other similar materials, and are absorbed by foods.

An electron tube called a magnetron produces microwaves within the oven. The microwaves are reflected within the oven's metal interior and absorbed by the food. Microwaves force water molecules in food to vibrate, generating heat that cooks it. As a result, foods with a high water content, such as fresh vegetables, can be cooked faster than other foods. When microwave radiation is absorbed by food, it is converted to heat, and the food is not transformed "radioactive" or "contaminated."

Even though heat is generated directly in the food, microwave ovens do not cook food from the "inside out." When thick foods are cooked, microwaves are used to heat and cook the outside layers, while heat conduction from the hot outer layers heats the inside layers.

Microwave cooking saves energy since food cooks faster and the energy warms only the food, not the entire oven compartment. Microwave cooking does not alter the nutritional content of foods in any way. Dishes cooked in a microwave oven can retain more vitamins and minerals than foods cooked in a conventional oven because microwave ovens may cook faster without adding water.

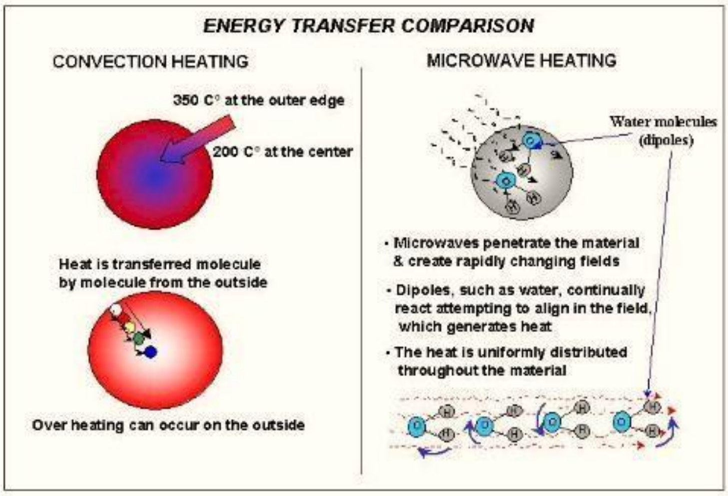


Figure 1.9 Transfer of energy Microwave heating vs. convection heating (Mainland, 2017).

Microwave heating of foods is caused by two basic mechanisms: dipolar rotation and ionic contact. Polar molecules spin in an electromagnetic field and try to align up with the field in the dipolar rotation process (Figure 1.9). Because the field's direction changes depending on the frequency of the oven, the polar molecules continue to rotate and collide with the rest of the molecules. As a result, the remaining molecules are set in motion, and kinetic energy is created. As a result, heating occurs.

The ions in the ionic conduction process attempt to align with the direction of the electromagnetic field. Positive ions will travel in the electromagnetic field's direction, whereas negative ions will move in the opposite way. The ions travel back and forth as the direction of the field changes. During this movement, molecules interact with the remainder of the molecules, causing friction and heating of the food. Internal heat generation in microwave heating promotes moisture vapor generation inside the product, which can result in high internal pressure. The resultant pressure gradient is an essential moisture transfer mechanism (Datta, 1990).

Heat is transferred from the heated oil to the food material being fried by convection and conduction through the solid food in conventional deep-fat frying. When microwaves are used for frying, heat is generated within the food as well. As a result, the frying time is reduced. Because foods include a considerable quantity of water, dipolar rotation causes heat buildup within the product. If the food to be fried has a considerable level of ash, ionic conduction is also necessary for microwave frying.

When compared to traditional heating or frying, microwave heating has a relatively large pressure gradient. In traditional heating, the pressure is about equal to that of the atmosphere. The greatest pressure value in frying may be noticed around the evaporation front (Datta, 2007). Pressure rapidly rises up towards the surface. Pressure, on the other hand, falls when the surface dries out. The pressure buildup in frying is minimal (approximately 1 kPa), yet it has a significant influence on moisture movement. Water convective and capillary diffusional fluxes are significant in the core area. Because the magnitudes of convective vapor flux and diffusional vapor flux are equivalent in the crust area, the convective term is considerable.

Microwave cooking should be performed in a microwave-transmitting container. To fry in a microwave oven, microwaves are used to heat oil from room temperature to frying temperature. The food is then put in heated oil and fried at the required power level for the set frying time.

A recent patent for a combination microwave frying device is available (Cheng and Peng, 2006). This equipment includes a frying device with an oil groove and a microwave emitting device. The goal of this technology is to deliver consistent heating in foodstuffs while saving oil. According to the manufacturer, a typical frying equipment has an oil groove for accepting oil and uses gas or electricity to heat the frying oil. The drawbacks of this technology include non-uniform heating and oil degradation at high temperatures. Microwaves provide an additional heating source when numerous magnetrons are installed within the frying apparatus and situated below the oil groove. As a result, food may be heated more consistently and frying time is shorter.

1.2.11 Dried products

Fruits and vegetables that have been dried. The food has been well received. It has long attracted the imagination of people in most countries. Because it can be preserved for an extended period of time. Although out of season, this is a healthy, inexpensive, and easily accessible food. Fruit and vegetable drying results in the development of modern color and a delicious taste similar to fresh fruit. As a result, the vacuum fried product development to satisfy the demands of consumers. By vacuum frying fruits and vegetables that are available in a variety of varieties and brands. Available on the internet and at general stores (Figure 1.10). The price of the product is listed in Tables 1.7. To analyze consumer reaction, the product was vacuum dried and fried. As a result, the focus of this research has been on the successful development of vacuum frying of durian. To assist farmers in adding value by increasing revenue from the sale of fresh fruit.

Figure 1.10 Vacuum dried and fried products from the department store Tesco Lotus stores and Tops supermarket of department store Robinson, Hat Yai, Songkhla province.

Table 1.7 Description of the product dried by vacuum drying and frying (Information from the department store Tesco Lotus stores and Tops supermarket of department store Robinson, Hat Yai, Songkhla province).

The product	Weight (g)	Production facilities.	Price (baht per unit)
Dried durian.	50	Jfruit TM	108
Durian chips.	50	Khunmaeju Co., Ltd	80
Durian chips.	70	Mr. Tong	97
Durian chips.	27	AunNae	29
Durian chips	100	Nong-Nam Gimyong market	80
Dried Durian.	50	Fruit Tech Co., Ltd.	57
Durian vacuum freeze dried.	100	Nature Vita	169

1.3 Review of Literatures

Vacuum drying of fruits has been the subject of several investigations. Swasdisevi et al. (2007) and Nimmol et al. (2007), for example, investigated banana slices drying in a vacuum drier with infrared radiation heating. A vacuum drier using infrared radiation has the benefit of being a high-efficiency dryer. Because infrared radiation has the ability to permeate materials. The material's water molecules vibrate, producing heat. The material's interior temperature is higher than the surface temperature. The material's exterior surface does not wrinkle as a result.

Junlakan et al. (2013) studied the efficient in performing for vacuum drying banana slices in a vacuum drier and discovered the best thin-layer equation for predicting banana drying kinetics. The drying studies were carried out at 30 mmHg absolute chamber pressure and 60, 70, 80, and 90°C drying temperatures. These were carried out until the moisture content of the sample was less than 3.4% (w.b.). The dried samples were then evaluated for physical quality (color, shrinkage, and texture) as well as sensory quality (in terms of color, texture, flavor, crispness, and overall acceptability). In comparison to the lower drying temperature, the drying time at the maximum temperature (90°C) was the fastest, and the dried banana slices at this temperature showed the highest degree of yellowness, reduced shrinkage, and more crispness. Sensory research found that the levels of general acceptability and sensory attributes of dried bananas were not significantly different in any drying condition. As a result, a drying temperature of 90°C was proposed as the optimum drying condition for sliced bananas. Furthermore, three mathematical models for thin layer drying (Newton, Logarithmic, and Page) were examined. The Logarithmic equation was determined to have the greatest R^2 and lowest χ^2 and RMSE of 0.9795, 0.0017, and 0.0434, respectively.

Wu et al. (2007) considered the vacuum drying properties of eggplant. Experiments were conducted at vacuum chamber pressures of 2.5, 5, and 10 kPa with drying temperatures ranging from 30 to 50°C. The findings revealed that raising the drying temperature increased the vacuum drying rate, however drying chamber pressure had no influence on the drying process within the temperature range studied. The drying shrinkage of the samples was found to be independent of drying temperature but increased significantly when drying chamber pressure rose. An Arrhenius-type relationship adequately defined the temperature dependency of the effective moisture diffusivity for vacuum drying of eggplant samples.

Moreover, Swasdisevi et al. (2007) studied the drying of Cavendish banana slices under vacuum using far infrared radiation. Cavendish banana slices with an initial moisture content of 300% (d.b.) were dried at different vacuum pressures (5, 10 and 15 kPa), temperatures (50, 55, and 60°C), and thicknesses (2, 3 and 4 mm) until a final moisture content of 7% (d.b.) was achieved. The findings demonstrated that vacuum pressure, temperature, and thickness all had a substantial impact on the drying kinetics and several attributes of the dried banana, including color, hardness, and shrinkage. The combination of FIR and vacuum drying has the ability to produce a fat-free shuck-like product from banana. Furthermore, the optimal conditions for infrared-vacuum drying are 50°C, 5 kPa pressure, and 2 mm thickness.

Junlakan et al. (2016) also investigated the impact of vacuum drying on structural changes in bananas, pineapples, and apples compared traditional convective drying. Experiments with drying air temperatures of 100, 110, and 120ºC and an absolute chamber pressure of 4 kPa were carried out. The vacuum drying at the highest temperature produced the fastest drying time, the lowest degree of lightness, reduced shrinkage, more crispness, more pores, and greater rehydration ability for all three types of fruits. Vacuum drying improved the quality of all varieties of dried fruits as compared to traditional convective drying. Furthermore, according to sensory study, vacuum dried bananas, pineapples, and apples had the greatest degree of approval at 8.00±0.79, 7.77±0.73, and 7.87±1.01, respectively, at 120ºC. As a result, vacuum drying at 120ºC drying air temperature was considered as the most effective drying condition.

In this investigation, however, a vacuum fryer was used. Many researchers investigated the impact of vacuum frying on agricultural product quality. For example, Garayo and Moreira (2002) investigated the effects of oil temperature and vacuum pressure on the drying rate and oil absorption of potato chips at 118, 132, and 144°C and 16.661, 9.888, and 3.115 kPa, respectively. Shrinkage, color, and texture were also evaluated as product quality factors. Furthermore, the properties of potato chips fried at ambient temperatures (165°C) were compared to those of vacuum-fried potato chips (144°C and 3.115 kPa). The findings demonstrated that the drying rate and oil absorption rate of potato chips were significantly affected by oil temperature and vacuum pressure during vacuum frying. The volume shrinkage of potato chips fried at a lower vacuum pressure and higher temperature was reduced. With higher oil temperatures and lower vacuum levels, hardness values increased. The color, however, was unaffected by the oil temperature or vacuum pressure. Potato chips fried under vacuum (144°C and 3.115 kPa) showed higher volume shrinkage, were slightly softer, and were lighter than potato chips fried under atmospheric conditions (160°C) in parts of the study. As a result, vacuum frying has the potential to be a viable option to producing low-oil potato chips with acceptable color and texture.

Ophithakorn and Yamsaengsung (2003) studied the drying rate and oil absorption of fish tofu at temperatures of 100, 120, and 140ºC and vacuum pressures of 50, 60, and 70 cmHg. The drying curves of fish tofu under high vacuum pressure (70 cmHg) resulted in a significant decrease in the product's moisture content, with the fastest drying happening at the highest oil temperature (140ºC). At the highest vacuum pressure, the oil absorption rate for vacuum frying at 120ºC was the quickest. Furthermore, there was no significant difference in the amounts of FFA between the vacuum fried oil and the atmospheric fried oil following batches of frying. When compared to atmospheric fried oil, vacuum fried oil showed lower TBA and PV values, as well as lighter color development. Furthermore, Yamsaengsung et al. (2017) found that the use of vacuum frying shown that it might be applied to minimize the final oil level of fish tofu. A high atmospheric frying temperature caused a rapid rise in temperature toward the core of the fried fish tofu, resulting in microstructure damage. It might be a reason for concern because changes in moisture content were delayed after 60 seconds. Surface collapse, on the other hand, increased oil absorption due to adsorption into the damaged regions. The outcome might be due to a structural alteration that altered the oil adsorption of the fried fish tofu. In addition to darkening the frying oil's color, high temperatures and oxidation also changed its chemical properties. As the number of frying batches grew, the b* and ΔE values rose, and the oil yellowed. The frying oil quality, however, was preserved while the product's light color was preserved when vacuum frying was used.

Villamizar et al. (2012) applied vacuum on a paste of mango pulp and starch to study the behavior of quality parameters in a fried snack prepared from mango. Temperatures of 100, 110, and 120ºC, vacuum pressures of 0.4, 0.5, and 0.6 bar, and times of 30, 45, 60, 75, and 90 seconds were used in the experiment. Improved snack quality attributes such as extremely low fat and humidity content, decreased water activity, a texture that satisfied market demands, and a minor color change with regard to paste color were all advantages of vacuum frying.

Moreira (2014) also studied at vacuum frying versus convectional frying. Deep-fat frying is routinely performed at a temperature of around 190ºC while under atmospheric pressure. The results suggest that excessive darkening on the product, even before it is finished cooking, is the most common problem. Furthermore, some oil breakdown products have been related to negative health impacts when frying oil is used repeatedly. In comparison to standard frying, vacuum fried products retain more nutritional quality, have less oxidation, and have less oil degradation.

The effects of oil temperature, frying duration, and ripeness on the properties of vacuum fried bananas were investigated by Yamsaengsung et al. (2011). After 20 minutes of frying, the %thickness, expansion, and hardness of vacuum fried banana slices at 100, 110, and 120ºC and 8.0 kPa. Numbers in the same data series with different superscripts indicate that the values are statistically different ($p<0.05$).The results revealed that frying at 110ºC caused the greatest amount of expansion. However, the product's hardness is unaffected by temperature. The hardness of vacuum-fried banana slices changes with frying duration at 110°C and 8.0 kPa. The findings revealed that water from within the product moved rapidly toward the product surface during the first 10 minutes of frying. The product became rubbery and soggy as a result of the water movement. At the same time, the starch granules inside the product begin to gelatinize when they are subjected to heat, water, and shear stress, giving the product structure and a more solid texture. The impact of days of ripeness on the total sugar content and hardness of vacuum fried bananas fried at T = 110ºC and p = 8 kPa was that day 1 represented the least ripened bananas and had the lowest sugar to starch ratio of 2.90±0.20, but its hardness value of 16.51±1.40 N was significantly greater than those of other days of ripeness.

According to Ayustaningwarno et al. (2020) study, Unripe mango moisture loss has a greater apparent E_a value than ripe mango moisture loss. This impact might also be attributed to matrix differences between ripe and unripe mangoes. Ripe mango has a lot of pectin, which has water binding abilities. Large molecules of pectin in ripe fruit rigidly retain the water, requiring more energy and time to evaporate the water molecules for a higher degree of ripeness. In contrast, when the moisture level of ripe mango reduces, the oil content increases. Moisture and oil content have a clear correlation because oil will enter the space left by moisture during and mostly after evaporation, as shown in ripe mango. Unripe mango, on the other hand, showed a distinct pattern, probably due to a less porous structure that might minimize oil absorption.

Furthermore, various research investigations on the impacts of pretreatment prior to drying and the quality of durian chips have been conducted. Similarly, Bai-Ngew et al. (2011b) evaluated the influence of pretreatment on the quality of durian chips prior to microwave vacuum drying (slicing-chilling at 4ºC, slicing-freezing at 18ºC, and freezing-slicing). SEM analysis revealed that slicing-freezing and freezing-slicing prior to drying affected the expansion of the durian tissue, lowering the hardness of the dried durian chips. When compared to deep-fried durian chips, the fat content of vacuum-dried durian chips was reduced by at least 90%. Furthermore, sensory assessment and consumer acceptability tests showed that slicing-freezing prior to drying resulted in the highest overall preferring scores ($p<0.05$) for durian chips.

Additionally, different research studies on the mechanism of oil absorption on chip quality have been conducted. According to Garayo and Moreira's (2002) study, three main processes defining oil absorption into the product have been described during frying. To beginning, while the frying process continues, surrounding oil enters the product surface via liquid diffusion, replacing the evaporated liquid water. As the rate of water evaporation slows and the product surface dries up, a crust forms on the product surface. This crust slows the rate of water vapor diffusion and increases gas pressure, which slows the rate of oil absorption into the product. The second process of oil absorption occurs at the end of the drying time when the vacuum is pressurized to atmospheric pressure. This process begins when the chips are removed from the frying oil and placed in a vacuum and temperature-controlled environment (the fryer vessel is still closed). The pressure in the pores of the chips rapidly climbs to atmospheric levels when the vessel is vented at this stage, as air and surface oil rush into the empty pores spaces until the pressure reaches atmospheric levels. Finally, the third primary process of oil absorption occurred after the product has been taken from the fryer. In conventional frying, when the gas inside the pores cools, the pressure declines drastically, allowing the oil at the product surface to enter by capillary diffusion. Furthermore, because surface drainage during depressurization and centrifugation causes less oil to attach to the surface of the chips after vacuum frying, less oil is absorbed into the product during the cooling process for VF.

Lumanlan et al. (2019) studied mechanisms of oil uptake during deep frying of the chips. It was found that when water evaporation is stopped, the pore volume decreases. It was thought that smaller pores would capture more air, increasing oil absorption. When pores are bigger, oil absorption in a vertical capillary is lower, and when pores are smaller, oil impregnation is deeper. Some larger pores are left with no fat when oil is drained and dripped during cooling. Smaller pores, on the other hand, account for more than 81% of total pore development in potato chips, resulting in higher fat content, supporting statements by Bouchon and Pyle (2005) that a smaller pore radius leads to a higher capillary pressure and faster oil absorption during cooling of fried products.

Moreover, various research investigations on the impacts of microwave assisted drying and the quality of durian chips have been performed. Paengkanya et al. (2015), for example, compared the use of alternate techniques such as microwave vacuum (MWVC) drying and combination microwave-hot air (MWHA) drying to hot air (HA) drying in the production of un-oily crispy durian chips. The combined microwave approaches had greater drying rates than the HA, and these rates rose as microwave power level increased, resulting in shorter drying times. The dried durian from the combined microwave processes had higher lightness and crispness, larger pore diameters, and a higher void area fraction than those from HA drying, but reduced shrinkage and hardness. When compared to commercial dried durian chips, the combined microwave methods dried durian chips were less desired in terms of color, shape (puffiness), texture, and overall preference, while the overall preference of dried durian chips from MWHA was greater than MWVC.

Bai-Ngew et al. (2011a) performed microwave vacuum drying at 13.33 kPa to investigate the characteristics of microwave vacuum-dried durian chips at different microwave power levels (3.88W/g, 5.49 W/g, and 7.23 W/g). The Page model was shown to be the best at describing the drying characteristics of durian chips among several thin-layer models. Microwave power intensity enhanced drying rate, while microwave vacuum power had no effect on the lightness and yellowness of durian chips ($p>0.05$). Moreover, the hardness of the durian chips decreased as the microwave power level increased from 3.88 to 5.49 W/g. A further increase to 7.23 W, on the other hand, was shown to be likely to form a hot spot and hence enhance the breaking resistance. Furthermore, the lipid content of the durian chips was lowered by at least 90%, which should improve their shelf life as well as human health.

Su et al. (2016) evaluated the ability of microwave-assisted frying (MWVF) technology to reduce the oil uptake and improve quality attributes of fried potato chips. According to the findings, the oil absorption in MWVF samples was much lower than that in VF samples resulting in crisper chips, falling from 39.14 to 29.35 g oil/100 g dry solid. The MWVF enhanced moisture evaporation rates, resulting in crisper chips with greater natural color. Higher microwave power density increased water evaporation and reduced breaking force. Microstructure analysis revealed that MWVF retained the cellular structure and cell wall integrity in chips better.

For drying durian chips, microwave vacuum drying (MWVC) and combination microwave-hot air drying (MWHA) with step-down microwave power input were proposed by Nathakaranakule et al. (2019). The drying rates of step-down MWHA and MWVC rose in proportion to increases in microwave power used during the first stage of drying and decreases in vacuum pressure utilized in the step-down MWVC. These increased drying rates resulted in shorter drying times and lower SEC in both heat and electricity. Increasing the microwave power in the step-down MWVC and MWHA resulted in increased values of lightness, crispness, big pore size, and void area fraction, but lower values of hardness and %shrinkage for dried durian chips.

1.4 Objectives

1. To determine the optimal conditions for microwave-vacuum frying process of durian chips.
2. To study the mathematical model of microwave-vacuum frying process of durian chips.
3. To study the physical, chemical and sensory properties of the microwave-vacuum fried durian chips.
4. To study the economics of microwave-vacuum frying of durian chips

CHAPTER 2

Research Methodology

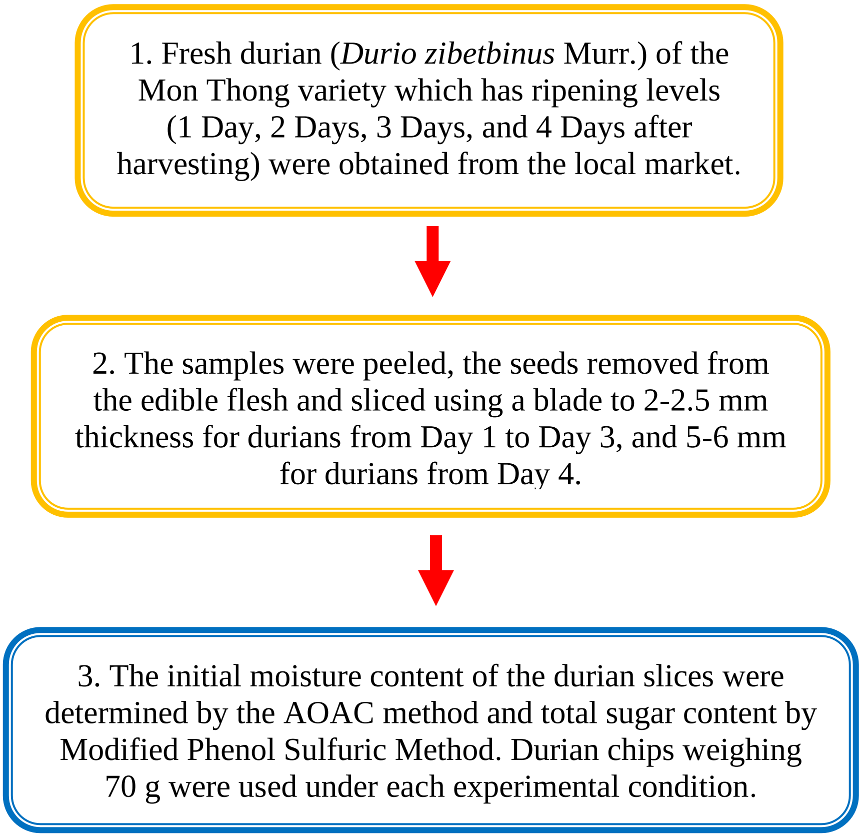
Research methodology has four main activities consist of

Activity 1 Study the optimal conditions for microwave assisted vacuum frying process of various ripening durian chips

Activity 2 Study the mathematical modeling of microwave assisted vacuum frying of various ripening durian chips

Activity 3 Study the physical, chemical, and sensory properties of the various ripening durian products were microwave-vacuum fried

Summary process of activities 1-3 depicts in Figure 2.1



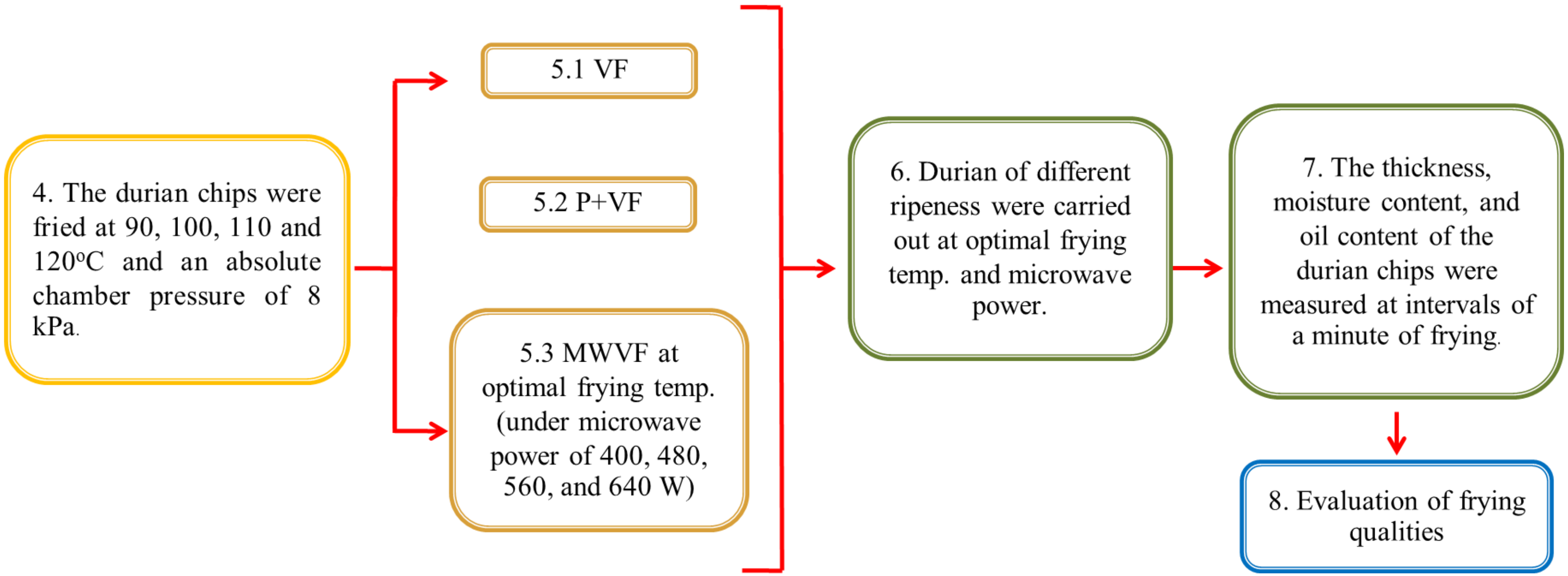


Figure 2.1 Processing summary of studying the optimum conditions for microwave vacuum frying of durian products.

Activity 4 Find specific energy consumption and economic analysis of microwave-vacuum frying of durian chips

2.1 Preparation of Raw Material

Fresh durians (Cultivated in the south of Thailand, cultivar: D159 or 'Durian Monthong' in Thai) were purchased in the local market. This study used the ripeness level in terms of total sugar content (g glucose/100g flesh durian) based on day of ripening (Day 1, Day 2, Day 3, and Day 4). The fresh durian had an initial moisture content of 54.78-71.32 % (w.b.) and was fried until it reached a final moisture content of 6.0% (w.b). The fresh durian was opened, and the flesh was removed and cut with a blade to a thickness of 2-2.5 mm for durians from Day 1 to Day 3, and 5-6 mm for durians from Day 4. For Day 4, The durian was too soft for slicing.

The sample of preparation was shown in Figure 2.2

Figure 2.2 The preparation of raw material for microwave-vacuum frying.

2.2 Experimental design

2.2.1 Microwave-assisted vacuum frying (MWVF) design

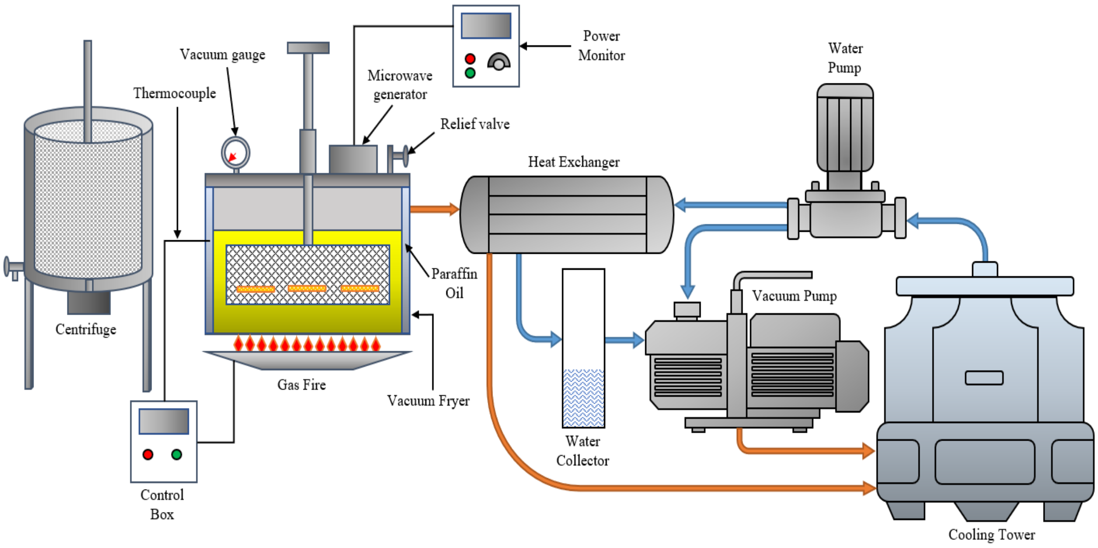


Figure 2.3 Modified schematic diagram of the microwave assisted vacuum frying operation (Modified from Thongcharoenpipat and Yamsaengsung, 2021).

From Figure 2.3, the experimental apparatus employed in this investigation included a vacuum fryer, a heat exchanger, a water pump, cooling water, a liquid ring vacuum pump (Model ET32030, Nash Trumbull, CT), a microwave generator magnetron, a power meter, and a centrifuge according to Thongcharoenpipat and Yamsaengsung (2022). All equipment (Figure 2.4) was assembled and gathered by the Department of Chemical Engineering, Prince of Songkla University, Hatyai, Thailand.

2.2.2 Methods

The durian chips were fried at 90, 100, 110, and 120°C under an absolute pressure of 8 kPa and three types of treatments: (1) VF; (2) P+VF (placed in a Ziplock bag and frozen at −18°C,24 h before vacuum frying); (3) MWVF. Each batch was made up of 70 g of samples that were deep-fried in 13 liters of palm oil (Figure 2.5). To keep the palm oil fresh, it was replenished every 10 batches of frying (Yamsaengsung et al, 2017). The sliced durians were vacuum fried using a combination of microwave power at 400, 480, 560, and 640 W. The moisture level of the durian chips was examined at one-minute intervals. The frying experiment was carried out until the moisture level in the final product reached 6.0% (w.b.). All of the experiments were carried out in triplicate. The products were centrifuged for 5 minutes at 450 rpm after frying to remove excessive oil on the surface and reduce oil absorption.

Figure 2.4 Photograph of microwave assisted vacuum frying system.

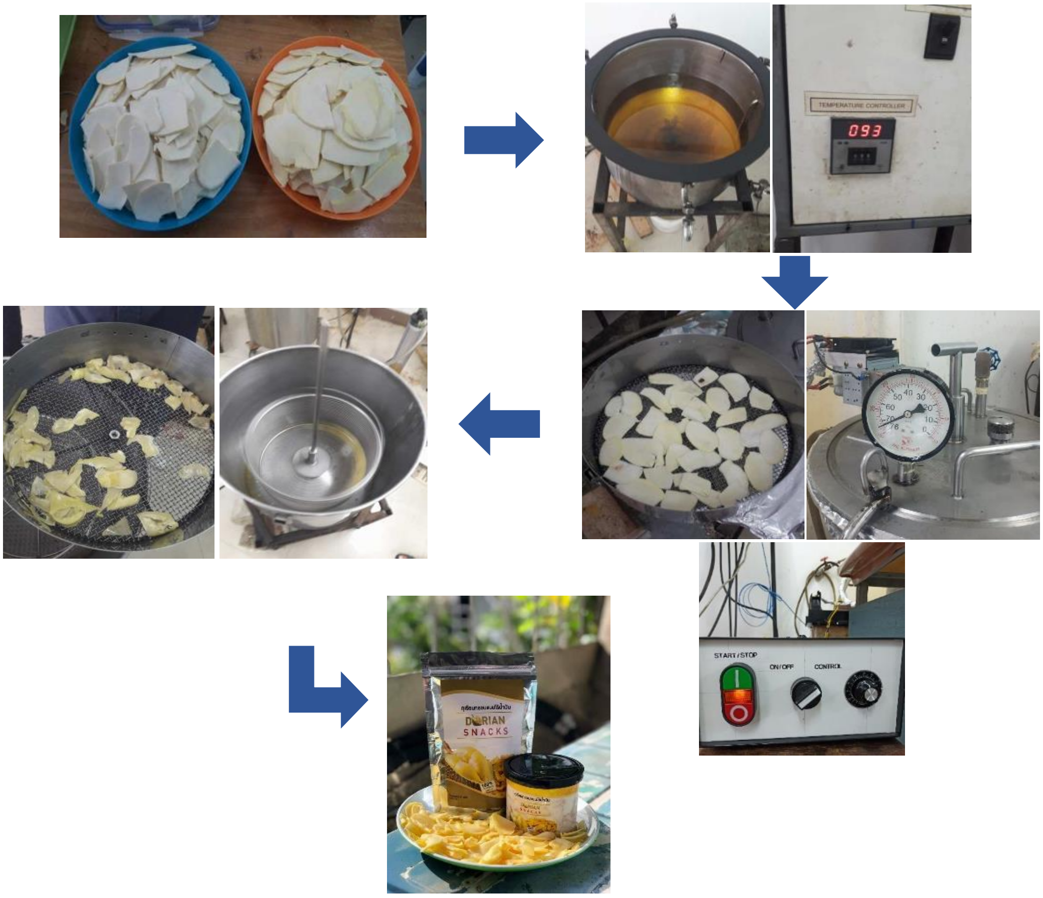


Figure 2.5 Vacuum frying and vacuum fried durian products.

2.3 Total sugar content

Fresh samples were evaluated for the total sugar content using Modified Phenol Sulfuric Method (Dubois et al., 1956). The total sugar content was calculated and calibrated using a glucose standard curve. All the tests were done in triplicate.

2.4 Moisture content and dehydration rate

The oven dried technique was used to evaluate the moisture content of the durian before and after frying. A total of 2 g of fresh durian was oven-dried for 72 hours at a temperature of 105°C (AOAC, 1990). The moisture content was then determined as a % (wet basis) using the equation:

$$M_w = \left(\frac{m_w}{m_w + m_d}\right) \times 100 \quad (36)$$

where: M_w= moisture content (% w.b.), m_d= mass of dry solid (g), m_w = mass of water (g).

The moisture ratio (MR) and the drying rate of each set of samples during frying were determined by the following equations:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (37)$$

$$\text{Drying rate} = \frac{W_L}{t} \quad (38)$$

where: M_0, M_t, and M_e = the moisture content (kg water kg dry solid^{-1}) at the beginning of frying, during frying, and at equilibrium, respectively

W_L= moisture loss in the weight of the sample

t = frying time (min). Following the work of Junlakan et al. (2016), the M_e was considered inconsequential. To demonstrate the drying curve for each condition, the MR was plotted versus the frying time.

2.5 Evaluation of Frying Qualities

2.5.1 Shrinkage

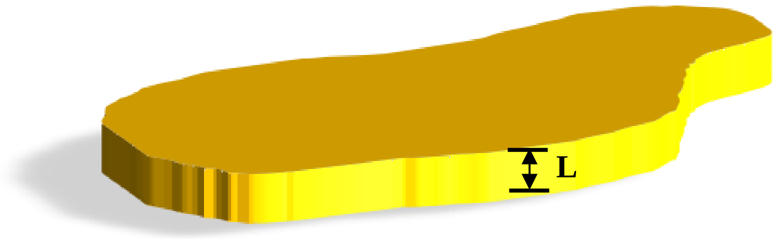


Figure 2.6 The shape of sliced durian chips in this study.

The shrinkage of durian chips was examined in order to identify the changes in the physical properties of the sample as a function of frying time and frying setting. Following each frying time interval, the samples were examined for thickness (Figure 2.6) and discarded, allowing new samples to be used for each set of studies. Using a Vernier caliper (0.05 mm precision), an average thickness value was derived from a batch of ten random samples. Equation (39) describes the % shrinkage:

$$\%\text{Shrinkage} = \left(\frac{L_0 - L}{L_0}\right) \times 100 \quad (39)$$

where: L and L_0 are the end-of-each-test and the original thicknesses (mm), respectively.

2.5.2 Color measurement

Figure 2.7 Hunter Lab color system colorimeter.

Using a Hunter Lab color system colorimeter (Juki Model JP100, Japan), the samples' colors were measured. The average value was calculated after ten samples were used to measure the color of the samples in each condition. The normalized color differences between products and fresh samples were calculated using the following equation:

$$\frac{\Delta L}{L_0}=\frac{L-L_0}{L_0}, \qquad \frac{\Delta a}{a_0}=\frac{a-a_0}{a_0}, \qquad \text{and} \qquad \frac{\Delta b}{b_0}=\frac{b-b_0}{b_0} \tag{40}$$

Using eq. (41), the total color change (ΔE) was calculated (Thongcharoenpipat and Yamsaengsung, 2021). The findings were used to report on the impact of frying temperature and vacuum frying conditions on product quality.

$$\Delta E=\left[\left(L_0 - L^*\right)^2+\left(a_0 - a^*\right)^2+\left(b_0 - b^*\right)^2\right]^{\frac{1}{2}} \tag{41}$$

where: L, a, and b = the lightness, redness and yellowness of the product, respectively, while L_0, a_0, and b_0 represent the initial values of the lightness, redness and yellowness of the original sample, respectively.

2.5.3 Oil content

Total oil content of the product was determined by using the Soxhlet extraction apparatus according to AOAC (1995). All the procedures were carried out in triplicate and mean values were reported.

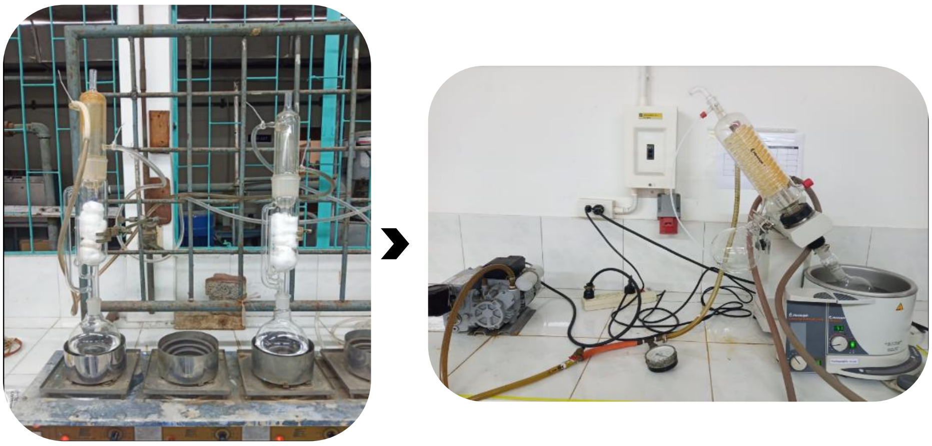


Figure 2.8 Oil content analysis by Soxhlet and Rotary evaporator.

2.5.4 Texture analysis

Textural properties of the durian chips (hardness and crispiness) were examined using a Texture Analyzer (Model TA-XTplus, Surrey, England) fitted with Crisp Fracture Rig consisting of the spherical 5 mm diameter probe set to move at travel distance of 5 mm and a cross-head speed of 1 mm/s until the sample cracked for measuring the maximum number of peaks. The maximum compression force and number of force curve peaks from the curve of force deformation of each sample were evaluated as indication of hardness and crispness, respectively. For each test run, a total of ten chips were used and the average value from each sample was taken. Data were analyzed using the Texture Expert Software (SMS Ltd., Version 1.19, Stable Micro Systems^{TM} Co., UK). Analytical results were indicated in g. All the sample were placed in separate sealed foil bags to avoid the humidity from the environment before the texture analysis was proceeded.

2.5.5 Structural analysis

The analysis of microstructure used a Scanning Electron Microscope (SEM, JEOL Model JSM 5800 LV, Tokyo, Japan) to observe the shape and change in pore size and the pore size distribution inside the product after vacuum frying. The voltage was applied between 10 and 20 kV depending on the detector particular area of the sample and spot sizes (between 8 and 10) fitting for it. The magnification was 100x. The ImageJ 1.53e Software was used to consider the number of pores along with the average diameter of pores for an individual SEM image.

Figure 2.9 Structural analysis by SEM 5800.

2.6 Sensory Analysis

A hedonic scale test for likeness was used to assess the acceptability of the durian chips (Thongcharoenpipat and Yamsaengsung, 2022). To minimize the difficulty of this discriminative group of Thai participants discriminating between phrases like 'dislike very much' (a '7' score) and 'dislike extremely' (a '9' score), the 7-point hedonic scale test was used instead of the 9-point hedonic scale test (see in Appendix A.6). Thirty random graduate students and staff members from the Department of Chemical Engineering at Prince of Songkla University (Thailand) were employed as panelists. Texture, color, aroma, taste, appearance, and overall acceptability were all evaluated.

2.7 Mathematical Modeling

2.7.1 Empirical models

The kinetics of the vacuum frying process were obtained by determining the moisture ratio (MR vs time) during varied vacuum fried conditions, plotted, and fitted by using eight empirical models.

Table 2.1 Selected thin-layer drying models for describing drying kinetics.

Model number	Model equation	Model name	References
1	$MR = \exp(-kt)$	Lewis	Doymaz and Ismail, 2011
2	$MR = \exp(-kt^n)$	Page	Jangam et al., 2008
3	$MR = a\exp(-kt) + c$	Logarithmic	Kingsly et al., 2007
4	$MR = a\exp(-kt)^n + c$	Demir et al.	Demir et al., 2007
5	$MR = a\exp(-kt)$	Henderson and Pabis	Toğrul and Pehlivan, 2004
6	$MR = a\exp(-k(t^n)) + bt$	Midilli	Midilli et al., 2002
7	$MR = a\exp(-kt)+(1-a)\exp(-kbt)$	Approximation of diffusion	Alibas, 2014
8	$MR = a/(1 + \exp(kt))$	Logistic	Alibas, 2014

In this research, it was considered the influence of the frying temperature. Therefore, k value, which was originally a constant, had been defined as a function of frying temperature and activation energy in the form of Arrhenius's equations as follows:

$$k = x \exp\left(-\frac{E_a}{RT}\right) \tag{42}$$

where: x = any constant

E_a = activation energy

R = gas constant (8.314 kJ kmol^{-1}K^{-1})

T = frying temperature (K).

Drying curves (MR vs time) are plotted and fitted by eight empirical drying models. The thin-layer drying equations in Table 8 are examined to determine the best model for characterizing the drying curve throughout the frying process. STATISTICA software is used to calculate model coefficients. The coefficient of determination of the regression (R^2), the root mean square error (RMSE), and the mean square of the deviations between the experimental and calculated values for the models, or chi square (χ^2), are used to assess the goodness of fit, as defined by Equations (43), (44), and (45), respectively.

$$R^2 = \frac{\sum_{i=1}^{N}(\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \tag{43}$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{1/2} \tag{44}$$

$$\chi^2 = \left[\frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{N-Z}\right] \tag{45}$$

where: y_i = the ith experimental value

$\bar{y}$ = the average of experimental value

$\hat{y}_i$ = the ith predicted model value

$MR_{exp,i}$ = the ith experimental moisture ratio

$MR_{pre,i}$ = the ith predicted model moisture ratio

N = the number of sampling times

z = the number of constants in the drying model.

2.7.2 Effective moisture diffusivity (D_{eff})

The effective moisture diffusivity is used to describe the overall mass transfer property of moisture in food products. During drying, the diffusivity, as described by Fick's diffusion equation, is considered to be the only physical mechanism for transferring water to the surface, and is impacted by moisture content, composition, temperature, and material structure (Junlakarn et al., 2016). As a result, the effective moisture diffusivity of water in ripened fried durian chips was determined in this study by solving the change in the moisture ratio versus frying time in an infinite slab using an analytical method and setting the appropriate initial and boundary conditions for the equation as shown in eq. (46)

$$MR = \frac{8}{\pi^2}\sum_{p=0}^{\infty}\left[\frac{1}{(2p+1)^2}\right]\exp\left[-\frac{(2p+1)^2\pi^2 D_{eff}\,t}{L^2}\right] \quad (46)$$

Considering only the first three terms;

$$MR = \frac{8}{\pi^2}\left[\exp\left(-\frac{\pi^2 D_{eff}\,t}{L^2}\right) + \frac{1}{9}\exp\left(-\frac{9\pi^2 D_{eff}\,t}{L^2}\right) + \frac{1}{25}\exp\left(-\frac{25\pi^2 D_{eff}\,t}{L^2}\right)\right] \quad (47)$$

where: D_{eff} = the effective diffusivity (m^2s^{-1})

L = the thickness of durian chips (m)

t = frying time (s)

MR = moisture ratio

The frying chamber pressure had no significant influence on the D_{eff} of the samples under the studied experimental conditions, while increasing the frying temperature resulted in an apparent improvement in the effective moisture diffusivity. The temperature dependence of D_{eff} was investigated using the Arrhenius type equation.

$$D_{\text{eff}} = D_0 \exp\left[-\frac{E_a}{RT_{abs}}\right] \qquad (48)$$

where: D_0 = Arrhenius factor of the heterogeneous solid, m^2/h or m^2/s

E_a = the activated energy, kJ/mol K

R = universal gas constant, 8.314 kJ/kmol K

T_{abs} = absolute temperature, K

2.8 Specific Energy Consumption (SEC)

The energy required to remove a unit mass of water content during frying of a durian sample from its initial moisture content to its final moisture content is defined as specific energy consumption (SEC). The following formula is used to evaluate SEC:

$$SEC = \frac{P}{(M_{in} - M_f)W_d} \qquad (49)$$

where: P = the total amount of energy consumed (kJ)

M_{in} = the initial moisture content (% d.b.)

M_f = the final moisture content (% d.b.)

W_d = the dry weight of the sample (kg).

The total amount of energy consumed included the thermal heating oil, evaporation, and electrical equipment power consumption.

2.9 Statistical Analysis

The mean values with standard deviations are presented in triplicate for the entire experiment. A one-way analysis of variance (ANOVA) was used to examine the experimental data. Duncan's multiple range test was used to establish multiple comparisons of mean values; a significant difference was considered at the 95% confidence level ($p \leq 0.05$). All statistical calculations were carried out using the statistical program SPSS (IBM SPSS software for Windows, SPSS Inc., USA).

CHAPTER 3

Results and Discussion

3.1 Moisture Dehydration

3.1.1 Drying curve comparison

The drying behavior indicated by changes in the natural logarithm of moisture ratio of fried durian chips during frying at different frying conditions of a) vacuum frying (VF) and b) microwave assisted vacuum frying (MWVF) of durian Day 1 as depicted in Figure 3.1. The initial moisture content of the durian samples was around 71.32±1.29% (w.b.) and the frying period was ended once the moisture content was lower than 6.0% (w.b.). At this moisture content, the durian chips were found to be crispy allowing for a fair comparison between each of the frying conditions. From Figure 3.1a, the time taken to reach the required moisture content was shorter at higher frying temperatures, owing to a larger driving force of heat and mass transfer. These results followed the same observations as previously described by other researchers for similar dried food products (Pedreschi, 2012; Thongcharoenpipat and Yamsaengsung, 2021).

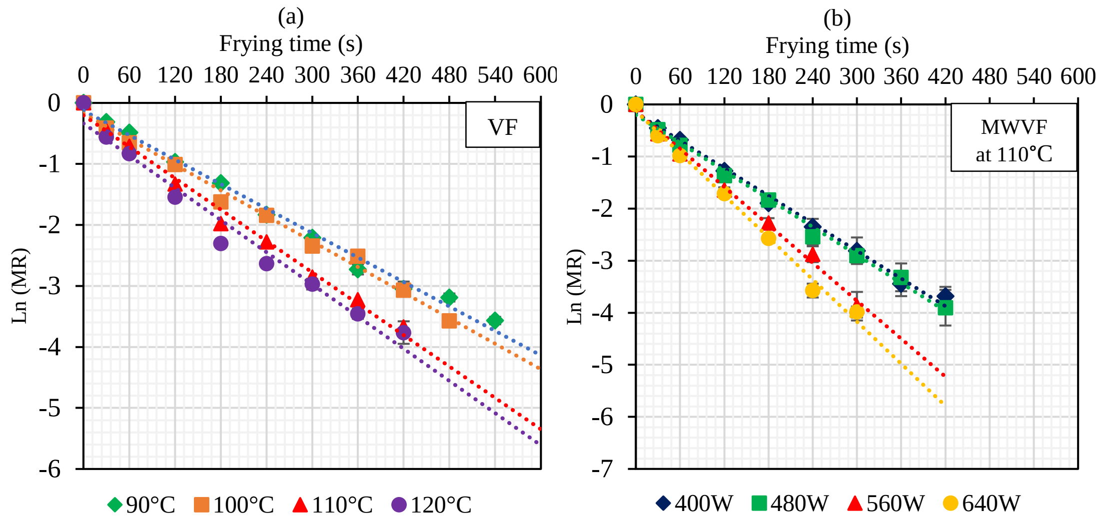


Figure 3.1 Plot of ln(MR) versus frying time of vacuum fried durian chips at different frying conditions of (a) vacuum frying (VF) and (b) microwave assisted vacuum frying (MWVF) of durian Day 1 at 110°C.

Furthermore, from Figure 3.1a, the frying temperature of 110°C led to the shortest frying time. However, higher frying temperatures would make the product burnt and were deemed unnecessary, since they did not improve the product characteristics significantly. Therefore, lowering the frying temperature would minimize the energy used in the process, while also decreasing the color change and nutritional loss caused by higher temperatures.

Durian chips fried at a microwave power of 640W produced a product that reached to the required moisture content quicker than those fried at a lower microwave power level (400, 480W, and 560W). This is because the heat generated inside the product led to a quick rise in the water temperature of the material to the boiling point and a faster rate of mass transfer due to pressure build up (Bai-Ngew et al., 2011; Thongcharoenpipat and Yamsaengsung, 2022). Moreover, from Figure 3.1b, the microwave power of 560W and 640W led to the shortest frying time and was considered the best frying time. However, higher microwave power level of 640W was deemed unnecessary, since it did not decrease the overall frying time. Therefore, using the microwave power level of 560W would minimize the energy used in the process.

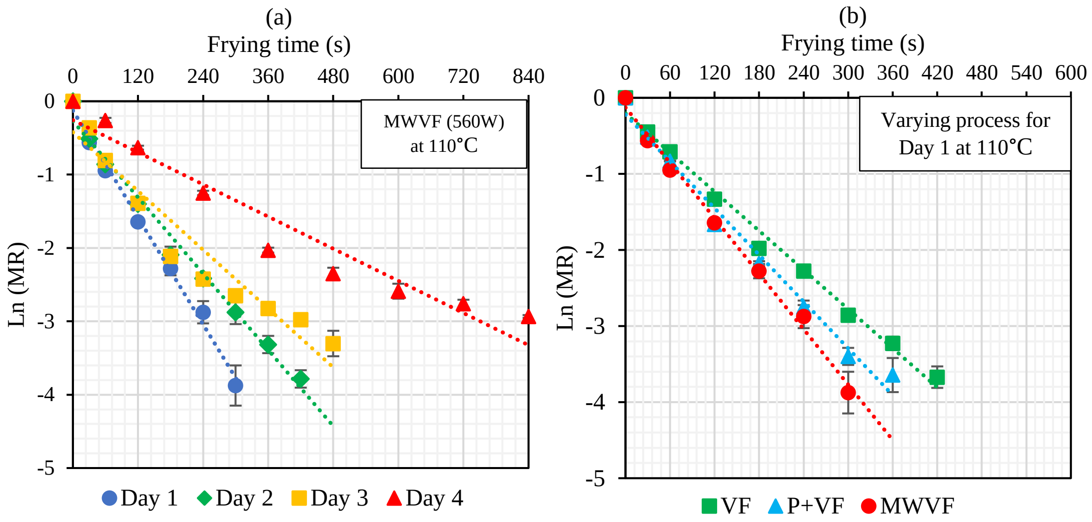


Figure 3.2 Plot of ln(MR) versus frying time of vacuum fried durian chips in different frying conditions of (a) MWVF of various ripening stages and (b) vacuum frying of durian at Day 1 using different processes at 110°C (VF, P+VF, MWVF at 560W).

The changes in natural logarithm of moisture content of microwave-vacuum fried durian chips at different ripening level (day of ripening) are presented in Figure 3.2a. It can be seen that lower degree of ripening resulted in shorter frying time as the higher initial moisture content of the samples allowed for more microwave energy absorption and rate of moisture removal. Besides from the conventional heating of the product from the frying oil, the liquid water molecule also becomes excited by the microwave energy, increasing the vaporization rate. This results in a higher pressure build-up inside the product as compared to VF alone and an increased in the driving force for convection and diffusion of water vapor toward the produce surface

(Yamsaengsung et al., 2011). However, from Figure 3.2b, the use of MWVF increased the rate of dehydration considerably. This was likely due to the heat generated inside the product leading to the quicker rise in the water temperature and vapor pressure toward the boiling point (Bai-Ngew et al., 2011a). Moreover, this created a high difference in vapor pressure between the surface and the center of the samples as reported in the drying of Chinese yam (Chitrakar et al., 2019).

3.1.2 Comparison of drying rate

Figure 3.3a-3.3d present the drying kinetics of microwave-vacuum fried durian chips at different conditions of a) VF at different frying temperature for durian Day 1, b) vacuum frying of durian Day 1 at different processes at 110°C, c) MWVF for microwave-assisted vacuum fried durian chips of durian Day 1 at different microwave power and 110°C, and d) MWVF for vacuum fried durian chips of different ripening level at 110°C and 560W. At the initial of frying, the trend of drying rate remained constant (constant rate period) for a period from 0-120 s before falling period. The drying rate at higher frying temperature was larger than those fried at lower frying temperature which was obviously noticed at 0-120 s of frying seen in Figure 3.3a, owing to a larger driving force of heat and mass transfer as mentioned previously. However, as shown in Figure 3.3b, the usage of MWVF significantly increased the drying rate. This was most likely owing to the heat generated well within product, which caused the water temperature and vapor pressure to develop faster towards the boiling point. Additionally, as compared to the VF illustrated in Figure 3.3b, P+VF offered a quicker drying rate because the water molecules were ice-crystal forms from freezing and could be evaporated easily (Bai-Ngew et al., 2011a).

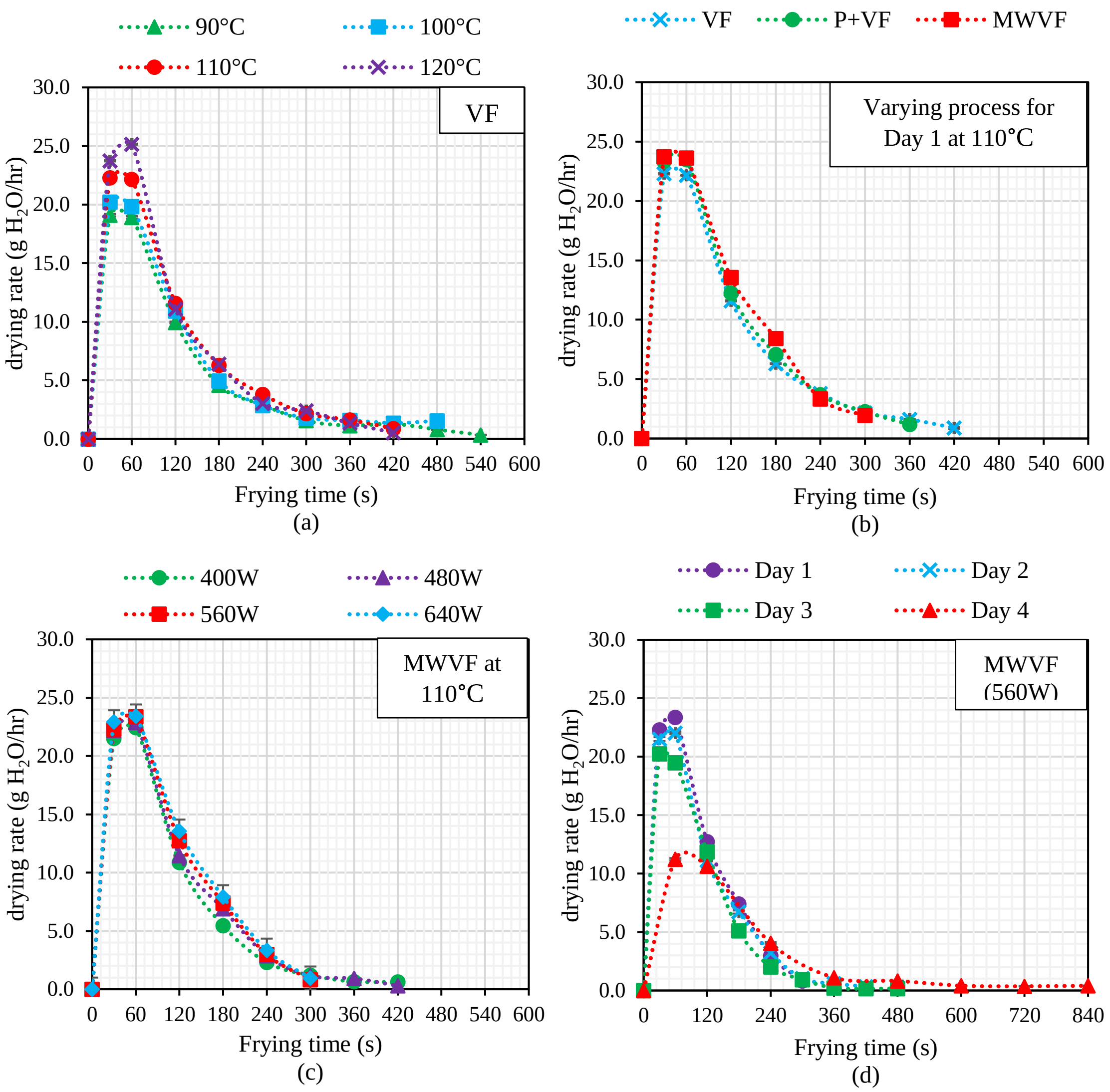


Figure 3.3 Drying rate versus frying time (s) of (a) VF at different frying temperature for durian Day 1, (b) vacuum frying of durian Day 1 at different processes at 110°C, (c) MWVF of durian Day 1 at different microwave power and 110°C, and (d) MWVF of different ripening level at 110°C and 560W.

From Figure 3.3c, durian chips fried at a microwave power of 640W produced a higher drying rate than those fried at a lower microwave power level (400, 480W, and 560W) corresponding to the data of effective moisture diffusivity in which will be discussed later in section 3.3 Effect of moisture diffusivity of fried durian products. For example, when the microwave power was increased from 400W to 640W, the effective diffusivity increased dramatically by 47%, 50%, 45%, and 21% for Day 1, Day 2, Day 3, and Day 4, respectively.

Furthermore, the high drying rate at the beginning stage of MWVF was a result of the high rate of moisture diffusion and the strong absorption of microwave energy (Bai-Ngew et al., 2015; Mojaharul Islam et al., 2019). Moreover, the higher microwave power level led to the improvement in the dehydration rate inside the product resulting in the reduction in frying time. This is because the heat generated inside the product led to a quick rise in the water temperature of the material to the boiling point and a faster rate of mass transfer due to pressure build up (Bai-Ngew et al., 2011a; Thongcharoenpipat and Yamsaengsung, 2022). This agreed with other studies, including those on durian chips (Paengkanya et al., 2015), durian flour (Bai-Ngew et al., 2015), and potato chips (Su et al., 2016).

The changes in drying rate of microwave-vacuum fried durian chips at different ripening level (day of ripening) are presented in Figure 3.3d. It can be seen that lower degree of ripening resulted in higher drying rates as the higher initial moisture content of the samples allowed for more microwave energy absorption and rate of moisture removal as mentioned before. Moreover, even though the more ripened durian had a lower initial moisture content, the ripening reactions that resulted in increasing amount of soluble sugars and the formation of water-binding pectin led to a lower rate of water removal. First of all, the present of sugar solutes increased the boiling point of water at the particular vacuum pressure as compared to no soluble sugars or lower amounts of sugar. Therefore, more energy and time is needed to vaporize the water molecules for higher degree of ripened durians. In addition, as sugar is a polar molecule with hygroscopic (water-binding) property, more energy is also needed to remove the water from the product during frying (Moreira et al., 2017). Furthermore, the ripening process causes a breakdown of protopectin into pectin with water trapping properties. This causes a decrease in the rate of moisture loss as more energy is also needed to separate the water molecule from the pectin (Ayustaningwarno et al., 2020). Finally, besides from the effects of the initial moisture content, total sugar content, and pectin content in the samples, the increase in the thickness of the samples from Day 4 (5-6 mm) compared to Days 1, 2, and 3 led to a significant increase in frying time. The higher thickness and increased amount of water content not only required a longer frying time to reduce the moisture content to required crispy level, but the development of the crust at the surface of the product during the initial stages of frying also decrease the rate of moisture removal from inside of the product (Yamsaengsung et al., 2008). Therefore, the overall frying time of the product from Day 4 increased by more than 70% compared to product from Day 3.

3.1.3 Overall effect of frying condition on the frying time

According to the findings, vacuum frying at 110°C resulted in the shortest frying time. Furthermore, P+VF gave a faster drying rate than VF since the water molecules were in ice-crystal forms from freezing and could be rapidly evaporated. In comparison to those fried at lower microwave power levels, durian chips fried at a higher power level produced a faster drying rate. However, using the microwave power level of 560W instead of 640W would consume less energy entirely. However, other characteristics including color, texture, oil absorption, microstructure, and overall acceptance must also be accounted for when assessing the influence of ripeness on the quality of durian chips.

3.2 Modeling of frying characteristics during frying

The drying curves between MR and frying time for VF, P+VF, and MWVF (560W) at different ripeness level were plotted and fitted to eight thin-layer drying models based on data collected in this research. The results with statistical analysis accepted on these models are presented in Table 3.1-3.5. Investigation of the R^2, ranging from 0.9457 to 0.9986, RMSE, ranging from 0.0664 to 0.0118, and χ^2 values, ranging from 0.005284 to 0.000160 pinpointed that all the several models fitted suitably to the data. From there, it can be seen that the R^2 values ranged from 0.9457 to 0.9986, the RMSE ranged from 0.0664 to 0.0118, and the last χ^2 values ranged from 0.005284 to 0.000160 pinpointing that several models fitted well with the experimental data. The best fit among all of these models for durian from Day 1 was the Approximation of diffusion equation providing the highest value of R^2 (0.9972, 0.9979, and 0.9965), the lowest values of RMSE (0.0167, 0.0145, and 0.0193) and χ^2 (0.000311, 0.000238, and 0.000425) for all frying temperatures and all frying processes, VF, P+VF and MWVF, respectively. The Midilli equation was also chosen as the best fit model to describe the drying characteristics of fried durian chips from Day 2, Day 3, and Day 4.

Table 3.1 Model parameters of the empirical models of vacuum fried durian chips for three different conditions of durian Day 1 (R^2 = Coefficient of determination, RMSE = root square error, and χ^2 = chi-square).

VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=1,063.19exp(-23,375.10/T)	0.9879	0.0345	0.001252
Page (MR = exp(- kt^n))	k=247.76exp(-18,455.64/T), n=0.82	0.9971	0.0169	0.000309
Logarithmic (MR = a exp(- kt) + c)	k=932.11exp(-22,753.79/T), a=0.94, c=0.04	0.9937	0.0250	0.000695
Demir et al. (MR = a exp(- kt)^n + c)	k=34.02exp(-23,466.75/T), a=0.94, c=0.04, n=34.63	0.9937	0.0249	0.000712
Midilli (MR = a exp(- k(t^n)) + bt)	k=241.03exp(-18,384.07/T), a=0.99, b=-0.001, n=0.81	0.9971	0.0168	0.000323
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=2,808.04exp(-20,923.98/T), a=0.19, b=0.14	**0.9972**	**0.0167**	**0.000311**
Logistic (MR = a/(1 + exp(kt)))	k=1,701.92exp(-23,973.65/T), a=1.84	0.9755	0.0490	0.002606
Henderson and Pabis (MR = a exp(- kt))	k=880.68exp(-22,969.65/T), a=0.96	0.9903	0.0308	0.001027
P+VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=9.28exp(-7,559.27/T)	0.9921	0.0284	0.000852
Page (MR = exp(- kt^n))	k=6.20exp(-6,151.24/T), n=0.83	0.9982	0.0136	0.000201
Logarithmic (MR = a exp(- kt) + c)	k=9.92exp(-7,512.44/T), a=0.95, c=0.03	0.9970	0.0175	0.000344
Demir et al. (MR = a exp(- kt)^n + c)	k=2.66exp(-7,424.54/T), a=0.95, c=0.03, n=3.63	0.9970	0.0175	0.000355
Midilli (MR = a exp(- k(t^n)) + bt)	k=6.34exp(-6,195.33/T), a=0.99, b=0.002, n=0.86	0.9986	0.0119	0.000165
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=15.70exp(-7,501.87/T), a=0.55, b=0.33	**0.9979**	**0.0145**	**0.000238**

P+VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Henderson and Pabis (MR = a exp(- kt))	k=8.96exp(-7,555.54/T), a=0.97	0.9929	0.0268	0.000783
MWVF (560W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=318.96exp(-18,872.40/T)	0.9902	0.0322	0.001103
Page (MR = exp(- kt^n))	k=112.40exp(-15,426.71/T), n=0.84	0.9964	0.0194	0.000417
Logarithmic (MR = a exp(- kt) + c)	k=136.24exp(-15,983.56/T), a=0.95, c=0.03	0.9937	0.0258	0.000759
Demir et al. (MR = a exp(- $kt)^n$ + c)	k=17.31exp(-18,429.60/T), a=0.95, c=0.03, n=17.31	0.9941	0.0251	0.000747
Midilli (MR = a exp(- k(t^n)) + bt)	k=108.59exp(-15,326.15/T), a=1.00, b=-0.001, n=0.83	0.9965	0.0194	0.000444
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=764.29exp(-18,318.02/T), a=0.28, b=0.26	**0.9965**	**0.0193**	**0.000425**
Logistic (MR = a/(1 + exp(kt)))	k=535.76exp(-19,490.99/T), a=1.89	0.9765	0.0499	0.002752
Henderson and Pabis (MR = a exp(- kt))	k=297.03exp(-18,756.06/T), a=0.97	0.9912	0.0305	0.001025

Note: Values marked in bold show applicability of Approximation of diffusion equation.

VF, vacuum frying; P+VF, pre-treatment before vacuum frying; MWVF, microwave assisted vacuum frying.

Table 3.2 Model parameters of the empirical models of vacuum fried durian chips for three different conditions of durian Day 2 (R^2 = Coefficient of determination, RMSE = root square error, and χ^2 = chi-square).

VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=207.81exp(-18,576.17/T)	0.9858	0.0366	0.001409
Page (MR = exp(- kt^n))	k=61.25exp(-14,317.66/T), n=0.81	0.9966	0.0178	0.000341
Logarithmic (MR = a exp(- kt) + c)	k=266.15exp(-18,966.08/T), a=0.93, c=0.05	0.9947	0.0224	0.000555
Demir et al. (MR = a exp(- kt)^n + c)	k=50.74exp(-18,966.04/T), a=0.93, c=0.05, n=5.24	0.9947	0.0224	0.000570
Midilli (MR = a exp(- k(t^n)) + bt)	k=80.28exp(-15,159.14/T), a=1.00, b=0.001, n=0.83	**0.9970**	**0.0171**	**0.000330**
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=99.83exp(-17,970.47/T), a=0.51, b=3.52	0.9969	0.0171	0.000322
Logistic (MR = a/(1 + exp(kt)))	k=285.43exp(-18,689.29/T), a=1.84	0.9714	0.0520	0.002905
Henderson and Pabis (MR = a exp(- kt))	k=177.75exp(-18,263.27/T), a=0.96	0.9882	0.0334	0.001202
P+VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=209.45exp(-17,748.43/T)	0.9660	0.0552	0.003217
Page (MR = exp(- kt^n))	k=35.39exp(-11,741.04/T), n=0.68	0.9983	0.0123	0.000164
Logarithmic (MR = a exp(- kt) + c)	k=194.74exp(-16,911.96/T), a=0.90, c=0.07	0.9890	0.0315	0.001108
Demir et al. (MR = a exp(- kt)^n + c)	k=41.73exp(-16,911.49/T), a=0.90, c=0.07, n=4.67	0.9890	0.0315	0.001141
Midilli (MR = a exp(- k(t^n)) + bt)	k=36.43exp(-11,822.20/T), a=1.00, b=0.001, n=0.69	**0.9984**	**0.0121**	**0.000169**

P+VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Logistic (MR = a/(1 + exp(kt)))	k=387.53exp(-18,868.8/T), a=1.81	0.9457	0.0698	0.005284
Henderson and Pabis (MR = a exp(- kt))	k=202.14exp(-17,942.51/T), a=0.93	0.9717	0.0504	0.002755
MWVF (560W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=1,268.63exp(-23,473.85/T)	0.9822	0.0413	0.001800
Page (MR = exp(- kt^n))	k=191.41exp(-17,223.82/T), n=0.77	0.9958	0.0201	0.000439
Logarithmic (MR = a exp(- kt) + c)	k=1,562.08exp(-23,762.51/T), a=0.93, c=0.05	0.9919	0.0279	0.000868
Demir et al. (MR = a exp(- kt)^n + c)	k=156.35exp(-23,761.03/T), a=0.93, c=0.05, n=9.99	0.9919	0.0279	0.000893
Midilli (MR = a exp(- k(t^n)) + bt)	k=201.53exp(-17,375.23/T), a=1.00, b=0.001, n=0.78	**0.9958**	**0.0202**	**0.000459**
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=529.81exp(-22,235.91/T), a=0.60, b=4.31	0.9956	0.0205	0.000470
Logistic (MR = a/(1 + exp(kt)))	k=1,109.08exp(-22,211.18/T), a=1.84	0.9664	0.0567	0.003486
Henderson and Pabis (MR = a exp(- kt))	k=783.80exp(-22,178.33/T), a=0.96	0.9845	0.0385	0.001603

Note: Values marked in bold show applicability of Midilli equation.

VF, vacuum frying; P+VF, pre-treatment before vacuum frying; MWVF, microwave assisted vacuum frying.

Table 3.3 Model parameters of the empirical models of vacuum fried durian chips for three different conditions of durian Day 3 (R^2 = Coefficient of determination, RMSE = root square error, and χ^2 = chi-square).

VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=79.75exp(-15,886.74/T)	0.9834	0.0388	0.001573
Page (MR = exp(- kt^n))	k=26.18exp(-11,874.17/T), n=0.79	0.9963	0.0183	0.000358
Logarithmic (MR = a exp(- kt) + c)	k=114.40exp(-16,510.02/T), a=0.92, c=0.06	0.9968	0.0171	0.000320
Demir et al. (MR = a exp(- kt)^n + c)	k=0.47exp(-16,484.76/T), a=0.92, c=0.06, n=241.02	0.9968	0.0171	0.000328
Midilli (MR = a exp(- k(t^n)) + bt)	k=33.64exp(-12,665.39/T), a=0.99, b=0.004, n=0.86	**0.9978**	**0.0143**	**0.000229**
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=28.18exp(-15,847.72/T), a=0.26, b=4.30	0.9977	0.0145	0.000230
Logistic (MR = a/(1 + exp(kt)))	k=113.60exp(-16,121.16/T), a=1.84	0.9690	0.0530	0.003007
Henderson and Pabis (MR = a exp(- kt))	k=67.04exp(-15,539.21/T), a=0.95	0.9864	0.0352	0.001324
P+VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=6.64exp(-7,252.26/T)	0.9702	0.0519	0.002845
Page (MR = exp(- kt^n))	k=3.96exp(-5,145.70/T), n=0.71	0.9981	0.0131	0.000185
Logarithmic (MR = a exp(- kt) + c)	k=6.88exp(-6,735.29/T), a=0.90, c=0.07	0.9919	0.0270	0.000815
Demir et al. (MR = a exp(- kt)^n + c)	k=2.47exp(-6,535.65/T), a=0.90, c=0.07, n=2.62	0.9919	0.0270	0.000839

P+VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Logistic (MR = a/(1 + exp(kt)))	k=9.26exp(-7,516.44/T), a=1.80	0.9511	0.0664	0.004793
Henderson and Pabis (MR = a exp(- kt))	k=6.29exp(-7,372.47/T), a=0.94	0.9758	0.0467	0.002371
MWVF (560W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=781.35exp(-22,491.78/T)	0.9860	0.0366	0.001406
Page (MR = exp(- kt^n))	k=199.40exp(-17,875.66/T), n=0.82	0.9940	0.0239	0.000613
Logarithmic (MR = a exp(- kt) + c)	k=674.21exp(-21,579.85/T), a=0.94, c=0.05	0.9963	0.0187	0.000386
Demir et al. (MR = a exp(- kt)^n + c)	k=27.10exp(-22,112.16/T), a=0.94, c=0.05, n=29.61	0.9964	0.0187	0.000395
Midilli (MR = a exp(- k(t^n)) + bt)	k=287.97exp(-19,003.64/T), a=1.00, b=0.01, n=0.91	**0.9967**	**0.0176**	**0.000353**
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=139.58exp(-21,886.65/T), a=0.14, b=6.04	0.9967	0.0176	0.000343
Logistic (MR = a/(1 + exp(kt)))	k=1,127.20exp(-22,669.53/T), a=1.87	0.9726	0.0512	0.002818
Henderson and Pabis (MR = a exp(- kt))	k=752.38exp(-22,505.25/T), a=0.97	0.9873	0.0348	0.001306

Note: Values marked in bold show applicability of Midilli equation.

VF, vacuum frying; P+VF, pre-treatment before vacuum frying; MWVF, microwave assisted vacuum frying.

Table 3.4 Model parameters of the empirical models of vacuum fried durian chips for three different conditions of durian Day 4 (R^2 = Coefficient of determination, RMSE = root square error, and χ^2 = chi-square).

VF				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=21.19exp(-13,613.66/T)	0.9798	0.0474	0.002362
Page (MR = exp(- kt^n))	k=28.43exp(-14,807.76/T), n=1.07	0.9805	0.0466	0.002342
Logarithmic (MR = a exp(- kt) + c)	k=26.99exp(-13,803.16/T), a=1.00, c=0.05	0.9871	0.0378	0.001587
Demir et al. (MR = a exp(- kt)^n + c)	k=-5.31exp(-13,803.20/T), a=1.00, c=0.05, n=-5.08	0.9871	0.0378	0.001631
Midilli (MR = a exp(- k(t^n)) + bt)	k=48.32exp(-16,835.15/T), a=1.01, b=0.01, n=1.28	**0.9942**	**0.0255**	**0.000739**
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=22.89exp(-13,664.50/T), a=0.99, b=-0.39	0.9855	0.0401	0.001784
Logistic (MR = a/(1 + exp(kt)))	k=38.94exp(-14,211.91/T), a=2.02	0.9778	0.0497	0.002668
Henderson and Pabis (MR = a exp(- kt))	k=22.54exp(-13,692.07/T), a=1.03	0.9810	0.0460	0.002284
MWVF (560W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=0.08exp(-8,337.69/T)	0.9916	0.0301	0.000959
Page (MR = exp(- kt^n))	k=0.08exp(-8,211.54/T), n=0.99	0.9916	0.0301	0.000982
Logarithmic (MR = a exp(- kt) + c)	k=0.08exp(-8,153.09/T), a=0.98, c=0.04	0.9961	0.0205	0.00047
Demir et al. (MR = a exp(- kt)^n + c)	k=0.09exp(-8,151.94/T), a=0.95, c=0.04, n=0.95	0.9961	0.0205	0.000485
Midilli (MR = a exp(- k(t^n)) + bt)	k=0.05exp(-8,592.17/T), a=1.01, b=0.0001, n=1.12	**0.9981**	**0.0145**	**0.000242**
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=0.07exp(-7,984.01/T), a=0.99, b=-0.42	0.9962	0.0203	0.000461

MWVF (560W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Henderson and Pabis (MR = a exp(- kt))	k=0.08exp(-8,331.32/T), a=1.01	0.9917	0.0300	0.000977

Note: Values marked in bold show applicability of Midilli equation.

VF, vacuum frying; MWVF, microwave assisted vacuum frying.

Table 3.5 Model parameters of the empirical models of vacuum fried durian chips for three different conditions of durian Day 1 at various microwave power level (R^2 = Coefficient of determination, RMSE = root square error, and χ^2 = chi-square).

MWVF (400W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=928.09exp(-22,934.41/T)	0.9891	0.0329	0.001138
Page (MR = exp(- kt^n))	k=231.94exp(-18,244.53/T), n=0.82	0.9977	0.0151	0.000247
Logarithmic (MR = a exp(- kt) + c)	k=765.37exp(-22,166.16/T), a=0.94, c=0.03	0.9940	0.0244	0.000663
Demir et al. (MR = a exp(- kt)^n + c)	k=-25.39exp(-22,990.50/T), a=0.94, c=0.03, n=-28.33	0.9940	0.0243	0.000679
Midilli (MR = a exp(- k(t^n)) + bt)	k=218.30exp(-18,073.46/T), a=1.00, b=-0.001, n=0.81	0.9978	0.0147	0.000249
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=3,653.95exp(-21,263.62/T), a=0.18, b=0.12	**0.9981**	**0.0136**	**0.000206**
Logistic (MR = a/(1 + exp(kt)))	k=1,506.34exp(-23,580.05/T), a=1.84	0.9769	0.0478	0.002471
Henderson and Pabis (MR = a exp(- kt))	k=835.30.68exp(-22,772.59/T), a=0.96	0.9914	0.0291	0.000917
MWVF (480W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=1,365.67exp(-23,982.64/T)	0.9877	0.0348	0.001276
Page (MR = exp(- kt^n))	k=267.26exp(-18,534.28/T), n=0.81	0.9979	0.0143	0.000221
Logarithmic (MR = a exp(- kt) + c)	k=1,495.15exp(-24,026.79/T), a=0.94, c=0.04	0.9940	0.0244	0.000663

MWVF (480W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Midilli (MR = a exp(- k(t^n)) + bt)	k=252.29exp(-18,363.92/T), a=1.00, b=-0.001, n=0.79	**0.9980**	**0.0141**	**0.000229**
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=3,354.50exp(-22,232.30/T), a=0.24, b=0.17	0.9979	0.0144	0.000231
Logistic (MR = a/(1 + exp(kt)))	k=2,399.01exp(-24,861.41/T), a=1.85	0.9740	0.0506	0.002783
Henderson and Pabis (MR = a exp(- kt))	k=1,202.49exp(-23,756.29/T), a=0.96	0.9901	0.0312	0.001059
MWVF (560W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Lewis (MR = exp(- kt))	k=318.96exp(-18,872.40/T)	0.9902	0.0322	0.001103
Page (MR = exp(- kt^n))	k=112.40exp(-15,426.71/T), n=0.84	0.9964	0.0194	0.000417
Logarithmic (MR = a exp(- kt) + c)	k=136.24exp(-15,983.56/T), a=0.95, c=0.03	0.9937	0.0258	0.000759
Demir et al. (MR = a exp(- kt)^n + c)	k=17.31exp(-18,429.60/T), a=0.95, c=0.03, n=17.31	0.9941	0.0251	0.000747
Midilli (MR = a exp(- k(t^n)) + bt)	k=108.59exp(-15,326.15/T), a=1.00, b=-0.001, n=0.83	0.9965	0.0194	0.000444
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=764.29exp(-18,318.02/T), a=0.28, b=0.26	**0.9965**	**0.0193**	**0.000425**
Logistic (MR = a/(1 + exp(kt)))	k=535.76exp(-19,490.99/T), a=1.89	0.9765	0.0499	0.002752
Henderson and Pabis (MR = a exp(- kt))	k=297.03exp(-18,756.06/T), a=0.97	0.9912	0.0305	0.001025
MWVF (640W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Page (MR = exp(- kt^n))	k=106.63exp(-15,061.90/T), n=0.82	0.9963	0.0199	0.000438
Logarithmic (MR = a exp(- kt) + c)	k=393.96exp(-19,065.61/T), a=0.95, c=0.04	0.9932	0.0270	0.000834
Demir et al. (MR = a exp(- kt)^n + c)	k=19.37exp(-19,064.83/T), a=0.95, c=0.04, n=20.33	0.9932	0.0270	0.000866

MWVF (640W)				
Model	Arbitrary constants	R^2	RMSE	χ^2
Approximation of diffusion (MR = a exp(- kt)+(1 - a)exp(- kbt))	k=0.04exp(-44.55/T), a=0.05, b=23.89	0.9814	0.0445	0.002271
Logistic (MR = a/(1 + exp(kt)))	k=647.86exp(-19,869.85/T), a=1.89	0.9750	0.0515	0.002941
Henderson and Pabis (MR = a exp(- kt))	k=324.84exp(-18,828.86/T), a=0.97	0.9901	0.0324	0.001163

Note: Values marked in bold show applicability of Midilli equation.
MWVF, microwave assisted vacuum frying.

Even though the Approximation of Diffusion Model was shown to be the best appropriate giving the highest R^2 value and the lowest RMSE and χ^2 values for MWVF for all frying temperatures at microwave power of 400W and 560W, the Midilli equation best fitted the durian chips from Day 1 at 480W and 640W. The slight difference in the third and forth-decimal place of R^2, RMSE, and χ^2 values could be considered negligible.

Additionally, it was noted that the Midilli model, which composes of an exponential and a linear component to describe the moisture ratio as a function of drying time (Ertekin and Ziya Firat, 2015), was effective when applied to investigate the drying characteristics of agricultural products such savory leaves (Arslan and Ozcan, 2012), purslane (Demirhan and Ozbek, 2010a), and eggplant (Ertekin and Yaldiz, 2004). Consequently, the Midilli model is the best one among the tested models that accurately express the thin-layer drying behavior of durian slices under the studied conditions.

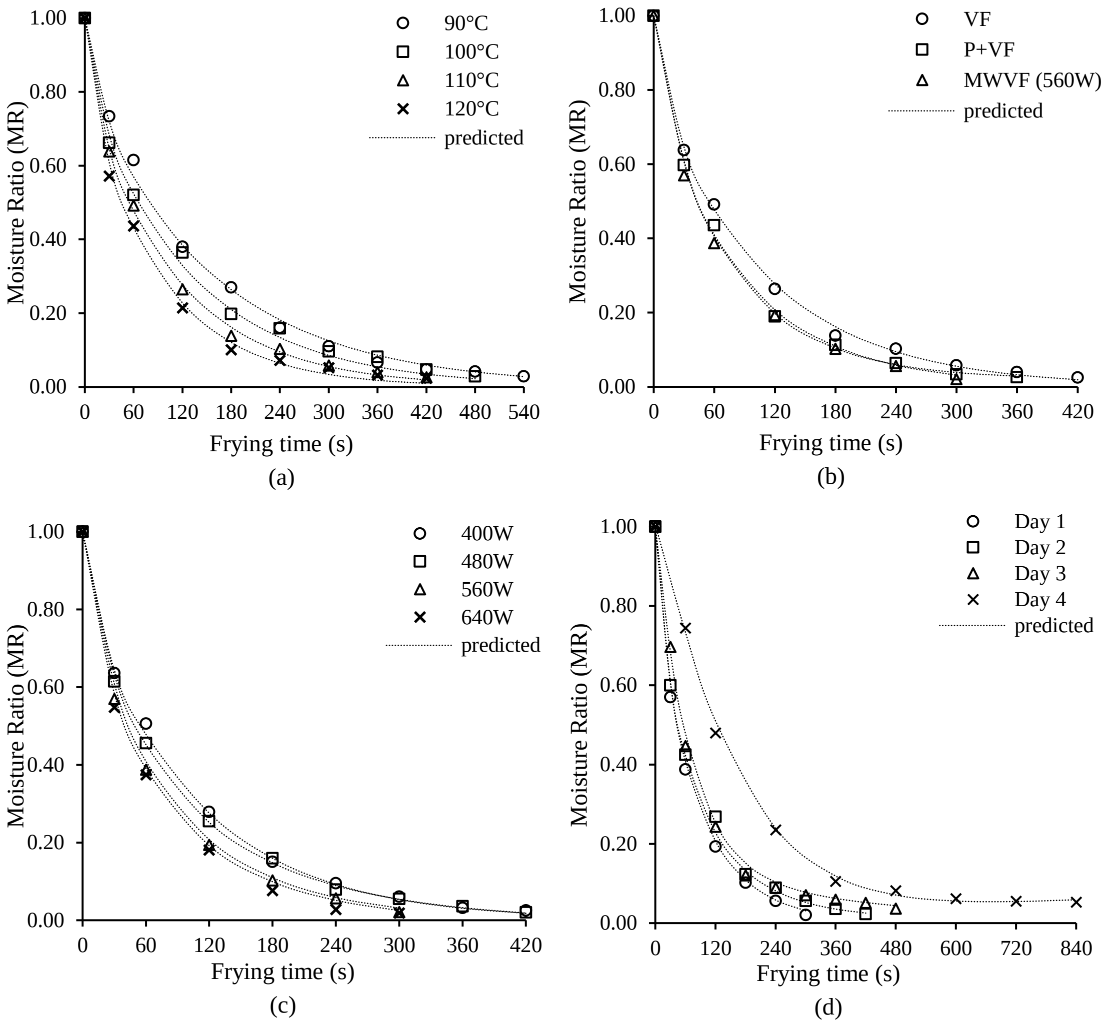


Figure 3.4 Prediction accuracy of Midilli model on vacuum frying curve at (a) different frying temperature of durian Day 1, (b) different frying conditions of durian Day 1 at 110°C, (c) various microwave power level of durian Day 1 at 110°C, and (d) different ripeness of product at 110°C.

The results were confirmed by Figure 3.4, which shows the prediction accuracy of mathematical model on vacuum frying curve at various frying conditions of different ripeness of product. The Midilli model could be used for the benefits of frying time prediction to reach the required moisture content, scaling-up production or even designing a processing equipment previously proposed by Mojaharul Islam et al. (2019) who reported that the Midilli equation was also chosen as the best fit model to describe the drying characteristics of fried edamame (immature soybean) when VF and MWVF were used.

3.3 Effect of moisture diffusivity of fried durian products

The effective moisture diffusivities were calculated using vacuum frying data and Eq. 47 which was assumed to represent the overall mass transfer property of the moisture in the sample. Table 3.6 shows the effective moisture diffusivities of fried durian at frying temperatures of 90, 100, 110, and 120°C for the different conditions. The values of D_{eff} in the table increased progressively as the frying temperature increased, owing to the higher temperature giving a greater driving force for heat and mass transport (Azizi and Peyghambarzadeh, 2010). The observations of Azizi and Peyghambarzadeh (2010) revealed that the evaporation rate of water in fruits increased significantly with higher temperature which was expedited by the rate of mass transfer in the material. Therefore, the D_{eff} values of fruits were markedly influenced by frying temperature.

In addition, the values of D_{eff} for P+VF ranged from 5.17×10^{-09} to 6.24×10^{-09} which were slightly higher compared to those for VF (3.17×10^{-09} to 5.57×10^{-09}). This result could be explained as a result of freezing prior to drying producing a large porous structure because of cell-damaging from crystal growth, leading to the breakdown of membranes and increasing the permeability of water (Bai-Ngew et al., 2011a). Furthermore, the MWVF ranged from 5.41×10^{-09} to 6.58×10^{-09} m^2/s providing a higher D_{eff} at each frying temperature compared to VF.

Table 3.6 Comparisons of effective moisture diffusivity (D_{eff}), activation energy (E_a), coefficient D_0 and related correlation coefficient of vacuum fried durian chips Day 1.

Methods	Temp. (°C)	D_{eff} (m^2/s)	R^2	E_a (kJ/mol)	D_0 (m^2/s)	R^2
VF	90	3.17×10^{-09}	0.9894	7.10×10^{-06}	2.34×10^{04}	0.9916
	100	3.64×10^{-09}	0.9932			
	110	4.59×10^{-09}	0.9936			
	120	5.57×10^{-09}	0.9929			
P+VF	90	5.17×10^{-09}	0.9921	6.76×10^{-08}	7.86×10^{03}	0.8903
	100	5.22×10^{-09}	0.9922			
	110	5.62×10^{-09}	0.9932			
	120	6.24×10^{-09}	0.9933			
MWVF (560W)	90	5.41×10^{-09}	0.9925	8.22×10^{-08}	8.28×10^{03}	0.9524
	100	5.54×10^{-09}	0.9927			
	110	6.11×10^{-09}	0.9937			
	120	6.58×10^{-09}	0.9934			

VF, vacuum frying; MWVF, microwave assisted vacuum frying.

Table 3.7 Comparisons of effective moisture diffusivity (D_{eff}), activation energy (E_a), coefficient D_0 and related correlation coefficient of microwave vacuum fried durian chips at 110°C.

Days of ripening	Initial moisture content (%w.b.)	Total sugar content (g /100g sample)	Microwave power (W)	Frying time (s)	D_{eff} (m^2/s)	R^2
Day 1	71.32±1.29[a]	6.41±0.20[d]	400	420	4.48×10^{-09}	0.9939
			480	420	4.83×10^{-09}	0.9945
			560	300	6.11×10^{-09}	0.9937
			640	300	6.62×10^{-09}	0.9939
Day 2	66.26±0.29[b]	8.17±0.06[c]	400	540	3.88×10^{-09}	0.9929
			480	480	4.09×10^{-09}	0.9905
			560	420	5.06×10^{-09}	0.9927
			640	420	5.83×10^{-09}	0.9915
Day 3	59.72±0.83[c]	14.83±0.80[b]	400	540	3.37×10^{-09}	0.9826
			480	540	3.75×10^{-09}	0.9801
			560	480	4.70×10^{-09}	0.9844
			640	420	4.89×10^{-09}	0.9842
Day 4	54.78±0.90[d]	35.04±0.86[a]	400	960	1.17×10^{-08}	0.9689
			480	960	1.20×10^{-08}	0.9733
			560	840	1.37×10^{-08}	0.9746
			640	840	1.42×10^{-08}	0.9773

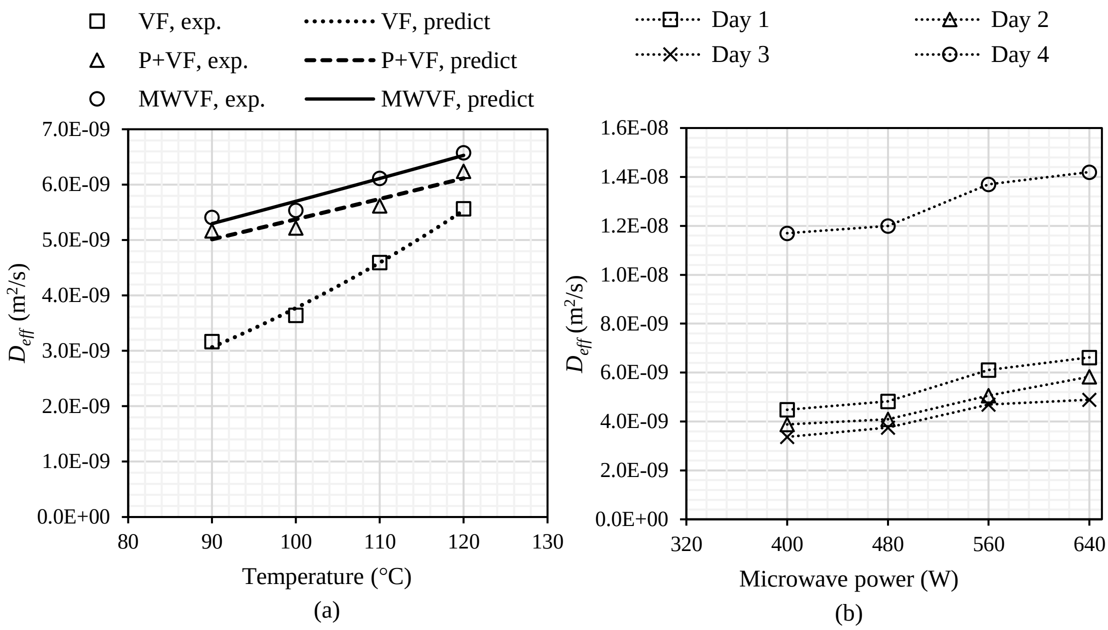


Figure 3.5 Comparisons of effective moisture diffusivity (D_{eff}) at (a) different frying conditions of durian Day 1 and (b) different ripeness at 110°C.

Furthermore, the vacuum frying combined with microwave heating (640W), ranged from 6.62×10^{-09} to 1.42×10^{-08} m^2/s providing the D_{eff} were higher compared with VF. It was consistent with the observations of Jamradloedluk et al. (2007) that the effective moisture diffusivity could be improved by using microwave vacuum drying, compared with hot air drying. In addition, the effective diffusivity also decreased as the days of ripening increased. For instance, at microwave power of 560W, the value decreased from $6.11\text{x}10^{-09}$ to $4.70\text{x}10^{-09}$ m^2/s for Day 1 to Day 3, respectively, which in turn, caused an increase in overall frying time by 60%. For Day 4, because of the higher overall thickness of the durian slices and more water mass, the effective diffusivity of the product more than doubled when compared to Day 3 (4.70×10^{-09} to 1.37×10^{-08} m^2/s). The activation energy (E_a) and diffusion constant (D_0) were evaluated by STATISTICA software and providing in Table 3.6. The value of E_a and D_0 could be improved by using MWVF (E_a = 8.22×10^{-08} kJ/mol, D_0 = 8.28×10^{03} m^2/s), compared with VF (E_a = 7.10×10^{-06} kJ/mol, D_0 = 2.34×10^{04} m^2/s) and P+VF (E_a = 6.76×10^{-08} kJ/mol, D_0 = 7.86×10^{03} m^2/s).

3.4 Physical changes during vacuum frying

3.4.1 Shrinkage

Figure 3.6a) to 3.6d) present the percent of shrinkage as a function of frying time at a) different frying temperature of durian ripening Day 1 during vacuum frying (VF), b) different frying conditions of durian during vacuum frying combined with microwave heating (MWVF) and pre-treatment prior to vacuum frying (P+VF) compared with vacuum frying (VF), c) different microwave power levels of durian Day 1 at 110°C, and the percent of shrinkage as a function of frying time at d) different ripeness of durian at 110°C of MWVF (560W).

From the Figure 3.6a), at the beginning of frying, durian chips shrank rapidly and became less shrinkage after then because of significant shrinkage in the product at the first minute of frying pinpointing rapid water loss. However, after a few minutes, the degree of shrinkage slightly decreased which probably have result from the formation of the crust and leading the gaseous vapor expands as it tries to expose (Yamsaengsung et al., 2011). It was found that the percent of shrinkage of fried durian chips at the higher temperature were significantly lower than the product that were performed at the lower frying temperatures, likewise the studies of Swasdisevi et al. (2007) and Panyawong and Devahastin (2007), for bananas, Wu, Orikasa, Ogawa and Tagawa (2007) for eggplants and Yan et al. (2008) for banana, pineapple and mango mentioned that at the highest drying temperature, the shrinkage was finally the least as following the Figure 3.6a). However, there was no significant difference in the degree of shrinkage between 110 and 120°C as both temperatures had comparable drying rate (Thongcharoenpipat and Yamsaengsung, 2021).

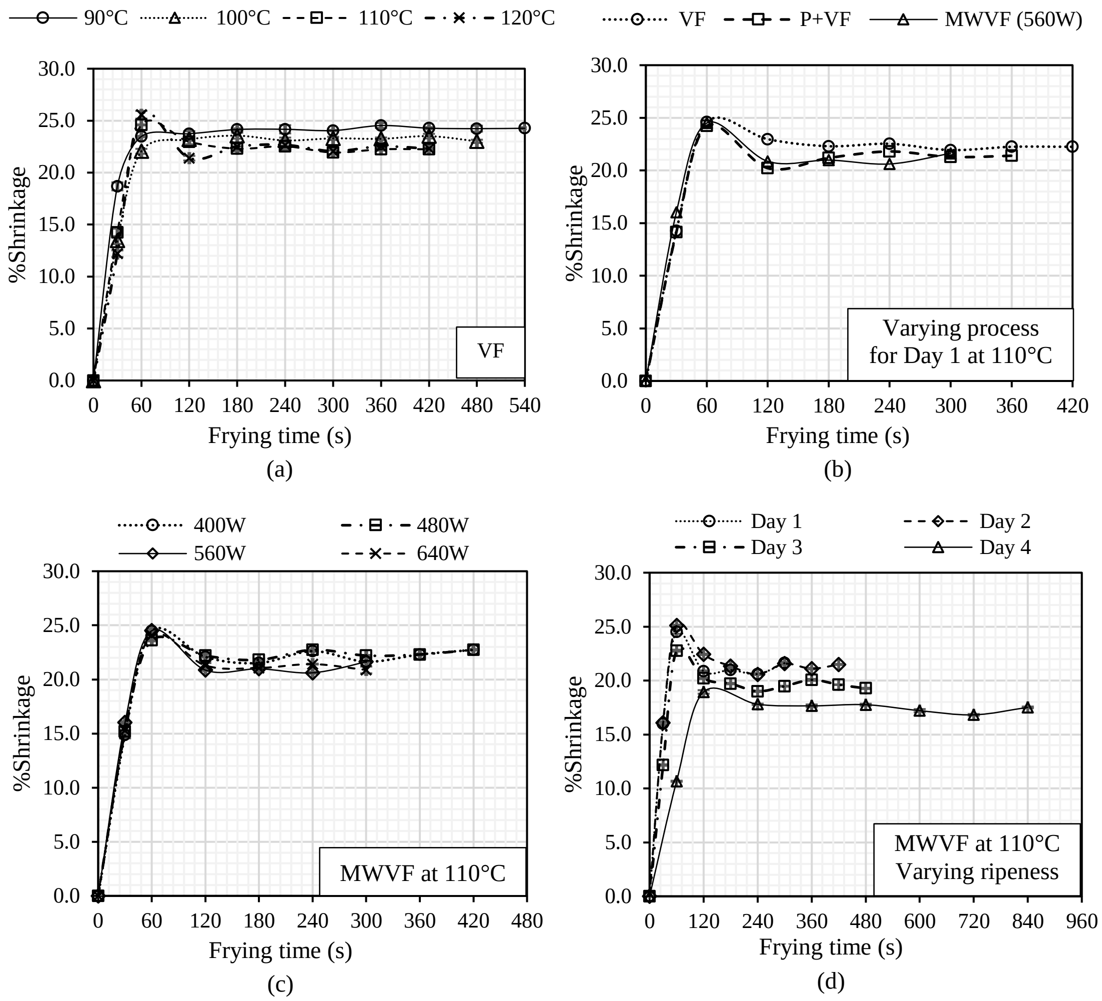


Figure 3.6 Percent of shrinkage versus frying time (s) of vacuum fried durian chips in (a) different frying temperature of durian Day 1, (b) different conditions of durian Day 1 at 110°C, (c) different microwave power levels of durian Day 1 at 110°C and (d) different ripeness of durian at 110°C, 560W.

Furthermore, since MWVF had the fastest drying rate, durian chips obtained at this condition also had the least amount of shrinkage, similar to that of Bai-Ngew et al. (2011a). Interestingly, even though all three conditions produced similar percent shrinkage after the first 90 seconds (approximately 23%), MWVF products showed a dramatic decrease in shrinkage or higher degree of puffing (increase in thickness) after 180 seconds of frying compared to VF and slightly higher than P+VF (Figure 3.2b). This could be due to the microwave radiation heating the remaining bound water inside the internal pores leading to a higher degree of expansion or puffing than those without microwave.

Figure 3.6c) and 3.6d) show the percent of shrinkage as a function of frying time at different microwave power at ripeness of Day 1 and the percent of shrinkage as a function of frying time at different ripeness of durian at microwave power of 560W. Durian chips shrank quickly at the beginning of frying showing rapid water loss causing a slight collapse in the cell walls of the product. Then after about 60 seconds the product began to expand slightly due to crust formation at the product surface and gas vapor expansion from pressure build up inside the product (Yamsaengsung et al., 2011). In addition, from Figure 3.6c), the higher microwave power treatment provided a slightly lower overall percent shrinkage. Because of the higher pressure build up from the faster rate of water evaporation and water vapor formation, the thickness of the product expanded during the final stage of frying. In addition, the impact of pectin and hygroscopicity of sugar at different stages of ripening could influence the rate of evaporation of the bound water that were found along the interior walls of the product (Orikasa et al., 2018). After much of the free water has been removed, the bound water that had turned into vapor were able to expand creating a high difference of vapor pressure between the surface and the center of the samples. Consequently, they were lower percentage of shrinkage from the durian chips from Day 3 of ripeness compared to Day 1 and Day 2 as shown in Figure 3.6d).

3.4.2 Color change of the product

The color changes of vacuum fried durian chips were evaluated based on frying temperatures and process conditions. From Table 3.8, P+VF, VF, and MWVF all had no significant effect on difference in lightness (L^*) of the product ($p>0.05$); however, increasing the frying temperature led to a larger decrease in the lightness of the products. As many researchers have reported, many chemical reactions such as oxidation, oil polymerization (Teruel et al., 2014), and Maillard reaction (Su et al., 2016) occur during frying of agricultural products causing the darker coloration.

Furthermore, as the frying temperature was increased from 90-110°C, the differences in redness (a^*) decreased. However, this value significant increased at 120°C compared to that of the fresh durian ($p<0.05$). This result agrees well with Pedreschi (2012) who noted that higher frying temperatures can increase browning reactions. Also, microwave heating produced a lower change in the redness of the product which may have been caused by the increase rate of moisture removal and shorter frying time (Chitrakar et al., 2019), leading to reduced non-enzymatic browning reactions. As for the b^* value of the products, MWVF may have maintained the yellowness of the products better than VF, even at higher temperatures. This may have manifested from shorter frying time and less exposure to the heat and frying oil as compared to VF and P+VF.

Table 3.8 Mean value for color change of different conditions at different temperatures for vacuum fried durian chips*.

Conditions	Temperature (°C)	Color change			
		L^*	a^*	b^*	ΔE
Fresh		90.34±0.20^{a}	0.58±0.09^{c}	27.17±0.09^{abc}	
VF	90	79.63±2.61^{bc}	-1.46±0.20^{ef}	23.59±1.41^{d}	11.51±2.76^{de}
	100	76.53±1.55^{cd}	-1.29±0.19^{ef}	23.87±2.88^{d}	14.48±2.00^{cd}
	110	71.74±1.88^{e}	-1.62±0.13^{f}	25.57±0.64^{bcd}	18.81±1.83^{b}
	120	63.30±2.13^{f}	4.05±0.67^{a}	28.54±1.04^{ab}	27.33±1.97^{a}
P+VF	90	79.53±2.32^{bc}	-0.79±0.28^{de}	25.72±1.73^{abcd}	11.09±2.29^{de}
	100	76.68±0.60^{cd}	-0.92±0.24^{def}	24.72±2.33^{cd}	14.07±1.00^{cd}
	110	71.46±1.45^{e}	-0.35±0.79^{d}	27.10±0.76^{abc}	18.93±1.42^{b}
	120	65.04±1.73^{f}	2.83±0.43^{b}	28.68±0.91^{a}	25.45±1.78^{a}
MWVF (560W)	90	80.97±1.90^{b}	-1.68±0.04^{f}	23.95±2.27^{d}	10.29±2.22^{e}
	100	77.26±1.19^{cd}	-0.95±0.84^{def}	25.91±2.19^{abcd}	13.38±0.99^{cde}
	110	74.73±1.72^{d}	-1.68±0.15^{f}	27.74±0.93^{abc}	15.80±1.72^{bc}
	120	65.85±1.53^{f}	3.09±0.23^{b}	28.08±0.67^{ab}	24.64±1.47^{a}

*Values are shown as mean ± standard deviation.

[a-f]The different superscripts in the same column mean that the values are significantly different ($p<0.05$).

In order to analyze the overall color change of the products, the total color differences (ΔE) were calculated and presented in Table 3.8. In conjunction with the results mentioned above, the overall change in color of the products was mainly due to longer frying time (Mojaharul Islam et al., 2019). Hence, it could be deducted that MWVF significantly reduced the change in ΔE and maintain the original color of durian than VF and P+VF ($p<0.05$). Previous research also reported that shorter frying led to less change in the color of the products (Chitrakar et al., 2019). Furthermore, Charoensiri et al. (2009) reported that 41.4 μg/100 g of beta-carotene in durian can lead to color change in the product due to the degradation of beta-carotene. The reaction with oxygen in atmosphere may also cause oxidation of the color pigment. At the same time, the change in color is also caused by the rate of oxidation and sensitivity to light, heat and oxygen intensity. Therefore, the closed system found in vacuum drying could improve the color change of the product as observed by Junlakan et al. (2016) for bananas, pineapples, and apples.

Table 3.9 Mean value for color change of different conditions at 110°C for microwave assisted vacuum fried durian chips*.

Day of ripening	Microwave power (W)	Color change			
		L*	a*	b*	ΔE
Day 1	Fresh	90.34±0.20^{a}	0.58±0.09^{bc}	27.17±0.09^{h}	
	400	73.32±1.12^{de}	-1.05±0.58^{de}	24.55±1.87^{ij}	17.36±1.29^{bc}
	480	73.07±2.00^{def}	-1.74±0.10^{e}	24.56±1.61^{ij}	17.66±2.09^{bc}
	560	75.06±1.17^{d}	-1.68±0.15^{de}	23.07±0.85^{j}	16.01±0.89^{c}
	640	74.39±0.83^{d}	0.42±1.97^{bc}	24.02±0.39^{j}	16.35±0.75^{bc}
Day 2	Fresh	87.26±0.59^{b}	1.17±0.05^{ab}	30.43±0.28^{efg}	
	400	70.03±0.64^{g}	-1.59±0.50^{de}	26.89±1.41^{hi}	17.85±0.73^{bc}
	480	70.51±0.68^{fg}	-1.65±0.33^{de}	27.47±2.47^{h}	17.36±0.88^{bc}
	560	70.87±0.61^{efg}	-1.14±0.05^{de}	29.44±0.69^{fgh}	16.59±0.57^{bc}
	640	70.68±1.38^{fg}	-0.48±1.42^{cde}	28.71±1.56^{fgh}	16.83±1.53^{bc}
Day 3	Fresh	86.63±0.56^{b}	1.36±0.08^{ab}	33.67±0.20^{cd}	
	400	68.14±1.67^{g}	-1.19±0.20^{de}	29.00±1.69^{fgh}	19.36±1.78^{b}
	480	68.60±1.62^{g}	-1.21±0.03^{de}	27.92±2.10^{gh}	19.04±1.82^{bc}
	560	68.72±1.45^{g}	-1.28±0.11^{de}	30.64±1.34^{ef}	18.74±1.47^{bc}
	640	68.68±1.44^{g}	-0.27±1.81^{cd}	32.38±2.05^{de}	18.20±1.50^{bc}
Day 4	Fresh	83.63±0.35^{c}	1.38±0.04^{ab}	38.67±0.26^{a}	
	400	54.94±2.27^{h}	1.65±0.45^{ab}	36.64±0.75^{ab}	28.78±2.21^{a}
	480	55.55±1.10^{h}	1.59±0.78^{ab}	34.76±1.54^{bcd}	28.38±1.19^{a}
	560	56.24±3.28^{h}	0.84±0.26^{bc}	37.00±0.82^{ab}	27.47±3.21^{a}
	640	56.23±1.95^{h}	2.30±0.22^{a}	35.90±2.03^{bc}	27.61±1.86^{a}

*Values are shown as mean ± standard deviation.

$^{a\text{-}j}$The different superscripts in the same column mean that the values are significantly different ($p<0.05$).

Color changes can occur during the frying process resulting from pigment degradation, oxidation, enzymatic browning, non-enzymatic browning, and phenol polymerization (Nguyen et al., 2019). Even though larger L^* and b^* values, as well as smaller a^* values, suggest higher product quality and a more desirable frying process (Xu et al., 2019), results from Table 3.9 indicated that there was a larger decrease in the L^*or lightness of the products as the ripeness increased (90.34±0.20 to 74.39±0.83 in Day 1 and 83.63±0.35 to 56.23±1.95 for Day 4). However, there were no significant difference ($p>0.05$) in the lightness of durian chips produced at different microwave levels for the same degrees of ripeness. This finding was consistent with the previously published conclusion that increasing the microwave power intensity had no effect on the lightness of the products (Bai-Ngew et al., 2011a; Su et al., 2018; Mojaharul Islam et al., 2019). Moreover, longer frying times resulted in considerably ($p<0.05$) lower L^*values and lower brightness in the more ripened samples. However, the b^* values of MWVF durian chips rose significantly ($p<0.05$) with frying time and durian ripeness as shown in Table 3.9. Furthermore, it was found that durian chips obtained from more ripened samples had a higher intensity of yellowness which is expected since the fresh ripened durian has that distinct coloration. After frying, it was shown that there was no significant change in the yellowness (b^*) of the samples for durian chips from Day 4 and other days which reaffirmed one of the advantages on vacuum frying compared to other frying and drying methods.

Finally, Table 3.9 shows that the total color difference (ΔE) values of MWVF samples from Day 4 (highest total sugar content) were significantly ($p<0.05$) lower than those of the durian samples from Day 1, Day 2, and Day 3. The degradation of total color can be attributed to moisture removal and the progression of nonenzymatic browning, which included the Maillard browning process and caramelization (Jiang et al., 2010). Although a lower value of ΔE correlates to better preservation of the natural color of the samples, higher ripeness of the durian chips generally resulted in a higher change in ΔE for fried products from the Maillard reaction between the carbonyl groups in proteins and the reducing sugars that developed during the ripening process. Nonetheless, although there were no significant differences ($p>0.05$) in ΔE values between durian chips obtained from using different microwave power, the higher ripeness of the samples led to the longer frying times which, consequently, resulted in a higher change in overall coloration of the products.

3.4.3 Oil Content of the product

Figure 3.7 presents the percentage of oil absorption at various frying temperature for VF, P+VF and MWVF. It could be concluded that higher frying temperature help to reduce the oil content of durian chips significantly ($p<0.05$) for all three processing conditions. This effect of VF temperature on the oil content agrees well with the study of Pedreschi (2012) on potatoes. One of the most important drawbacks for frying is oil absorption leading to undesired calories intake and risk of heart diseases and obesity. During frying, three main mechanisms have been proposed in previous research describing oil absorption into the product. Firstly, as frying proceeds, surrounding oil penetrates the product surface via liquid diffusion replacing the liquid water that has evaporated. For a VF process, the lower oil temperature (100ºC compared to 180ºC) significantly reduces the effective diffusivity of the oil, leading to a reduced rate of oil absorption during this constant rate of drying. However, as the rate of water evaporation begins to decrease and the product surface dries out, a crust begins to form at the product surface. This crust causes a decrease in the rate of water vapor diffusion and causes gas pressure build-up which, in turn, reduces the rate of oil absorption into the product. With VF and even more with MWVF, the crust begins to form even faster and the gas pressure build-up becomes even higher because of the microwave energy directly exciting the water molecules. This higher pressure build-up have a positive effect on reducing the overall rate of oil absorption (Lumanlan et al., 2019). Next, the second stage of oil absorption occurs during the pressurization of vacuum to atmospheric condition at the end of the drying period. This step begins when the chips are taken from the frying oil and maintained in a vacuum and temperature-controlled setting (the fryer vessel is still closed). As the vessel is vented at this point, the pressure in the pores of the chips rapidly rises to atmospheric levels as air and surface oil rushes into the empty pores spaces until the pressure reaches atmospheric levels. Due to the low pressure, however, gas diffuses much faster into the pore space, limiting the oil flow into the product pores (Mehta and Swinburn, 2001). Finally, the third major mechanism of oil absorption occurs during the cooling period after the product is removed from the fryer. In conventional frying, as the gas inside the pores cool down, the pressure drops dramatically, causing capillary diffusion of the oil at the product surface to enter into the product. As a result of a higher frying temperature and pressure buildup compared to VF, more surface oil is absorbed in conventional frying (Dueik and Bouchon, 2011). Moreover, since less oil adheres to the surface of the chips after vacuum frying due to surface drainage during depressurization and centrifugation, less oil is absorbed into the product during the cooling process for VF (Garayo and Moreira, 2002).

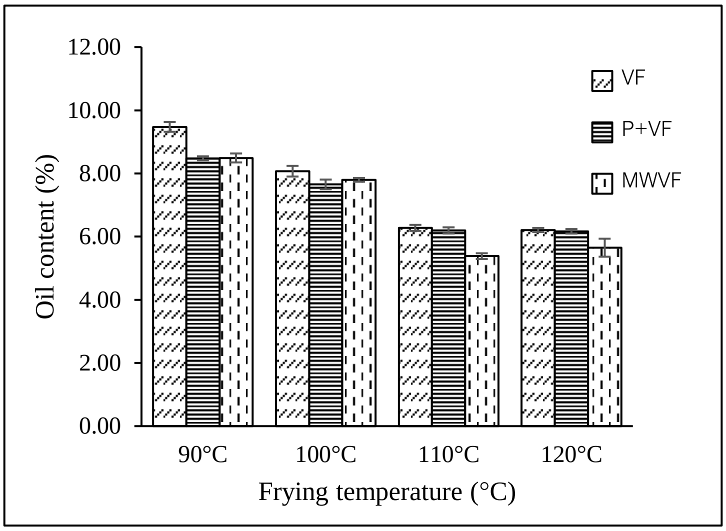


Figure 3.7 Percent of oil content at various conditions of vacuum fried durian chips from Day 1 (VF, vacuum frying; P+VF, pre-treatment before vacuum frying; MWVF, microwave assisted vacuum frying) at different frying temperature.

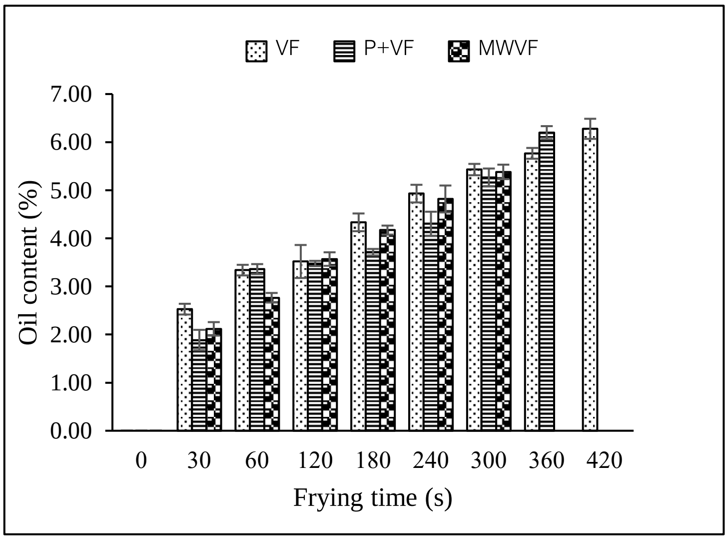


Figure 3.8 Percent of oil content versus frying time (s) of vacuum fried durian Day 1 in different frying conditions (VF, vacuum frying; P+VF, pre-treatment before vacuum frying; MWVF, microwave assisted vacuum frying) at 110°C.

Moreover, it can be seen from Figure 3.7 that the MWVF led to significantly lower ($p<0.05$) oil content compared to VF and P+VF. Related results were reported in the investigation of effect of ultrasound and microwave on vacuum fried Chinese yam (Chitrakar et al., 2019). The researcher concluded the highest microwave power level led to more rapid heating, reduced frying time, increased rate of dehydration, and minimized oil absorption. From Figure 3.8, the oil content of the durian chips rose with the increase in frying time. From Figure 3.2b), after 180 seconds of frying, the oil content began to increase as oil penetrated the surface of the durian chips and entered the pores left vacant by the free water (Su et al., 2016). However, the %oil content of MWVF was significantly lower than VF product. This could be explained from microstructure analysis using the SEM as shown in Figure 3.17. For MWVF, the structure was more porous and fractured, resulting from a higher rate of moisture removal, shorter frying time, and consequently, shorter exposure to the surrounding oil (Su et al., 2016).

Furthermore, P+VF durian chips also contained significantly lower oil content than VF at 6.17-8.48% (w.b.). From Figure 3.17, the microstructure of P+VF chips had much more uniform size pores caused by ice crystal formation and crystal growth during freezing. In addition, the ice crystal growth ruptured cell walls giving the pre-treated durian a more porous structure, allowing for faster moisture transport to the product surface during frying. Moreover, as water evaporated from the product surface, it helped block oil from permeating into the product. Finally, using lower frying pressure, the driving force for oil penetration into the product is less than at atmospheric pressure; therefore, all VF conditions helped reduce the oil content of the durian chips by at least 70% compared to commercially fried durian chips (32.19-36.54%) as reported by Bai-Ngew et al. (2011a).

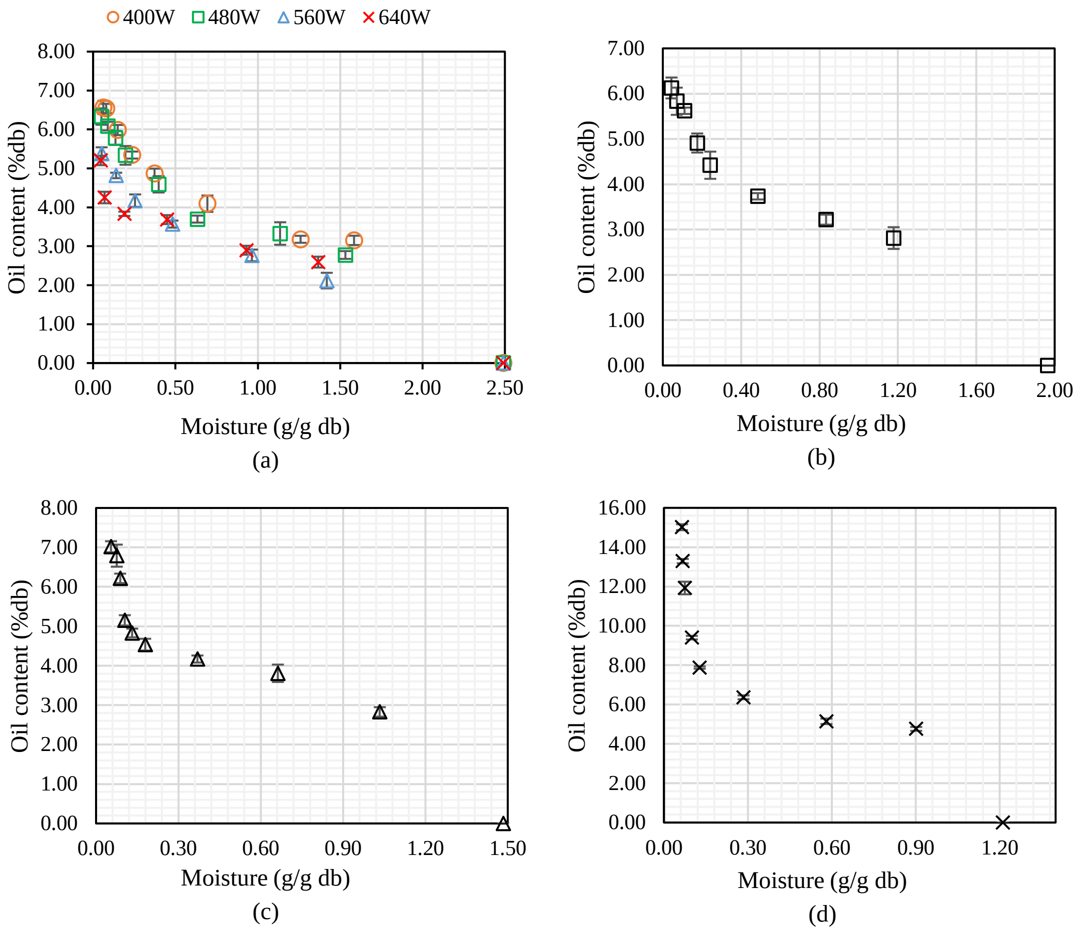


Figure 3.9 Percent of oil content versus moisture content of microwave-assisted vacuum fried durian chips in different frying conditions at 110°C: (a) chips from Day 1 (400, 480, 560, and 640W), (b) chips from Day 2 (560W), (c) chips from Day 3 (560W), and (d) chips from Day 4 (560W).

The amount of oil in fried foods is another key quality indicator. Low-oil products are more popular in the markets because of their lower risk to consumer health (Huang et al., 2018). Figure 3.9 illustrates the percent oil content for vacuum fried durian chips at different microwave power and durian ripeness level. As shown in Figure 3.9, after the moisture content dropped to 0.3 g/g d.b., the oil content of the samples began to increase more dramatically as oil penetrated the surface of the durian chips and occupied the pores left vacant by the free water during the frying process (Su et al., 2016). According to Shi et al., (2019), moisture removal is an endothermic energy transfer process that results in an increase in oil content as oil molecules diffuse by ways of molecular thermal motion and pressure difference between the interior and exterior of the product. From Figure 3.9a) there was a gradual increase in oil content as the frying time increases with the highest amount found at the microwave power of 400 and 480 W because of longer frying time.

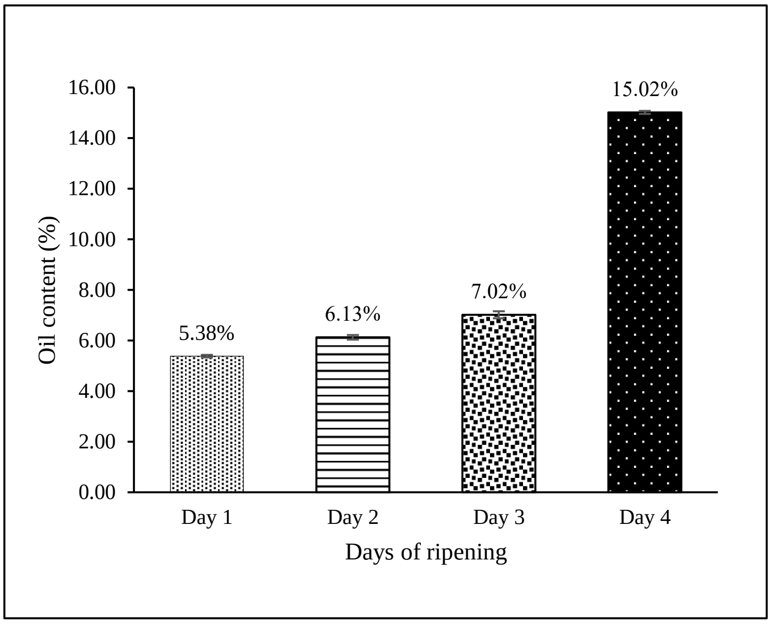


Figure 3.10 Percent of oil content of microwave-assisted vacuum fried durian chips at 110°C in different ripeness of durian at 560W.

Likewise, Fig 3.10 depicts a slightly higher oil content for Day 2 and Day 3 of ripened compared to Day 1 resulting similarly to the longer frying time. More evidently, it could be seen that for Day 4 products, the total oil content increased significantly ($p<0.05$) from 7.02% to 15.02% as the total frying time increased from

480 s to 840 s. Of course, the longer time was due to the higher thickness of the sliced durian chips from Day 4, but it also supported the fact that longer frying time led to higher oil absorption in ripened fruits (Diamanté, 2008). In addition, the lowest amount of oil absorption was found for the highest microwave power, because the greater the dehydration rate, the more free water and water vapor transferring to the product surface and partially blocking the oil from entering the chips during frying (Chitrakar et al., 2019). Furthermore, the ripeness of the durian also may have increased the rate of oil absorption toward the end of the frying process. Due to the lower amount of initial moisture content and a structure more prevalent with water binding pectin and hygroscopic reducing sugar, more energy is needed to remove this bound water (Yamsaengsung and Moreira, 2002a). As mentioned in the discussion on frying time, the lower initial moisture content and the increased amounts of water binding pectin and reducing sugar led to a longer frying time. As a result, longer frying time increases the contact time between the surface of the sample and frying oil allowing for more surface oil to penetrate into the product (Thongcharoenpipat and Yamsaengsung, 2022). Moreover, as ripened durians produced a more porous microstructure with larger pores, more oil is able to fill up the empty cells within the product even after centrifugation (Shi et al., 2019) resulting in higher oil uptake.

3.5 Textural Changes: Hardness and Crispness of fried products

From Table 3.10, As the frying temperature rose from 90°C to 120°C, the durian chips' hardness appeared to decrease. This is due to the dried durian chips' increased pore density, which indicates a more porous structure. The durian chips fried by the VF at the higher temperature of 110°C and 120°C provided less hardness than the lower frying temperature, but there was no significant difference in the crispness. The hardness and crispiness value of durian chips at different frying condition at 110°C ranged from 4.72-5.26 N and 1.65-1.93, respectively. The hardness values are comparable with those found for un-ripened durian chips (5.0-7.0 N) as mentioned by Bai-Ngew et al. (2011a). As can be noticed from the table, pre-freezing of durian helped to reduce the hardness of the fried durian chips and increased the crispiness as the crystal ice formed during freezing created a more uniform porous structure when compared to both VF or MWVF. Likewise, Bai-Ngew et al. (2011a) concluded that freezing resulted in more crispiness of the products. Even though the P+VF had a slightly lower crispiness value than VF and MWVF, it still had a comparable hardness value which is considered crispy according to Bai-Ngew et al. (2011a).

Table 3.10 Textural quality and pore size diameter of vacuum fried products at different frying conditions of durian Day 3[*].

Samples	Thickness of fresh sample (mm)	Total sugar content (g glucose/100g sample)	Hardness (N)	Crispness	Number of pores	Diameter of pores		
						Average (µm)	Min (µm)	Max (µm)
VF	2.0-2.5	14.83±0.80						
- 90°C			5.26±1.11[a]	1.65±0.54[a]	35	60.98	23.13	177.11
- 100°C			5.23±1.03[a]	1.68±0.59[a]	27	67.84	22.16	175.89
- 110°C			5.20±1.11[a]	1.76±0.70[a]	52	67.92	24.13	127.09
- 120°C			5.18±0.95[a]	1.79±0.59[a]	43	65.04	18.18	301.20
P+VF								
- 110°C	2.0-2.5	14.83±0.80	4.72±1.04[a]	1.93±0.58[a]	132	49.59	20.34	117.91
MWVF (560W)								
- 110°C	2.0-2.5	14.83±0.80	5.14±1.05[a]	1.85±0.78[a]	53	65.98	20.95	196.38

[*]Values are shown as mean ± standard deviation.

[a]The different superscripts in the same column mean that the values are significantly different ($p<0.05$).

In addition, when considering the effect of microwave heating on the VF process, there were no significant difference in the crispiness of the products using VF and MWVF ($p<0.05$), even though there were a slight increase in crispiness when microwave power was utilized. Nonetheless, many investigators reported that microwave power helped create s more porous and ruptured structure causing a decrease in hardness and improving the crispiness value (Chitrakar et al., 2019). This is due to the interior structure of the puffed samples being hollow and the shell becoming very thin which led to a lower breaking force during the texture analysis.

Furthermore, Nimmol et al. (2007) also found no significant difference in the hardness at different drying temperatures (70-90°C) using low LPSSD (low pressure superheated steam drying), LPSSD-FIR (low pressure superheated steam & far infrared radiation), and vacuum-FIR (far infrared radiation under VD). Thus, it could be inferred that the value of hardness and crispness are process dependent and structure dependent deriving from the disruption of physical cell, the inactivation-activation of enzymes and its shrinkage (Thuwapanichayanan et al., 2012), and P+VF and MWVF are viable alternative in producing high crispiness texture comparable to VF.

Table 3.11 Textural quality and pore size diameter of microwave-assisted vacuum fried products at various microwave power level for different days of ripeness*.

Samples	Thickness of fresh sample (mm)	Total sugar content (g glucose/100g sample)	Hardness (N)	Crispness	Number of pores	Diameter of pores		
						Average (µm)	Min (µm)	Max (µm)
Day1	2.0-2.5	6.41±0.20[d]						
- 560W			5.23±0.85[b]	1.63±0.59[b]	25	49.72	20.12	113.75
Day2	2.0-2.5	8.17±0.06[c]						
- 560W			5.27±1.18[b]	1.68±0.80[b]	26	50.19	23.88	136.77
Day3	2.0-2.5	14.83±0.80[b]						
- 400W			5.21±0.73[b]	1.74±0.67[b]	49	63.28	22.44	124.70
- 480W			5.22±0.88[b]	1.76±0.65[b]	48	60.12	19.33	158.94
- 560W			5.14±1.05[b]	1.85±0.78[b]	53	65.98	20.95	196.38
- 640W			5.13±0.93[b]	1.88±0.59[b]	61	87.14	36.93	215.32
Day4	5.0-6.0	35.04±0.86[a]						
- 560W			15.39±3.48[a]	9.26±2.13[a]	58	69.92	25.84	351.47

*Values are shown as mean ± standard deviation.

[a-b]The different superscripts in the same column mean that the values are significantly different ($p<0.05$).

According to Shi et al. (2019), the hardness of the fried products were caused primarily by pores formed from water evaporation and crust material created by different degrees of degradation of the cell surface (Shi et al., 2019). As previously mentioned, a porous texture is expected to improve the crispness of durian chips and various parameters including ripeness and rate of water evaporation greatly influence the resulting texture of the durian chips. As shown in Table 3.11, while Day 1 durian was the least ripened and had the lowest total sugar content of 6.41±0.20, its hardness value of 5.27±1.18 was slightly higher than that of Day 2 and Day 3 products, which were in the same range as the traditionally fried durian chips of 5.0 - 7.0 N (2-3 mm. initial thickness). This revealed that the texture of the durian chips developed was comparable to that available in the market fried durian chips (Bai-Ngew et al., 2011a). Moreover, there were more shrinkage of durian chips in Day 1 compared to Day 2 and Day 3 products, implying a more compact and harder structure as opposed to a crispier, porous structure. This effect may be seen in the SEM images, which agreed with Yamsangsung et al. (2011)'s findings that the ripened bananas had a lower breaking force (less hardness) than the lower degree of ripened bananas. As a consequence, even while Day 4 durian samples had the highest total sugar content, their sliced thickness was 5-6 mm, which may explain why they had the maximum hardness and crispness despite having a more porous structure than those with lower degree of ripening. As a result of longer frying time, the more oil entered the product and filled the pores left by the evaporation of water, which in turn, increased the breaking force required to break the products (Shi et al., 2019). Consequently, the hardness and crispness of the products from Day 4 increased significantly ($p<0.05$) from 5.14±1.05 to 15.39±3.48 N) and from 1.85±0.78 to 9.26±2.13, respectively, when compared to Day 3 products. Furthermore, there were a slightly increase in the crispness of the product from Day 1 to Day 3 as the degree of ripeness and the number of pores increased. Even though, Day 4 products did not have a significant difference ($p>0.05$) in the average pore size diameter, nor the number of pores in the given area compared to Day 3 products, there were a higher number of larger pores (above 125 µm) for the more ripened Day 4 samples. This may have resulted in the dramatically increase in the crispness of the sample despite having a higher hardness value compared to less ripened products. The hardness of the durian chips seemed to decrease with microwave power increased from 400 to 640W. Comparably, Zhang et al. (2007) reported that higher microwave power might improve the expansion ratio and crispness of fish slices. This is because of more porous structure inside the dried durian chips indicated by more numbers of pore. Also, the application of MWVF techniques and the higher microwave power level produced higher crispness but lower hardness values in the dried durian chips. The durian chips fried by the MWVF at the microwave power of 560 and 640W provided less hardness than the lower microwave power level of MWVF durian chips, but there was no significant difference in the crispness.

3.6 Microstructural observation

SEM images of the microstructure of the cross section of durian chips are shown in Figure 3.11. It was found that the fried durian chips produced by VF at higher frying temperatures had a more porous structure than those made at lower frying temperatures. For the reason that the rapid evaporation of moisture inside the durian chips during frying and the development of high vapor pressure, which led to the porous structure. As seen in Figure 3.13, the higher microwave power leads to larger pore diameters, because there was a quick and extensive vaporization during the microwave vacuum frying. As a result, vapor could increase the pressure inside the chips, as well as enhancing the porosity.

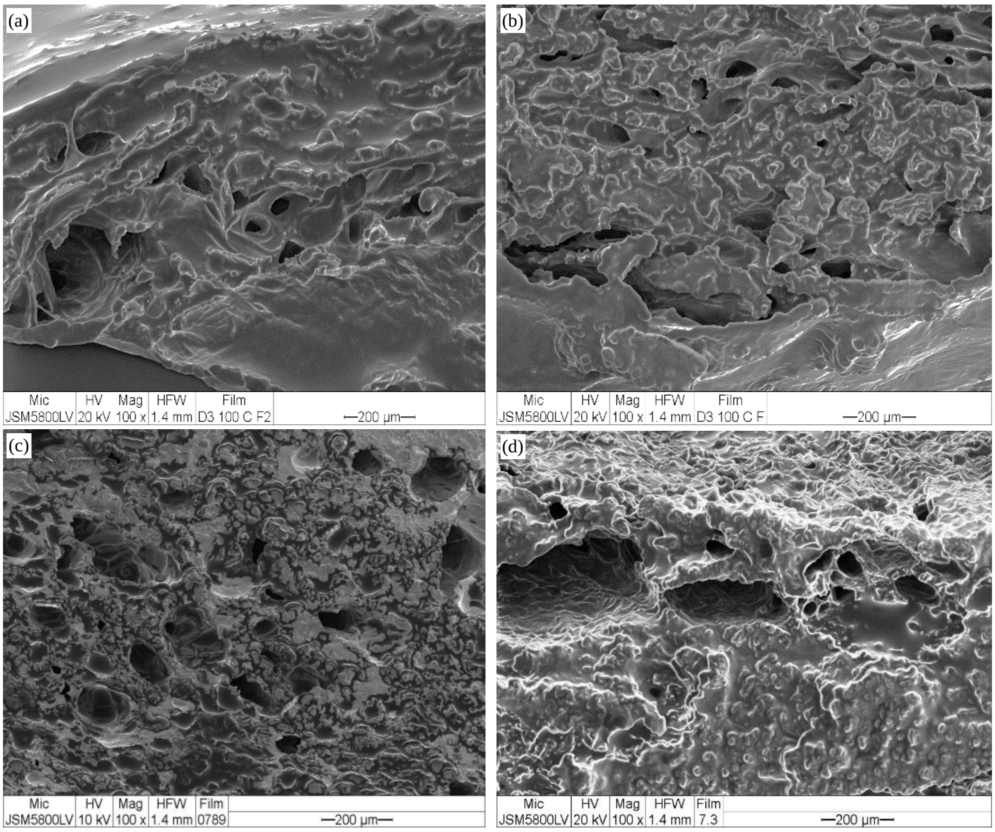


Figure 3.11 SEM images of vacuum fried durian chips at different frying temperature (100x) of chips from Day 3 at (a) 90°C, (b) 100°C, (c) 110°C, and (d) 120°C.

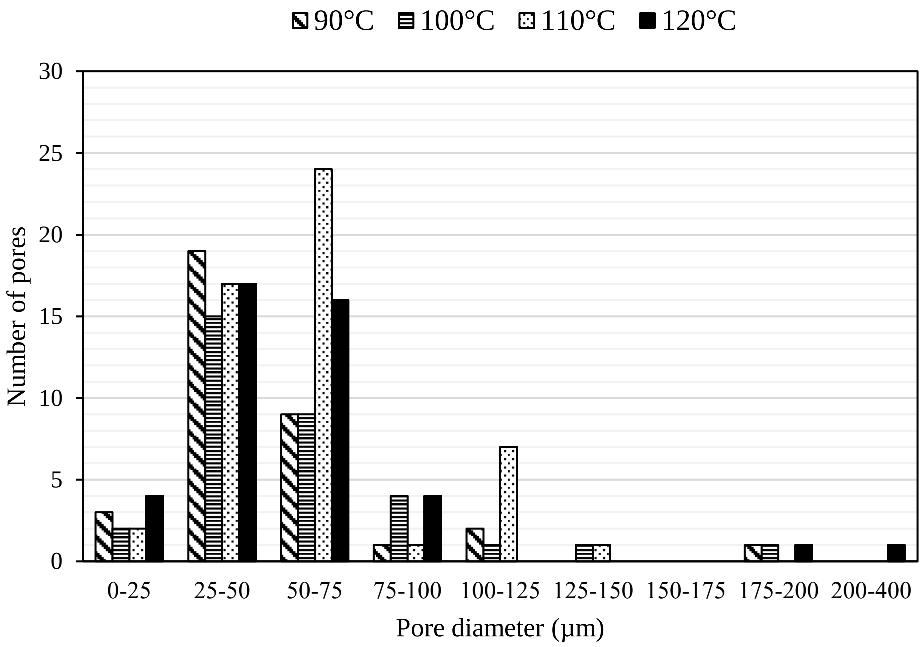


Figure 3.12 Pore size distribution of vacuum fried durian chips at different frying temperatures of product Day 3.

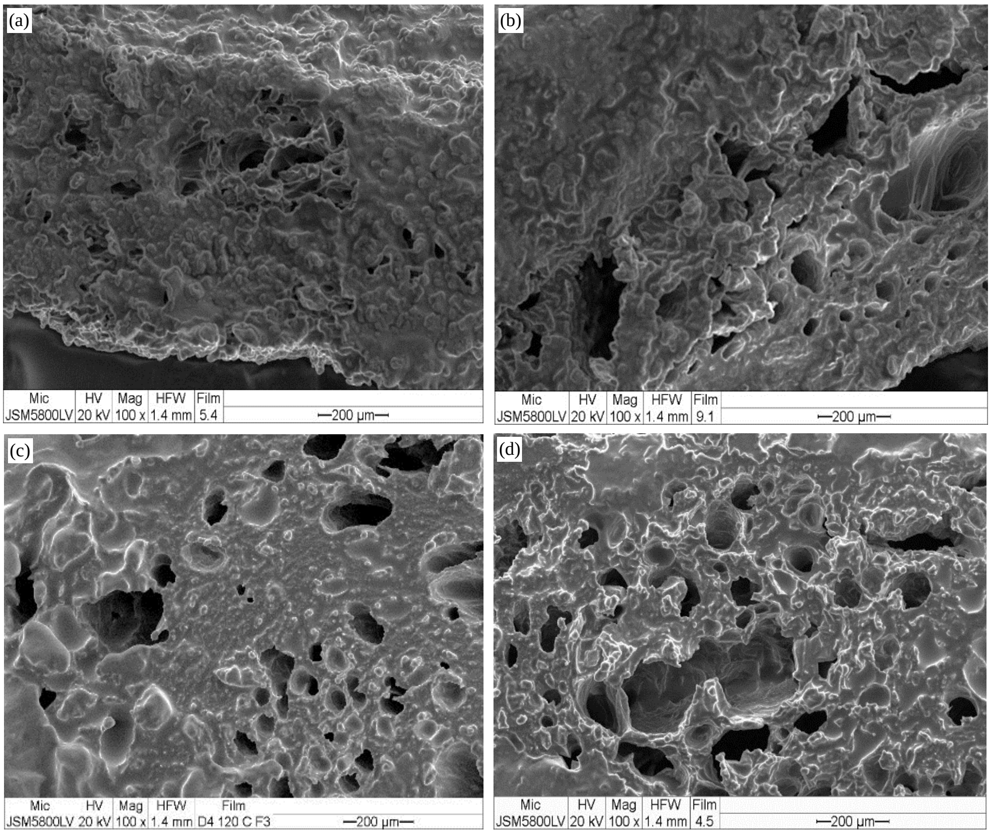


Figure 3.13 SEM images of microwave-assisted vacuum fried durian chips at 110°C at various microwave power level (100x) of product from Day 3 at (a) 400W, (b) 480W, (c) 560W, and (d) 640W.

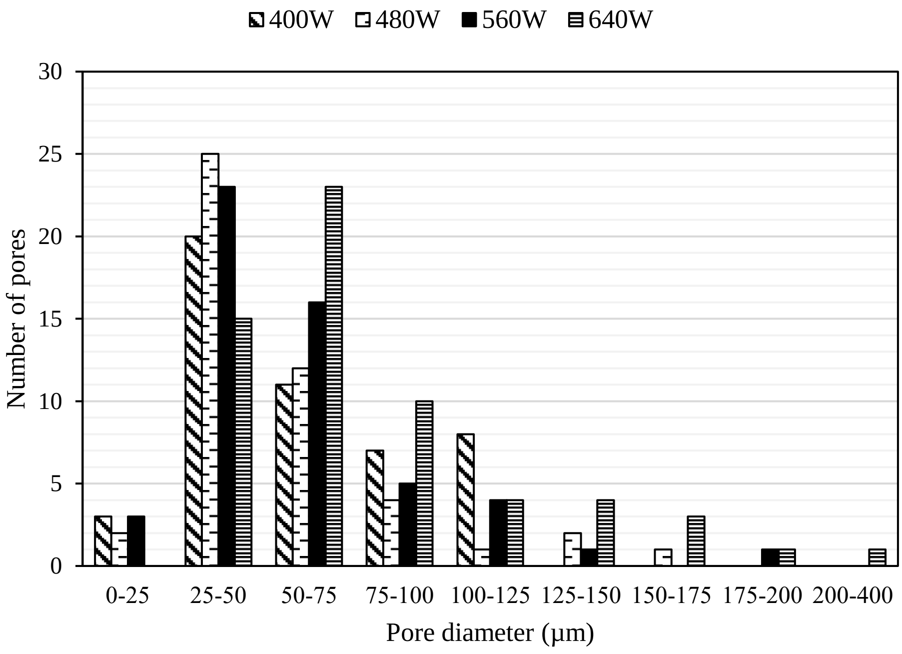


Figure 3.14 Pore size distribution of microwave-assisted vacuum fried durian chips at different microwave power level of product Day 3 (110°C).

The SEM from Figure 3.13 are presented in order to examine the influence of microwave power level on the structure of the products. The vacuum-fried durian chips obtained from higher microwave power had larger pores and higher porosity. This may have been caused by the more intense heating and vaporization which led to a higher-pressure gradient build-up inside the samples. As a result, the size of the pores gradually expanded as the frying time increased. As mentioned previously regarding oil absorption, the increase in pectin and hygroscopicity of ripened durian substantially encouraged gas vapor expansion, increasing the pressure inside the chips while also increasing the porosity (Bai-Ngew et al., 2011a). Similar results were reported by Moreira et al. (1997). During frying, starch gelatinizes and moisture evaporates rapidly, causing capillary pores to expand. During this time, oil at the surface of the chip penetrates into the product. A product with a higher pectin and sugar content has a greater potential to build up pressure inside the pores during frying due to the faster formation of the crust which, inturns, limits the flow of air and water vapor from the product interior (Lumanlan et al., 2019). At the same time, the quick and continual evaporation of water during frying caused structural changes, greater pressure builds up inside due to gaseous expansion, resulting in a more porous microstructure with larger pores (Yamsaengsung et al., 2011). These developments resulted in the enhancement of the crispness and crunchiness of the chips. Moreover, Thongcharoenpipat and Yamsaengsung (2022) found that MWVF of durian chips produced a more porous structure with larger pore radius compared to VF. This led also to a higher amount of oil absorption for VF which agreed statements by Bouchon and Pyle (2005) that a smaller pore radius leads to a higher capillary pressure and faster oil absorption during cooling of fried products. Furthermore, Garayo and Moreira (2002) claimed that due to the lower pressure differential between the surface and the pores of the VF chips generates a smaller driving force for the oil and air to penetrate the chips. VF generates a lesser driving force and less cohesiveness between the oil and the pores at the surface. As a result, vacuum frying produces less oil absorption during the cooling stage. From Table 3.11, the average pore diameter grew considerably from 49.72 μm for products from Day 1 to 69.92 μm for products from Day 4. However, there were no significant differences in the average pore diameter between products from Day 1 and 2 owing to the small difference in the degree of ripeness.

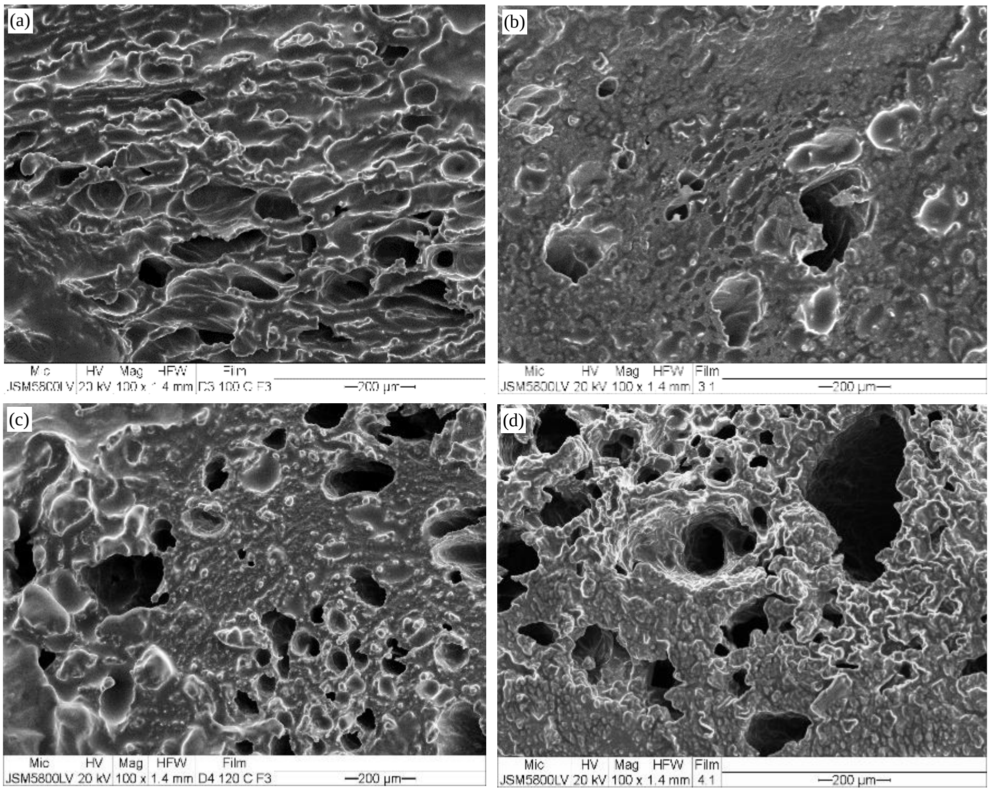


Figure 3.15 SEM images of microwave-assisted vacuum fried durian chips (560W) at 110°C at various ripening (100x) of (a) chips from Day 1, (b) chips from Day 2, (c) chips from Day 3, and (d) chips from Day 4.

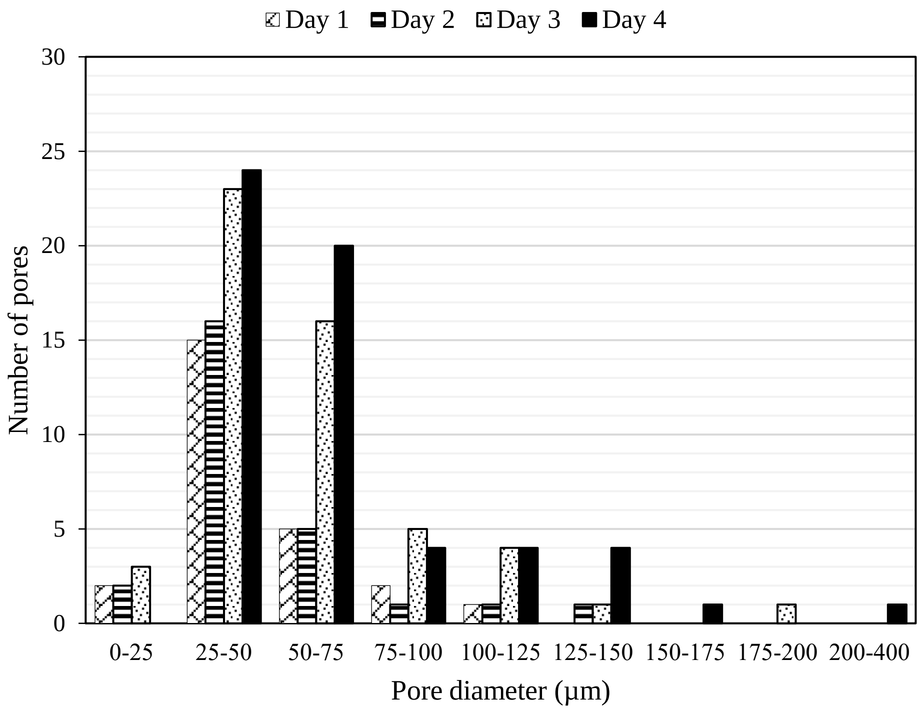


Figure 3.16 Pore size distribution of microwave-assisted vacuum fried durian chips of different ripeness of product at 110°C (560W).

Furthermore, according to Figure 3.15, Day 1 products had the highest hardness value (among samples with the same initial thickness), because it had the fewest number of pores, which is consistent with the observation of Yamsaengsung et al. (2011) for banana chips. Despite the fact that Day 4 had the largest average pore size diameter, as well as the highest hardness and crispness, it also had a higher thickness (5-6 mm). The higher thickness which led to a longer frying time may have resulted in even more pressure build up and thickness expansion as can be seen from the decrease in shrinkage of the product from Figure 3.6 after about 120 seconds of frying. This correlated with the falling rate period of drying from Figure 3.3 which indicated the presence of crust formation and reduced rate of water removal (Yamsaengsung et al., 2008). Consequently, Day 4 products had the greatest average pore diameter, the highest number of pores, and the largest pore size diameter (351.47 µm).

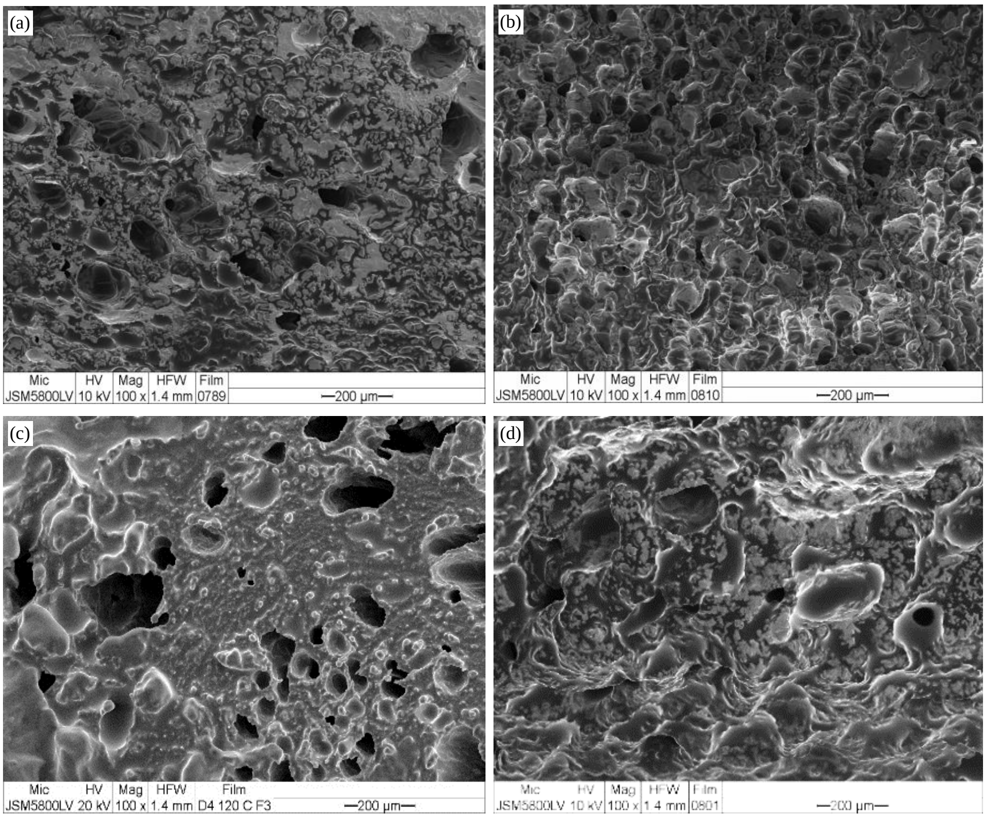


Figure 3.17 SEM images of vacuum fried durian chips at 110°C at various conditions (100x) of a) vacuum frying (VF), b) pre-treatment prior to vacuum frying (P+VF), c) microwave assisted vacuum frying at 560W (MWVF), and d) un-ripened chips from commercial.

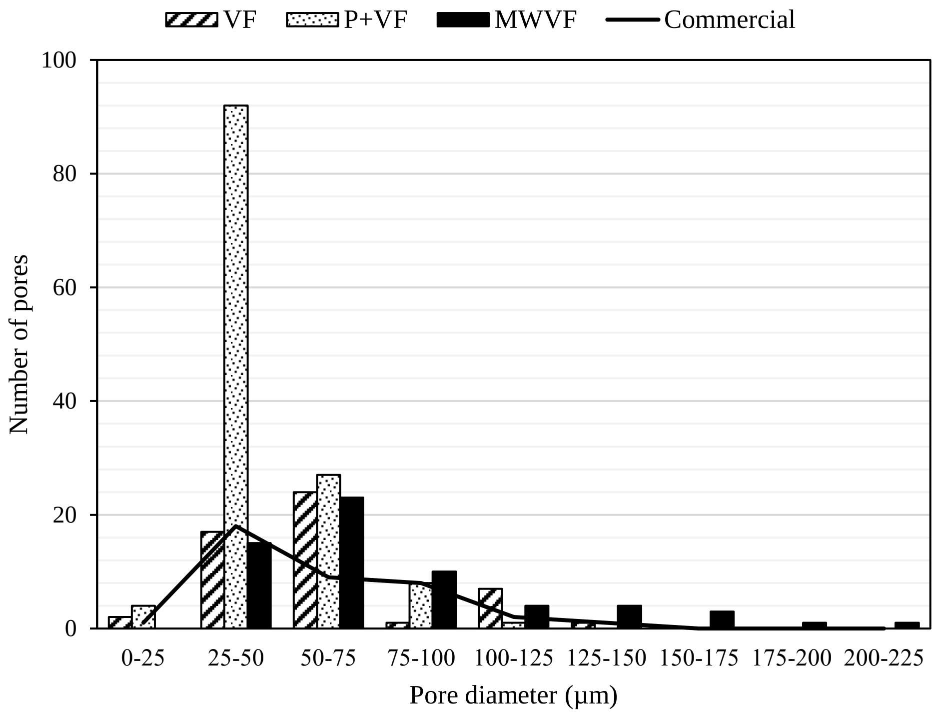


Figure 3.18 Pore size distribution of vacuum fried durian chips of different frying conditions compared to commercial product at 110°C.

Figure 3.17 and Figure 3.18 depict SEM images and pore size distribution of the microstructure of the durian chips based on each processing condition. From the SEM images and Figure 3.18, MWVF durian chips had larger pore size and greater pore size distribution compared with the samples from VF. This result could be due to the rapid vaporization inside the product caused by the microwave heating which helped to increase the porosity (Bai-Ngew et al., 2011a). Compared to VF and MWVF, the pre-treatment sample had a more uniform pores size distribution. This is due to the ice crystal formation during freezing and its rapid removal during VF. For VF, even though the longer frying time may have caused only a slight increase the pore sizes within product, the extended heating of the vapor inside product caused significant expansion of the pores resulting in more puffing or increased thickness toward the latter part of frying as compared to P+VF (Yamsaengsung et al., 2011). From Table 3.10 the maximum pore diameter increased from 127.09 μm for VF to 196.38 μm for MWVF. Therefore, from Figure 3.17 and Table 3.10, the effects of treatments on the structure of the fried durian Day 3 were compared. Results revealed that the microwave combined with VF could improve pore size diameter compared to VF and P+VF. Nonetheless, all three frying conditions had no significant effects on the hardness and crispiness of the products ($p<0.05$). Although small, the slightly lower value for hardness for P+VF compared to the other two processes may be due to the smaller pore size distribution which may have led to slightly more firmness in the structure. Previous works by Nimmol et al. (2007) and Yamsaengsung et al. (2011) also concluded that smaller and less porosity products have gradually lower hardness than those with larger pore sizes. Finally, from Figure 3.18, the pore size distribution of the MWVF durian chips were equivalent to those of commercially fried durian chips. Therefore, MWVF can produce improved structures and similar textural properties, while reducing the processing time by 20%. This, in turn, could lead to greater production capacity and increase market sales.

3.7 Sensory evaluation

Figure 3.19 presents the result of the sensory evaluation representing the acceptability of the vacuum fried durian chips in terms of crispness, color, aroma, taste, and texture. From the results, MWVF chips presented the highest level of acceptance for crispness (5.97±0.72), color (5.87±0.78), aroma (5.73±0.87), taste (6.10±0.55), appearance (5.70±0.65), and overall acceptance (6.07±0.64) which represents a level between ‘like moderately’ and ‘like very much’.

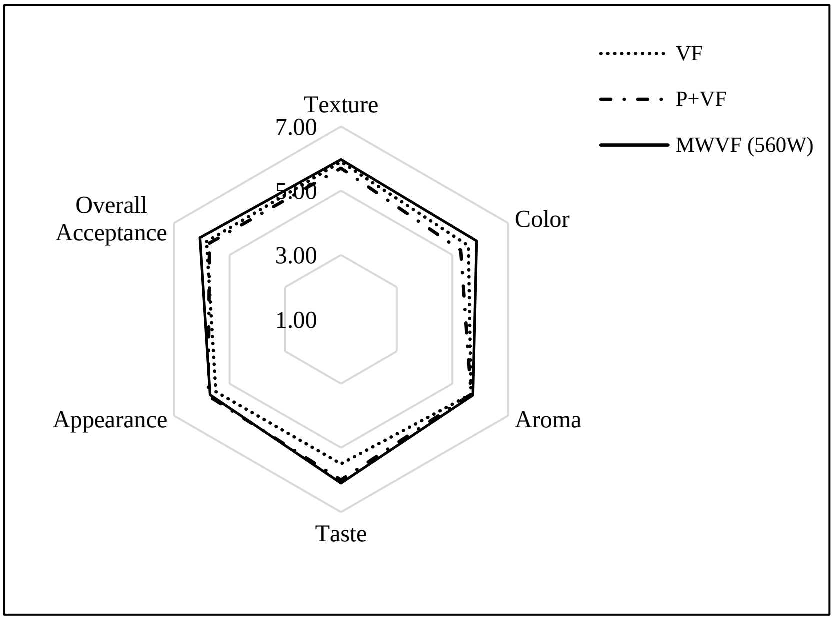


Figure 3.19 Effects of ripeness on sensory assessment and acceptance for vacuum fried durian chips from Day 3 at different conditions (110°C).

Since the MWVF product had the shortest frying time, the sensory panelists may have observed significant differences ($p<0.05$) in the color and appearance of the durian chips as well as in the taste. This may be due to the shorter frying time retaining more of the flavonoid's compounds found in the product (Fu et al., 2021) and minimizing the color change of the ripened durian (L^* = 68.19, a^* = 0.40, and b^* = 28.22). In contrast, the commercial un-ripened durian chips fried at 160-180ºC have a much darker and less yellow coloration with values of L^*, a^*, and b^* of 62.7, -6.4 and 40.3, respectively (Nathakaranakule et al. (2019). Therefore, with regards to its low oil content and its preferable physical and textural properties, MWVF durian chips may provide consumers with a healthier and more attractive choice compared to the un-ripened durian chips and the expensive freeze-dried durian chips. This study also concludes that the effect of process condition may affect the final characteristics and acceptability of the product. More investigations into the effect of ripening on these parameters are also crucial in determining the ideal processing conditions for industrial production of ripened durian chips.

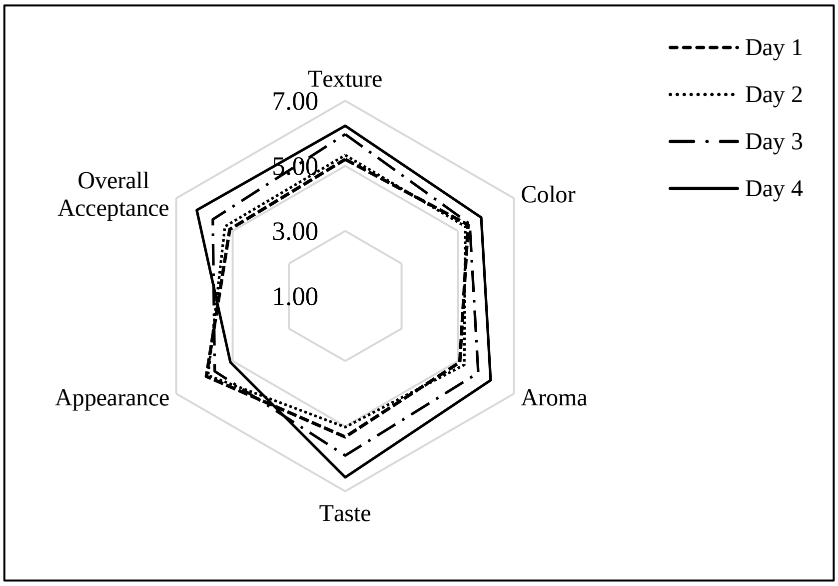


Figure 3.20 Effects of ripeness on sensory assessment and acceptance for microwave assisted vacuum fried durian chips at 110°C (560W).

Figure 3.20 presents the result of the sensory evaluation for appearance, colour, aroma, taste, and overall acceptability of MWVF durian chips at 110°C, 8 kPa, 560 W, and different days of ripeness. From the results, durian chips from Day 4 presented the highest level of acceptance with the highest score for texture (6.23±0.82), colour (5.83±0.87), aroma (6.17±1.05), taste (6.57±0.86), and overall acceptability (6.27±0.87). These scores were considered to be in the 'Like' (6/7) to 'Strongly Like' (7/7) range for all product attributes tested by the taste panel. Despite being the same relative thickness, the panel showed a significant preference ($p<0.05$) for the Day 3 products compared to Days 1 and 2 products for texture, aroma, and taste. Hence, the degree of ripeness player a key role in the increase in acceptability of the durian chips among durian lovers. Furthermore, despite, the higher overall acceptability score for the durian chips from Day 4, their appearance score was slightly lower than those from the less ripened counterpart. This may be due to the tendency of the thicker, more ripened durian chips, to break off into non-uniform shapes during frying as a result of its high porosity and crispiness rather than maintaining the more familiar flat-shaped pieces. Nonetheless, it can be concluded that the higher degree of ripeness, more sugar content, and the stronger distinct durian smell made the consumer preference for durian chips from Day 4 significantly higher ($p<0.05$) than those from the other days. Therefore, MWVF has the capability of producing high quality ripened durian snacks and presents a viable alternative for the durian snack industry in Thailand and the Southeast Asia region.

3.8 Specific Energy Consumption (SEC) of vacuum frying

The specific energy consumption (SEC) for VF, P+VF and MWVF in terms of thermal and electrical consumption at different frying temperature of VF durian Day 1 and the various frying conditions at the frying temperature of 110°C are shown in Table 3.12.

Table 3.12 Specific energy consumption (SEC) of frying process with different frying conditions of durian Day 1.

Frying method	Frying time (s)	Water evaporated (kg)	SEC (MJ/kg water evaporated)							
			Water pump	Cooling tower	Vacuum pump	Microwave	Thermal heating oil	Water evaporation	Total	
									Heat	Electricity
Day 1										
VF at 90°C	540	0.0486	8.290	6.217	8.290	N/A	2.671	2.363	5.034	22.797
VF at 100°C	480	0.0486	7.369	5.527	7.369	N/A	3.116	2.378	5.495	20.264
VF at 110°C	420	0.0487	6.429	4.822	6.429	N/A	3.551	2.393	5.944	17.680
VF at 120°C	420	0.0488	6.416	4.812	6.416	N/A	3.987	2.396	6.383	17.644
Day 1 at 110°C										
VF	420	0.0487	6.429	4.822	6.429	N/A	3.551	2.393	5.944	17.680
P+VF	360	0.0487	5.515	4.136	5.515	N/A	3.554	2.424	5.978	15.167
MWVF (560W)	300	0.0490	4.572	3.429	4.572	3.43	3.535	2.408	5.943	16.003

Interestingly, although many research investigations reported that the shorter drying time results in the lower energy consumption (Paengkanya et al., 2015), P+VF provided the lowest SEC value, even though MWVF produced the shortest frying time. This was probably due to the higher energy involved in implementing microwave as a combined heating source. In terms of electric energy consumption, the higher frying temperature of VF consumed less SEC than the lower frying temperature. This is due to the fact that increased frying temperature reduced the frying time and accelerate the drying rate of the durian chips. Finally, MWVF could improve 7% decrease in SEC which enabling an increase by 20% in production capacity as mentioned in the previous section. Hence, it is advisable that industries should select and optimized their production process based on considerations of the pre-treatment procedure, the addition of microwave heating and the overall SEC in their cost and economic analysis.

Table 3.13 Specific energy consumption (SEC) of frying process with different microwave power level of various ripeness.

Frying method	Frying time (s)	Water evaporated (kg)	SEC (MJ/kg water evaporated)							
			Water pump	Cooling tower	Vacuum pump	Microwave	Thermal heating oil	Water evaporation	Total	
									Heat	Electricity
Day 1 at 110°C										
400W	420	0.0487	6.429	4.822	6.429	3.45	3.551	2.392	5.943	21.127
480W	420	0.0490	6.395	4.796	6.395	4.11	3.532	2.390	5.923	21.701
560W	300	0.0490	4.572	3.429	4.572	3.43	3.535	2.408	5.943	16.003
640W	300	0.0491	4.560	3.420	4.560	3.91	3.526	2.436	5.962	16.453
Day 2 at 110°C										
400W	540	0.0449	8.967	6.725	8.967	4.81	3.852	2.233	6.085	29.467
480W	480	0.0446	8.034	6.025	8.034	5.17	3.883	2.240	6.123	27.263
560W	420	0.0453	6.912	5.184	6.912	5.19	3.818	2.382	6.200	24.198
640W	420	0.0449	6.974	5.231	6.974	5.98	3.852	2.379	6.231	25.162
Day 3 at 110°C										
400W	540	0.0398	10.131	7.598	10.131	5.43	4.352	2.131	6.484	33.293
480W	540	0.0398	10.110	7.582	10.110	6.50	4.343	2.144	6.487	34.307
560W	480	0.0403	8.892	6.669	8.892	6.68	4.298	2.337	6.634	31.128
640W	420	0.0400	7.824	5.868	7.824	6.71	4.322	2.352	6.674	28.230
Day 4 at 110°C										
400W	960	0.0360	19.877	14.908	19.877	10.66	4.803	2.070	6.873	65.321
480W	960	0.0360	19.877	14.908	19.877	12.79	4.803	2.104	6.908	67.452
560W	840	0.0360	17.393	13.044	17.393	13.06	4.803	2.185	6.988	60.886
640W	840	0.0360	17.393	13.044	17.393	14.92	4.803	2.187	6.990	62.751

Table 3.13 shows the specific energy consumption (SEC) of the MWVF process in terms of total energy required, including the thermal and electrical energy consumption. Due to the shorter frying duration, the SEC for Day 1 products was found to be lower than those for the more ripened durians from Day 2 and Day 3. However, as expected, the samples from Day 4 which had higher original thickness also required a greater amount of energy to achieve the desired product quality (in terms of final moisture content and crispness texture). In addition, even though the frying process with higher microwave power level demanded more electrical input, using lower microwave power level led to higher SEC at the same ripeness level due to the significantly longer frying time (Su et al., 2018). Similar results were reported by Nathakaranakule et al. (2010), Puente-Diaz et al. (2013), and Paengkanya et al. (2015). In terms of the SEC, the optimum frying process was at 560W, 110°C and 8 kPa absolute pressure for all ripeness level.

3.9 Economic analysis

The Net Present Value (NPV) approach, which calculates the present value of net cash inflows resulting from a plan's development and production, was used in the research to decide whether or not the plan should be performed. If the predicted free cash flows have a better current value than the investment costs, the project is considered to be profitable (Junlakan, 2014). In this study, the economic feasibility of fruit frying was assessed using the frying condition at temperature of 110°C and absolute chamber pressure of 8 kPa. From one to four times each day, an economic study of the durian frying process was completed. The economic viability of durian frying was examined using the fresh durian and the technical information of each operation, as shown in Tables 3.14 and 3.15.

The labor expenses, the sale prices of the fried durian chips, and the costs of the raw materials, which are provided in Table 3.16, are also significant data points for the estimation of Net Present Value. The NPV for selecting the optimal choices for vacuum frying durian chips was calculated using this data.

Tables 3.17 and 3.18 present the results of the NPV for vacuum frying of durian chips. It was revealed that certain operations had a positive NPV, considering them interesting as investment ventures. Additionally, the vacuum frying of durian on Days 1 (un-ripened) at four times of the frying each day for all frying conditions had the negative NPV, while the MWVF of durian on Day 4 at three times of the frying each day had the largest NPV. Therefore, three times of the frying each day were the optimum possibilities for the microwave-assisted vacuum frying of durian on Day 4.

Table 3.14 Fresh durian and technical information to determine the economic feasibility for VF, P+VF, and MWVF of durian Day 1 (un-ripened).

Detail	Frying once a day (MWVF)	Frying four times a day (MWVF)	Frying four times a day (VF)	Frying four times a day (P+VF)
1. The cost of electricity (THB/month) (See in Appendix B.1)	318.06	1,507.46	1,441.28	1,869.14
2. Feeding rate of fresh durian (grams/day)	6,870	27,480	27,480	27,480
3. The cost of LPG (THB/day)	15.33	61.32	61.32	61.32
4. The cost of palm oil (THB/day)	5,175	5,175	5,175	5,175
5. Yield of fried durian (grams of fried durian/grams of fresh durian)	34.68	34.68	34.68	34.68
6. Rated operating capacity (grams of fried durian/day)	2,382.52	9,530.06	9,530.06	9,530.06
7. The service life of vacuum fryer (Year)	10	10	10	10
8. Average Operating Time (min/day)	130	430	510	470
9. Total fixed-capital investment of vacuum frying system (THB) (See in Appendix B.2)	957,000	957,000	902,550	927,300
10. Depreciation cost of vacuum fryer – 10% of fixed capital investment (THB/year) (León et al., 2020)	95,700	95,700	90,255	92,730

Table 3.15 Fresh durian and technical information to determine the economic feasibility for MWVF of durian Day 4 (ripened).

Detail	Frying once a day	Frying two times a day	Frying three times a day
1. The cost of electricity (THB/month) (See in Appendix B.1)	542.93	1,250.88	1,938.78
2. Feeding rate of fresh durian (grams/day)	5,727	11,454	17,181
3. The cost of LPG (THB/day)	12.90	25.79	38.69
4. The cost of palm oil (THB/day)	5,175	5,175	5,175
5. Yield of fried durian (grams of fried durian/grams of fresh durian)	51.22	51.22	51.22
6. Rated operating capacity (grams of fried durian/day)	2,933.37	5,866.74	8,800.11
7. The service life of vacuum fryer (Year)	10	10	10
8. Average Operating Time (min/day)	190	350	510
9. Total fixed-capital investment of vacuum frying system (THB) (See in Appendix B.2)	957,000	957,000	957,000
10. Depreciation cost of vacuum fryer – 10% of fixed capital investment (THB/year)	95,700	95,700	95,700

Table 3.16 The costs of each operation to determine the economic feasibility for MWVF of durian of each ripening (see in Appendices B.2-B.7).

Days of ripening	Detail	The costs of each operation (THB per month)			
		Frying one time per day	Frying two times per day	Frying three times per day	Frying four times per day
Day 1 (un-ripened) MWVF	1. The costs of raw materials	51,525	N/A	N/A	206,100
	2. The costs of labors	2,200.25	N/A	N/A	7,277.75
	3. The sale prices of the products	83,983.83	N/A	N/A	335,934.5
Day 1 (un-ripened) VF	1. The costs of raw materials	N/A	N/A	N/A	206,100
	2. The costs of labors	N/A	N/A	N/A	8631.75
	3. The sale prices of the products	N/A	N/A	N/A	335,934.5
Day 1 (un-ripened) P+VF	1. The costs of raw materials	N/A	N/A	N/A	206,100
	2. The costs of labors	N/A	N/A	N/A	7,954.75
	3. The sale prices of the products	N/A	N/A	N/A	335,934.5
Day 4 (ripened)	1. The costs of raw materials	42,922.5	85,905	128,857.5	N/A
	2. The costs of labors	3,215.75	5,923.75	8,631.75	N/A
	3. The sale prices of the products	371,800	743,600	1,115,414	N/A

Table 3.17 Net Present Value of the durian Day 1(un-ripened) frying projects (see Appendix B.7).

The number of operations per day	Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1 time per day (MWVF)	Revenues	997,826.7	1,985,773.9	2,963,939.6	3,932,420.4	4,891,312.3	5,840,710.2	6,780,708.1	7,711,399.1	8,632,875.3	9,545,228.1
	Costs	3,377,858.5	5,774,748.1	8,147,906.1	10,497,567.4	12,823,964.9	15,127,328.6	17,407,886.8	19,665,865.2	21,901,487.4	24,114,974.7
	Cash flow	-2,380,031.7	-3,788,974.1	-5,183,966.5	-6,565,147.1	-7,932,652.6	-9,286,618.5	-10,627,178.7	-11,954,466.1	-13,268,612.1	-14,569,746.7
4 times per day (MWVF)	Revenues	3,991,301.0	7,943,084.2	11,855,740.7	15,729,658.2	19,565,220.0	23,362,806.0	27,122,792.0	30,845,550.5	34,531,450.0	38,180,855.4
	Costs	5,441,378.3	9,881,356.3	14,277,375.0	18,629,868.4	22,939,267.7	27,205,999.8	31,430,487.0	35,613,147.5	39,754,395.6	43,854,641.2
	Cash flow	-1,450,077.3	-1,938,272.6	-2,421,634.3	-2,900,210.2	-3,374,047.8	-3,843,193.9	-4,307,695.0	-4,767,597.0	-5,222,945.6	-5,673,785.8
4 times per day (VF)	Revenues	3,991,301.0	7,943,084.2	11,855,740.7	15,729,658.2	19,565,220.0	23,362,805.9	27,122,792.0	30,845,550.5	34,531,450.0	38,180,855.4
	Costs	5,427,054.24	9,906,761.40	14,342,115.0	18,733,554.3	23,081,513.9	27,386,424.5	31,648,712.1	35,868,798.9	40,047,102.7	44,184,037.1
	Cash flow	-1,435,753.2	-1,963,677.25	-2,486,374.3	-3,003,896.1	-3,516,293.9	-4,023,618.6	-4,525,920.1	-5,023,248.4	-5,515,652.7	-6,003,181.6
4 times per day (P+VF)	Revenues	3,991,301.0	7,943,084.2	11,855,740.7	15,729,658.2	19,565,220.0	23,362,805.9	27,122,792.0	30,845,550.5	34,531,450.0	38,180,855.4
	Costs	5,435,925.2	9,899,910.4	14,319,697.9	18,695,725.0	23,028,425.2	27,318,227.3	31,565,556.1	35,770,832.2	39,934,471.9	44,056,887.4
	Cash flow	-1,444,624.2	-1,956,826.3	-2,463,957.1	-2,966,066.9	-3,463,205.2	-3,955,421.4	-4,442,764.2	-4,925,281.7	-5,403,021.9	-5,876,031.9

Note: The expected service life of the system is 10 years.

MARR is 1%

Table 3.18 Net Present Value of the durian Day 4 (ripened) MWVF projects (see Appendix B.7).

The number of operations per day	Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1 time per day	Revenues	4,417,482.2	8,791,226.9	13,121,667.2	17,409,231.9	21,654,345.5	25,857,428.2	30,018,896.2	34,139,161.6	38,218,632.3	42,257,712.2
	Costs	3,322,713.7	5,665,004.6	7,984,104.4	10,280,242.9	12,553,647.3	14,804,542.7	17,033,152.1	19,239,696.0	21,424,393.0	23,587,459.2
	Cash flow	1,094,768.4	3,126,222.3	5,137,562.8	7,128,989.1	9,100,698.2	11,052,885.5	12,985,744.1	14,899,465.6	16,794,239.3	18,670,252.9
2 times per day	Revenues	8,834,964.4	17,582,453.8	26,243,334.5	34,818,463.8	43,308,690.9	51,714,856.4	60,037,792.4	68,278,323.2	76,437,264.6	84,515,424.3
	Costs	3,948,240.0	6,909,863.8	9,842,164.5	12,745,432.6	15,619,955.4	18,466,017.7	21,283,901.1	24,073,884.6	26,836,244.6	29,571,254.4
	Cash flow	4,886,724.4	10,672,590.1	16,401,170.0	22,073,031.2	27,688,735.5	33,248,838.7	38,753,891.4	44,204,438.6	49,601,020.0	54,944,169.9
3 times per day	Revenues	13,252,443.6	26,373,674.8	39,364,992.9	52,227,684.1	64,963,021.8	77,572,267.2	90,056,668.5	102,417,461.9	114,655,871.1	126,773,108.1
	Costs	4,573,528.0	8,154,248.9	11,699,517.0	15,209,683.5	18,685,095.9	22,126,098.2	25,533,031.2	28,906,232.1	32,246,035.2	35,552,770.8
	Cash flow	8,678,915.5	18,219,426.0	27,665,475.9	37,018,000.5	46,277,926.0	55,446,169.0	64,523,637.3	73,511,229.6	82,409,836.0	91,220,337.3

Note: The expected service life of the system is 10 years.

MARR is 1%

CHAPTER 4

Conclusions and Suggestions

4.1 Conclusions

1. Effect of process conditions on vacuum frying of durian chips

This research evaluated the effects of process conditions on the physiochemical properties of vacuum fried durian chips. Durians were sliced and fried at 90, 100, 110, and 120°C under 8 kPa absolute pressure. From this study, microwave-assisted vacuum frying (MWVF) significantly reduced the frying time by 20% compared to VF ($p<0.05$) with the effective moisture diffusivity for VF, P+VF, and MWVF at 110°C determine to be 4.59×10^{-09}, 5.62×10^{-09}, and 6.11×10^{-09} m^2/s, respectively.

Moreover, eight mathematical models (i.e., Newton's model, Page's model, Logarithmic's model, Demir et al. model, Midilli's model, Approximation of diffusion model, Logistic's model, and Henderson and Pabis model) describing thin layer drying were considered. It was obtained that the best fit among all of these models for durian at different ripeness was the Midilli equation providing the highest value of the lowest values of RMSE and χ^2 for all frying temperature of VF, P+VF and MWVF.

The study found that MWVF produced chips with significantly lower shrinkage, more yellowness, and higher crispiness (consistent with the microstructure from scanning electron microscopy). In addition, MWVF drastically decreased oil absorption by 10%, while P+VF yielded the lowest specific energy consumption (SEC). From sensory evaluation, taste panelists gave the highest overall acceptability score to of 6.07±0.64 for the products from MWVF among different process conditions, thus making the product fall into the 'Good' to 'Very Good' range. Therefore, MWVF of durian chips could be viable alternative for food processors enabling them to reach a wider target market and meet consumer demands.

2. Effect of microwave power level on microwave-assisted vacuum frying of durian chips

The microwave assisted vacuum frying (MWVF) of Durian cv. Monthong was performed to investigate the effect of microwave power levels (400, 480, 560, and 640W) and ripening stages (1 Day, 2 Days, 3 Days, and 4 Days after harvesting) on the kinetics of the durian chips. The physio-chemical properties, the specific energy consumption (SEC) and product acceptability using sensory evaluation were also determined at 110°C and absolute pressure of 8 kPa. At the higher microwave power, the frying time was reduced leading to a lower SEC. Moreover, it also resulted in decreasing oil absorption, decreasing shrinkage, and increasing porosity.

3. Effect of ripeness on microwave-assisted vacuum frying of durian chips

The ripeness of durian led to longer frying times with significantly less shrinkage, higher oil absorption, and more yellowness for durians from Day 3 compared to Day 1. Furthermore, the increased amount of pectin and sugar in more ripened durians affected the vapor pressure build-up inside the product and consequently, increase the internal pore size and the crispiness of the durian chips. From sensory evaluation, the taste panellists gave a higher rating for the durian chips with higher ripeness, indicating a preference for ripened products compared to conventionally fried un-ripened durian chips. This makes ripened MWVF durian chips and possibly other ripened fruits a feasible alternative to the un-ripened snacks and the more expensive freeze-dried products.

4. Economic analysis

In this study, the economic feasibility of fruit frying was assessed using the frying condition at temperature of 110°C and absolute chamber pressure of 8 kPa. From one to four times each day, an economic study of the durian frying process was completed. The results of the NPV for vacuum frying of durian chips presented the economic viability of durian frying was examined using the fresh durian and the technical information of each operation. It was revealed that certain operations had a positive NPV, considering them interesting as investment ventures. Additionally, the vacuum frying of durian on Days 1 (un-ripened) at four times of the frying each day for all frying conditions had the negative NPV, while the MWVF of durian on Day 4 (ripened) at three times of the frying each day had the largest NPV. Therefore, MWVF has the capability of producing high quality ripened durian snacks and presents a viable alternative for the durian snack industry in Thailand and the Southeast Asia region.

4.2 Suggestions

1. Future investigation of the optimum conditions for pre-treatment prior to the microwave assisted vacuum frying process of the fruits because the development of ice crystals may limit the water molecules' ability to move about in the frozen substance, which may impact dipole rotation during microwave heating.

2. Develop procedures for storing fried fruits to extend the shelf life of the products.

3. Increase the vacuum fryer's efficiency to prepare fruits in greater quantities while maintaining the quality of the fried fruit.

REFERENCES

Afzal, T. M., and Abe, T. (1998). Diffusion in potato during far infrared radiation drying. *Journal of Food Engineering*, 37(4), 353-365.

Alibas, I. (2014). Microwave, Air and Combined Microwave-Air Drying of Grape Leaves (Vitis vinifera L.) and the Determination of Some Quality Parameters. *International Journal of Food Engineering*, 10(1), 69-88.

Ammawath, W., Che Man, Y. B., Yusof, S., and Rahman, R. A. (2001). Effects of variety and stage of fruit ripeness on the physicochemical and sensory characteristics of deep-fat-fried banana chips. *Journal of the Science of Food and Agriculture*, 81(12), 1166-1171.

AOAC. (1990). In Official Methods of Analysis (15th ed.). Washington, DC: Association of Official Analytical Chemists.

AOAC. (1995). In Official Methods of Analysis (16th ed.). Washington, DC: Association of Official Analytical Chemists.

Arancibia-Avila, P., Toledo, F., Park, Y., Jung, S., Kang, S., Heo, B. G., Lee, S., Sajewicz, M., Kowalska, T., and Gorinstein, S. (2008). Antioxidant properties of durian fruit as influenced by ripening. *LWT - Food Science and Technology*, 41(10), 2118-2125.

Arévalo-Pinedo, A., and Murr, F. (2006). Kinetics of vacuum drying of pumpkin (Cucurbita maxima): modeling with shrinkage. *Journal of Food Engineering*, 76(4), 562-567.

Arslan, D., and Ozcan, M. M. (2012). Evaluation of drying methods with respect to drying kinetics, mineral content, and color characteristics of savory leaves. *Food and Bioprocess Technology*, 5(3), 983-991.

Artman, N. R. (1969). Advances in Lipid Research (Vol. 7). (R. Paoletti, Ed.) New York: Academic Press.

Atom. (2011). Durian Information-A Durian blog Devoted To "The King of Fruits". Available from: http://durianinfo.blogspot.com/p/durian-cultivars-or-clones-cultivated.html. Accessed March 2017.

Ayustaningwarno, F., Verkerk, R., Fogliano, V., and Dekker, M. (2020). The pivotal role of moisture content in the kinetic modelling of the quality attributes of vacuum fried chips. *Innovative Food Science and Emerging Technologies*, 59, 102251.

Azizi, S., and Peyghambarzadeh, S. M. (2010). Effect of temperature history on mass transfer diffusivity in convection drying process. *World Applied Sciences Journal*, 10(10), 1216-1224.

Bai-Ngew, S., Therdthai, N., and Dhamvithee, P. (2011a). Characterization of microwave vacuum-dried durian chips. *Journal of Food Engineering*, 104(1), 114-122.

Bai-Ngew, S., Therdthai, N., and Dhamvithee, P. (2011b). Effect of pretreatment prior to microwave vacuum drying on quality of durian chips. In proceedings of the 49th Kasetsart University Annual Conference: Agro-Industry Kasetsart University. Bangkok, Thailand.

Bai-Ngew, S., Therdthai, N., Dhamvithee, P., and Zhou, W. (2015). Effect of microwave vacuum drying and hot air drying on the physicochemical properties of durian flour. *International Journal of Food Science and Technology*, 50(2), 305-312.

Banerjee, S., and Kumar, C. (2017). A short review on vacuum frying a promising technology for healthier and better fried foods. *International Journal of Nutrition and Health Science*, 1(2), 68-71.

Bank of Thailand. (2022). Deposit Rates for Individuals of Commercial Banks as of 9 November 2022. Available from: https://www.bot.or.th/thai/statistics/_layouts/application/interest_rate/in_rate.aspx. Accessed November 2022.

Barutcu, I., Sahin, S., and Sumnu, G. (2007). Effects of batters containing different types of flours on quality of microwave fried chicken fingers. CIGR section VI 3rd international symposium. Naples, Italy.

Bouchon, P. (2002). Modeling oil uptake during frying. PhD thesis, Reading University, England.

Bouchon, P., and Pyle, D. L. (2004). Studying oil absorption in restructured potato chips. *Journal of Food Science*, 69(3), 115-122.

Bouchon, P., and Pyle, D. L. (2005). Modelling oil absorption during post-frying cooling II: Solution of the mathematical model, model testing and simulations. *Food and Bioproduct Processing*. 83, 261-272.

Bouchon, P., Aguilera, J. M., and Pyle, D. L. (2003). Structure oil-absorption relationships during deep-fat frying. *Journal of Food Science*, 68(9), 2711-2716.

Bourne, M. C., Moyer, J. C., and Hand, D. D. (1966). Measurement of food texture by a universal testing machine. *Food Technology*, 57, 89-92.

Cape, J. N., and Percy, E. (1996). The interpretation of leaf-drying curve. *Plant Cell and Environment*, 19(3), 356-361.

Chang, S. S., Peterson, R. J., and Ho, C. T. (1978). Lipids as a source of flavour. (M. K. Supran, Ed.) USA: American Chemical Society.

Charoensiri, R., Kongkachuichai, R., Suknicom, S., and Sungpuag, P. (2009). Beta-carotene, lycopene, and alpha=tocopherol contents of selected Thai fruits. *Food Chemistry*, 113(1), 202-207.

Cheng, F. J., and Peng, K. J. (2006). United States Patent No. 7053346.

Chitrakar, B., Zhang, M., and Fan, D. (2019). The synergistic effect of ultrasound and microwave on the physical, chemical, textural, and microstructural properties of vacuum fried Chinese yam (Dioscorea polystachya). *Journal of Food Processing and Preservation*, 42(2), e14073.

Costa, R. M., Oliveira, F. R., and Boutcheva, G. (1997). Structural changes and shrinkage of potato during frying. *International Journal of Food Science & Technology*, 36(1), 11-23.

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

Dadali, G., Apar, D. K., and Özbek, B. (2007). Color change kinetics of okra undergoing microwave drying. *Drying Technology*, 25(5), 925-936.

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

Datta, A. K. (2007). Porous media approaches to studying simultaneous heat and mass transfer in food processes. II: Property data and representative results. *Journal of Food Engineering*, 80(1), 96-110.

Davidson, A. (1999). The Oxford Companion to Food. Oxford: Oxford University Press.

Demir, V., Gunhan, T., and Yagcioglu, A. K. (2007). Mathematical modelling of convection drying of green table olives. *Biosystem Engineering*, 98(1), 47-53.

Demirhan, E., and Ozbek, B. (2010). Drying kinetics and effective moisture diffusivity of purslane undergoing microwave heat treatment. *Korean Journal of Chemical Engineering*, 27(5), 1377-1383.

Diamante, L. M. (2008). Vacuum fried jackfruit: effect of maturity, pre-treatment and processing on the physiochemical and sensory. In Annual Scientific Meeting of the Nutrition Society of Australia. New Zealand: Nutrition Society of New Zealand (Inc).

Doymaz, I. (2004). Drying kinetics of white mulberry. *Journal of Food Engineering*, 61(3), 341-346.

Doymaz, I., and Ismail, O. (2011). Drying characteristics of sweet cherry. *Food and Bioproducts Processing*, 89(1), 31-38.

Dubois, M., Gilles, K. A., Hamilton, J. K., Rebers, P. A., and Smith, F. (1956). Colorimeter method for determination of sugars and related substances. *Analytical Chemistry*, 28(3), 350-356.

Dueik, V., and Bouchon, P. (2011). Development of healthy low-fat snacks: understanding the mechanisms of quality changes during atmospheric and vacuum frying. *Food Reviews International*, 27, 408-432.

Energy Policy and Planning Office. (2022). LPG Price 9 Nov 2022. Available from: http://www.eppo.go.th/index.php/en/. Accessed November 2022.

Ertekin, C., and Yaldiz, O. (2004). Drying of eggplant and selection of a suitable thin layer drying model. *Journal of Food Engineering*, 63(3), 349-359.

Ertekin, C., and Ziya Firat, M. (2015). A Comprehensive Review of Thin Layer Drying Models Used in Agricultural Products. *Critical Reviews in Food Science and Nutrition*, 57(4), 701-717.

Farkas, B. E., Singh, R. P., and Rumsey, T. R. (1996). Modeling heat and mass transfer in immersion frying: Part I: Model development. *Journal of Food Engineering*, 29(2), 211-226.

FDA, U. F. (2016). Microwave Oven Radiation. Available from: https://www.fda.gov/radiation-emittingproducts/resourcesforyou radiationemittingproducts/ ucm252762.htm. Accessed March 2017.

Fellows, P. (1988). Food processing technology: Principles and Practice. England: Ellis Horwood.

Fu, Y., Liu, W., and Soladoye, O. P. (2021). Towards innovative food processing of flavonoid compounds: Insights into stability and bioactivity. *LWT-Food Science and Technology*, 150, 111968.

Garayo, J., and Moreira, R. G. (2002). Vacuum frying of potato chips. *Journal of Food Engineering*, 55(2), 181-191.

Gasik, L. (2014). The Durian Tourist's Guide to Thailand: Volume 1 of The Durian Tourist. Available from yearofthedurian.com/books. Accessed February 2017.

Gould, G. W. (1995). Biodeterioration of foods and an overview of preservation in food and dairy industries. *International Bioderioration and Biodegradation*, 36(3-4), 267-277.

Granda, C., Moreira, R., and Tichy, S. E. (2004). Reduction of acrylamide formation in potato chips by low-temperature vacuum frying. *Journal of Food Science*, 69(8), 405-411.

Gupta, M. K. (2005). Bailey's industrial oil & fat products (6th ed., Vol. 4). (F. Shahidi, Ed.) Canada: Wiley-Interscience.

Gupta, M. K., Grant, R., and Stier, R. F. (2004). Critical factors in the selection of an industrial fryer. In M. K. Gupta, K. Warner, & P. J. White (Eds.), Frying technology and practices (pp. 91-109). Champaign, IL: AOCS Press.

Heldman, R. (1992). Global telecommunications (ed.): Layered networks' layered services. Newyork: McGraw-Hill.

Henderson, S. M., and Pabis, S. (1961). Grain drying theory (I) Temperature effect on drying coefficient. *Journal of Agricultural Engineering Research*, 6(3), 169-174.

Hill, K. A., and Pyke, N. (1997). Influence of commercial drying in maize grain attributes-1997. Available from Foundation for arable research (far) arable update no. 10: https://www.far.org.nz/. Accessed March 2017.

Hindy, J. (2015). Durian Is The Smelliest Yet One Of The Most Nutritious Fruits In The World. Available from http://www.lifehack.org/articles/lifestyle/ 10-benefits-and-uses-durian-fruit-that-will-surprise-you.html. Accessed March 2017

How, M. (2016). 5 durian products any true S'porean would avoid. Available from http://mothership.sg/2016/12/5-durian-products-any-true-sporean-would-avoid/. Accessed March 2017.

Huang, M.-s., Zhang, M., and Bhandari, B. (2018). Synergistic effects of ultrasound and microwave on the pumpkin slices qualities during ultrasound-assisted microwave vacuum frying. *Journal of Food Process Engineering*, 42(4), e13050.

Hunterlab. (1995). Use hunterlab images and color solid figures, a color-vision system. 11491 Sunset Hills Road, Reston, VA, US.

Hutchings, J. B. (1994). Food colour and appearance. London: Blackie Academic and Professional.

International Research Rice Institute (IRRI). (2009). Paddy drying. Available from http://www.knowledgebank.irri.org/rkb/drying-basics/the-drying-process.html. Accessed March 2017

Jamradloedluk, J., Nathakaranakule, A., Soponronnarit, S., and Prachayawarakorn, S. (2007). Influences of drying medium and temperature on drying kinetics and quality attributes of durian chip. *Journal of Food Engineering*, 78(1), 198-205.

Jangam, S. V., Joshi, V. S., Mujumda, A. S., and Thorat, B. N. (2008). Studies of dehydration of sapota (Achras zapota). *Drying Technology*, 26(3), 369-377.

Jayas, D. S., Cenkowski, S., Pabis, S., and Muir, W. E. (1991). *Review of thin-layer drying and rewetting equations. Drying* Technology, 9(3), 551-558.

Jiang, H., Zhang, M., and Mujumdar, A. S. (2010). Physio-chemical changes during different stages of MFD/FD banana chips. *Journal of Food Engineering*, 101(2), 140e145.

Junlakan, W. (2014). Effect of drying kinetics on the quality of vacuum-dried banana, pineapple and apple slices. PhD. Eng thesis, Department of Chemical Engineering, Prince of Songkla University.

Junlakan, W., Tirawanitchakul, S., and Yamsaengsung, R. (2016). Effects of vacuum drying on structural changes of banana, pineapples, and apples. *Journal of Food Processing and Preservation*, 41(6), e13264.

Junlakan, W., Yamsaengsung, R., and Tirawanichakul, S. (2013). Effects of vacuum drying on structural changes of banana slices. *ASEAN Journal of Chemical Engineering*, 13, 1-10.

Karathanos, V. T., and Belessiotis, V. G. (1999). Application of a thin layer equation to drying data fresh and semi-dried fruits. *Journal of Agricultural Engineering Research*, 74(4), 355-361.

Kawas, M. L., and Moreira, R. G. (2001). Characterization of product quality attributes of tortilla chips during the frying process. *Journal of Food Engineering*, 47(2), 97-107.

Kingsly, R. P., Goyal, R. K., Manikantan, M. R., and Ilyas, S. M. (2007). Effects of pretreatments and drying air temperature of drying behavior of peach slice. *International Journal of Food Science and Technology*, 42(1), 65-69.

Krokida, M. K., Oreopolou, V., and Maroulis, Z. B. (2000). Effect of frying conditions on shrinkage and porosity of fried potatoes. *Journal of Food Engineering*, 43(3), 147-154.

Landers, R. E., and Rathman, D. N. (1981). Vegetable oils: Effects of processing, storage and use on nutritional values. *Journal of the American Oil Chemists' Society*, 58, 255-259.

León, M., Silva, J., Carrasco, S., and Barrientos, N. (2020). Design, cost estimation and sensitivity analysis for a production process of activated carbon from waste nutshells by physical activation. *Processes*, 8(8), 945.

Lewis, W. K. (1921). The rate of drying of solid materials. *Journal of Industrial and Engineering Chemistry*, 13(5), 427-432.

Ling, D., Gennadios, A., Hanna, M. A., and Cuppett, S. L. (1998). Quality evaluation of deep-fat fried onion rings. *Journal of Food Quality*, 21(2), 95-105.

Luikov, A. V. (1996). Heat and Mass Transfer in Capillary-Porous Bodies. Oxford: PERGAMO N PRESS.

Lumanlan, J. C., Binosha Fernando, W. M. A. D., and Jayasena, V. (2019). Mechanisms of oil uptake during deep frying and applications of predrying and hydrocolloids in reducing fat content of chips. *International Journal of Food Science and Technology*. 55, 1661-1670.

Mainland High School ISTF. (2017). Microwave Properties. Available from http://mainland.cctt.org/istf2008/microwaves.asp. Accessed March 2017

Mariscal, M., and Bouchon, P. (2008). Conparison between atmospheric and vacuum frying of apple slices. *Food Chemistry*, 107(4), 1561-1569.

Marmesat, S., Rodrigues, E., Velasco, J., and Dobarganes, M. C. (2005). Performance of sunflower oil with high level of oleic and palmitic acids during industrial frying of almonds, peanuts and sunflower seeds. *Journal of the American Oil Chemist Society*, 82, 505-510.

Mehta, U., and Swinburn, B. (2001). A review of factors affecting fat absorption in hot chips. Crit. Rev. *Food Science and Nutrition*, 41, 133-154.

Mellema, M. (2003). Mechanism and reduction of fat uptake in deep-fat fried foods. *Trends in Food Science and Technology*, 14(9), 364-373.

Midilli, A., Kucuk, H., and Yapar, Z. (2002). A new model for single layer drying. *Drying Technology*, 20(7), 1503-1513.

Mohammadi, A., Rafiee, S., Keyhani, A., and Emam-Djomeh, Z. (2008). Estimation of Thin-layer Drying Characteristics of Kiwifruit (cv. Hayward) with Use of Page's Model. *Journal of Agricultural and Environmental Science*, 3(5), 802-805.

Mojaharul Islam, M., Zhang, M., Bhandari, B., and Guo, Z. (2019). A hybrid vacuum frying process assisted by ultrasound and microwave to enhance the kinetics of moisture loss and quality of fried edamame. *Food and Bioproducts Processing*, 118, 326-335.

Montagne, P. (2001). Larousse Gastronomique. Newyork: Clarkson Potter.

Moreira, R. G. (2014). Vacuum frying versus conventional frying. *European Journal of Lipid Science and Technology*, 116(6), 723-734.

Moreira, R. G., Castell-Perez, M. E., and Barrufet, M. A. (1999). Deep-far frying: Fundamentals and applications. Gaithersburg, MD: Aspen.

Moreira, R. G., Sun, X., and Chen, Y. (1997). Factors affecting oil uptake in tortilla chips in deep-fat frying. *Journal of Food Engineering*, 31(4), 485-498.

Moreira, R., Chenlo, F., and Torres, M. D. (2017). Statistical criteria for modelling of water desorption isotherms of sugars. Estimation of Sucrose Hygroscopic Properties from Glucose and Fructose Data. *Advances in Food Science and Engineering*, 1, 18-27.

Mujumdar, A. S., and Menon, A. s. (1995). Handbook of Industrial Drying. Boca Raton: CRC Press.

Nathakaranakule, A., Jaiboon, P., and Soponronnarit, S. (2010). Far-infrared radiation assisted drying of longan fruit. *Journal of Food Engineering*, 100(4), 662-668.

Nathakaranakule, A., Paengkanya, S., and Soponronnarit, S. (2019). Durian chips drying using combined microwave techniques with step-down microwave power input. *Food and Bioproducts Processing*, 116, 105-117.

Nguyen, T. L., Nguyen, P. D., Luu, X. C., Huynh, B. L., Krishnan, S., and Huynh, P. T. (2019). Kinetics of nutrient change and color retention during low-temperature microwave=assisted drying of bitter melon (Momordica charantia L.). *Journal of Food Processing and Preservation*, 43(12), e14279.

Nimmol, C., Devahastin, S., Swasdisevi, T., and Soponronnarit, S. (2007). Drying and heat transfer behavior of banana undergoing combined low-pressure superheated steam and far-infrared radiation drying. *Journal of Applied Thermal Engineering*, 27(14-15), 2483-2494.

Niponsak, A., Laohakunjit, N., Kerdchoechuen, O., Wongsawadee, P., and Uthairatanakij, A. (2020). Novel ripeness label based on starch/chitosan incorporated with pH dye for indicating eating quality of fresh-cut durian. *Food Control*, 107, 106785.

Office of Agricultural Economics, Thailand. (2021). Import-export statistic. Available from https://www.oae.go.th/. Accessed January 2022

Ophithakorn, T., and Yamsaengsung, R. (2003). Oil absorption during vacuum frying of fish tofu. In Proceeding from the PSU-UNS International Conference 2003, Energy and Environment. Hatyai, Thailand.

Orikasa, T., Koide, S., Sugawara, H., Yoshida, M., Kato, K., Matsuchima, U., Okada, M., Waranabe, T., Ando, Y., Shiina, T., and Tagawa, A. (2018). Applicability of vacuum-microwave drying for tomato fruit based on evaluations of energy cost, color, functional components, and sensory qualities. *Journal of Food Processing and Preservation*, 42(6), e13625.

Ozbek, B., and Dadali, G. (2007). Thin-layer drying characteristics and modeling of mint leaves undergoing microwave treatment. *Journal of Food Science*, 83(4), 541-549.

Oztop, M., Sahin, S., and Sumnu, G. (2007). Optimization of microwave frying of potato slices by using taguchi technique. *Journal of Food Engineering*, 79(1), 83-91.

Paengkanya, S., Soponronnarit, S., and Nathakaranakule, A. (2015). Applications of microwaves for drying of durian chips. *Food and Bioproducts Processing*, 96, 1-11.

Page, C. (1949). Factors influencing the maximum rate of drying shelled corn in layers. Dissertation, Purdue University, M.Sc., Indiana, USA.

Panyawong, S., and Devahastin, S. (2007). Determination of deformation of a food product undergoing different drying methods and conditions via evolution of a shape factor. *Journal of Food Engineering*, 78(1), 151-161.

Paradise, A. J., and Nawar, W. W. (1981). A gas chromatographic method for the assessment of used frying oils: Comparison with other methods. *Journal of the American Oil Chemists' Society*, 58(5), 635-638.

Parti, M. (1993). Selection of mathematical model for drying grain in thin-layers. *Journal of Agricultural Engineering Research*, 54(4), 339-352.

Pedreschi, F. (2012). Frying of Potatoes: Physical, chemical, and microstructural changes. *Drying Technology*, 30(7), 707-725.

Pedreschi, F., and Moyano, P. (2005). Oil uptake and texture development in fried potato slices. *Journal of Food Engineering*, 70(4), 557-563.

Pedreschi, F., Aguilera, J. M., and Brown, C. A. (2000). Characterization of food surfaces using scale-sensitive fractal analysis. *Journal of Food Process Engineering*, 23(2), 127-143.

Pedreschi, F., Aguilera, J. M., and Pyle, L. (2001). Textural characterization and kinetics of potato strips during frying. *Journal of Food Science*, 66, 314-318.

Pinthus, E. J., Weinberg, P., and Saguy, I. S. (1992). Gel-strength in restructured potato products affects oil uptake during deep-fat frying. *Journal of Food Science*, 57(6), 1359-1360.

Pinthus, E. J., Weinberg, P., and Saguy, I. S. (1995). Oil uptake in deep fat frying as affected by porosity. *Journal of Food Science*, 60(4), 767-772.

Puente-Díaz, L., Ah-Hen, K., Vega-Gálvez, A., Lemus-Mondaca, R., and Scala, K. D. (2013). Combined infrared-convective drying of murta (Unagi milinae

Turcz) berries: kinetic modeling and quality assessment. *Drying Technology*, 31(3), 329-338.

Ross, K. A., and Scanlon, M. G. (2004). A fracture mechanics analysis of the texture of fried potato crust. *Journal of Food Engineering*, 62(4), 417-423.

Saeed, I. E., Sopian, K., and Zainol Abidin, Z. (2008). Thin-layer drying of Roselle (I): Mathematical modeling and drying experiments. Agricaltural Engineering International: the CIGR Ejournal, Manuscript FP 08 015. Vol.X.

Saguy, I. S., and Dana, D. (2003). Integrated approach to deep fat frying: Engineering, nutrition, health and consumer aspects. *Journal of Food Engineering*, 56(2-3), 143-152.

Sahin, S., and Sumnu, S. G. (2009). Advanced in Deep-Fat Frying of Foods. New York: CRC Press.

Salvatori, D., Andrés, A., Chiralt, A., and Fito, P. (1998). The response of some properties of fruits to vacuum impregnation. *Journal of Food Process Engineering*, 21(1), 59-73.

Segnini, S., Dejmek, P., and Öste, R. (1999). Reproducible texture analysis of potato chips. *Journal of Food Science*, 64(2), 309-312.

Shi, H., Zhang, M., and Yang, C. (2019). Effect of low-temperature vacuum frying assisted by microwave on the property of fish fillets (Aristichthys nobilis). *Journal of Food Process Engineering*, 42(4), e13050.

Shyu, S. L., Hau, L. B., and Hwang, L. S. (2005). Effects of processing conditions on the quality of vacuum-fried carrot chips. *Journal of the Science of Food and Agriculture*, 85(11), 1903-1908.

Siriboon, N., and Banlusilp, P. (2004). A study on the ripening process of 'Namwa' banana. *AU Journal of Technology*, 7, 159-164.

Sone. (2011). Advertisement, Craving, Frozen Dissatisfaction. Available from https://stinkyspikes.wordpress.com/tag/thailand/. Accessed March 2017

Stevenson, S. G., Vaisey-Genser, M., and Eskin, N. M. (1984). Quality control in the use of deep-frying oils. *Journal of the American Oil Chemists' Society*, 61, 1102-1108.

Su, Y., Zhang, M., Fang, Z., and Zhang, W. (2017). Analysis of dehydration kinetics, status of water and oil distribution of microwave-assisted vacuum frying potato chips combined with NMR and confocal laser scanning microscopy. *Food Research International*, 101, 188-197.

Su, Y., Zhang, M., Zhang, W., Adhikari, B., and Yang, Z. (2016). Application of novel microwave-assisted vacuum frying to reduce the oil uptake and improve the quality of potato chips. *LWT - Food Science and Technology*, 73, 490-497.

Su, Y., Zhang, M., Zhang, W., Liu, C., and Adhikari, B. (2018). Ultrasonic microwave-assisted vacuum frying technique as a novel frying method for potato chips at low frying temperature. *Food and Bioproducts Processing*, 108, 95-104.

Sun, D. (1999). Comparison and selection of EMC/ERH isotherm equations for rice. *Journal of Stored Products Research*, 35(3), 249-264.

Swasdisevi, T., Devahastin, S., Ngamchum, R., and Soponronnarit, S. (2007). Optinization of a drying process using infrared vacuum drying of Cavendish banana slices. Songklanakarin *Journal of Science and Technology*, 29(3), 809-816.

Szczesniak, A. S. (1963). Classification of textural characteristics. *Journal of Food Science*, 28(4), 385-389.

Teruel, M. R., García-Segovía, P., Martínez-Monzó, J., Linares, M. B., and Dolores, M. D. (2014). Use of vacuum-frying in chicken nugget processing. *Innovative Food Science & Emerging Technologies*, 26(5), 482-489.

Thompson, R. A., and Foster, G. H. (1963). Stress cracks and breakage in artificially dried corn. Available from United States Department of Agriculture. Marketing research report no. 631: https://www.ars.usda.gov/. Accessed March 2017.

Thongcharoenpipat, C., and Yamsaengsung, R. (2021). Physiochemical properties of vacuum fried durian (Durio Zibethinus Murr.) chips combined with microwave heating. the 9th International Conference on Engineering and Technology. Krabi, Thailand.

Thongcharoenpipat, C., and Yamsaengsung, R. (2022). Improving the Drying Kinetics and Microstructure of Vacuum Fried Ripened Durian Chips. *International Journal of Food Science and Technology*, 57(5), 2862-2871.

Thuwapanichayanan, R., Prachayawarakorn, S., and Soponronnarit, S. (2012). Effects of foaming agents and foam density on drying characteristics and textural property of banana foams. *LWT - Food Science and Technology*, 47(2), 348-357.

Toğrul, I. T., and Pehlivan, D. (2004). Modelling of thin layer drying kinetics of some fruits under open-air sun drying process. *Journal of Food Engineering*, 65(3), 413-425.

TPUB. (2007). Food deterioration. Available from http://armymedical.tpub.com/MD0723/index.htm. Accessed March 2017.

U.S. Department of Agricultural Research Service. (2016). USDA National Nutrient Database for Standard Reference. Available from https://ndb.nal.usda.gov/ndb/search/list. Accessed February 2017.

United Nations Industrial Development Organization. (2012). Quality of dried foods and deteriorative reactions during drying. Available from http://www.unido.org/fileadmin/import/32142_31QualityiofDriedFoods.14.pdf. Accessed March 2017.

Velasco, J., Marmesat, S., Márquez-Ruiz, G., and Dobarganes, M. C. (2004). Formation of short-chain glycerol-bound oxidation compounds and oxidised monomeric triacylglycerols during deep-frying and occurrence in used frying fats. *European Journal of Lipid Science and Technology*, 106(11), 728-735.

Velez-Ruiz, J. F., and Sosa-Morales, M. E. (2003). Evaluation of physical properties of dough of donut during deep-fat frying at different temperatures. *International Journal of Food Properties*, 6(2), 341-353.

Villamizar, R. V., Quiceno, M. G., and Giraldo, G. G. (2012). Effect of vacuum frying process on the quality of a snack of mango (Manguiferaindica L.). *ACTA AGRONÓMICA*, 61(1), 40-49.

Waimaleongora-Ek, C., and Chen, T. C. (1983). Effects of shortening color, frying temperature and coating ingredients on color of fried chicken parts. *Poultry Science*, 62(5), 793-797.

Waltner, A. (2019). Durian Fruit – Why it smells so bad and other interesting facts. Available from https://www.swedishnomad.com/durian-fruit/. Accessed May 2022.

Wang, J. (2010). Vapor pressure of water (mmHg). Available from http://www.docstoc.com/docs/34118783/Vapor-Pressure-of-Water-(mm-Hg). Accessed March 2017.

Wu, L., Orikasa, T., Ogawa, Y., and Tagawa, A. (2007). Vacuum drying characteristics of eggplants. *Journal of Food Engineering*, 83(3), 422-429.

Xu, G., Yin, H., He, X., Wang, D., Zhao, Y., and Yue, J. (2019). Optimization of microwave vacuum drying of okra and the study of the product quality. *Journal of Food Process Engineering*, 43(2), e13337.

Yamsaengsung, R., and Moreira, R. G. (2002a). Modeling the transport phenomena and structural changes during deep fat frying Part I: model development. *Journal of Food Engineering*, 53, 1-10.

Yamsaengsung, R., and Moreira, R. G. (2002b). Modeling the transport phenomena and structural changes during deep-fat frying: Part II: Model solution and validation. *Journal of Food Engineering*, 53(1), 11-25.

Yamsaengsung, R., Ariyapuchai, T., and Prasertsit, K. (2011). Effects of vacuum frying on structural changes of bananas. *Journal of Food Engineering*, 106(4), 298-305.

Yamsaengsung, R., Rungsee, C., and Prasertsit, K. (2008). Simulation of the heat and mass transfer processes during the vacuum frying of potato chips. Songklanakarin *Journal of Science and Technology*, 30(1), 109-115.

Yamsaengsung, R., Yaeed, S., and Ophithakorn, T. (2017). Vacuum frying of fish tofu and effect on oil quality usage life. *Journal of Food Process Engineering*, 40(6), e12587.

Yan, S. H., Yin, Y. P., Li, W. Y., Liang, T. B., Wu, Y. H., Geng, Q. H., and Wang, Z. L. (2008). Effect of high temperature after anthesis on starch formation of two wheat cultivars differing in heat tolerance. *Ace Ecologica Sinica*, 28, 6138-6147.

Yi, T. X., Misran, A., Whye, C. K., Daim, L. J., Ding, P., and Dek, M. P. (2020). Postharvest quality indices of different durian clones at ripening stage and their volatile organic compounds. *Scientia Horticulturae*, 264, 109169.

Zamora, R., and Hidalgo, F. J. (2005). Coordinate contribution of lipid oxidation and maillard reaction to the nonenzymatic food browning. *Critical Reviews in Food Science and Nutrition*, 45(1), 49-59.

Zhang, J., Zhang, M., Shan, L., and Fang, Z. (2007). Microwave-vacuum heating parameters for processing savory crisp bighead carp (Hypophthalmichthys nobilis) slices. *Journal of Food Engineering*, 79(3), 885-891.

APPENDICES

Appendix A

Experimental Data

A.1 Drying data of fried durian in vacuum system

Table A.1 Data of vacuum frying (VF) durian Day 1 at different frying temperatures.

Frying time (s)	MR of VF (90°C)				MR of VF (100°C)				MR of VF (110°C)			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
30	0.735	0.742	0.722	0.733	0.663	0.654	0.666	0.661	0.639	0.644	0.631	0.638
60	0.623	0.618	0.604	0.615	0.523	0.531	0.506	0.520	0.490	0.496	0.490	0.492
120	0.388	0.374	0.375	0.379	0.365	0.359	0.368	0.364	0.258	0.266	0.268	0.264
180	0.268	0.271	0.268	0.269	0.197	0.203	0.194	0.198	0.141	0.139	0.134	0.138
240	0.158	0.163	0.159	0.160	0.159	0.161	0.154	0.158	0.105	0.098	0.106	0.103
300	0.114	0.110	0.106	0.110	0.101	0.094	0.093	0.096	0.063	0.055	0.056	0.058
360	0.069	0.059	0.067	0.065	0.083	0.077	0.083	0.081	0.044	0.039	0.037	0.040
420	0.052	0.048	0.041	0.047	0.050	0.043	0.045	0.046	0.029	0.024	0.022	0.025
480	0.042	0.043	0.038	0.041	0.030	0.026	0.028	0.028				
540	0.030	0.027	0.027	0.028								

MR, moisture ratio; VF, vacuum frying.

Table A.1 Data of vacuum frying (VF) durian Day 1 at different frying temperatures (cont.).

Frying time (s)	MR of VF (120°C)			
	Sample 1	Sample 2	Sample 3	Average
0	1.000	1.000	1.000	1.000
30	0.577	0.569	0.567	0.571
60	0.440	0.437	0.431	0.436
120	0.215	0.218	0.209	0.214
180	0.106	0.098	0.096	0.100
240	0.074	0.070	0.072	0.072
300	0.053	0.054	0.046	0.051
360	0.033	0.029	0.034	0.032
420	0.027	0.020	0.028	0.023

MR, moisture ratio; VF, vacuum frying.

Table A.2 Data of frying durian Day 1 at different frying conditions (110°C).

Frying time (s)	MR of VF				MR of P+VF				MR of MWVF			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
30	0.639	0.644	0.631	0.638	0.598	0.590	0.603	0.597	0.582	0.571	0.557	0.570
60	0.490	0.496	0.490	0.492	0.433	0.437	0.438	0.436	0.378	0.374	0.409	0.387
120	0.258	0.266	0.268	0.264	0.191	0.193	0.186	0.190	0.184	0.195	0.203	0.194
180	0.141	0.139	0.134	0.138	0.117	0.112	0.110	0.113	0.092	0.103	0.111	0.102
240	0.105	0.098	0.106	0.103	0.065	0.069	0.058	0.064	0.065	0.055	0.048	0.056
300	0.063	0.055	0.056	0.058	0.034	0.029	0.036	0.033	0.023	0.025	0.015	0.021
360	0.044	0.039	0.037	0.040	0.027	0.020	0.031	0.026				
420	0.029	0.024	0.022	0.025								

MR, moisture ratio; VF, vacuum frying; P+VF, pre-treatment prior to vacuum frying; MWVF, microwave-assisted vacuum frying.

Table A.3 Data of microwave-assisted vacuum frying (MWVF) durian Day 1 at different microwave power level (110°C).

Frying time (s)	MR of MWVF (400W)				MR of MWVF (480W)				MR of MWVF (560W)			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
30	0.639	0.642	0.627	0.636	0.625	0.623	0.597	0.615	0.582	0.571	0.557	0.570
60	0.513	0.508	0.497	0.506	0.448	0.451	0.469	0.456	0.378	0.374	0.409	0.387
120	0.286	0.271	0.280	0.279	0.271	0.263	0.231	0.255	0.184	0.195	0.203	0.194
180	0.144	0.152	0.154	0.150	0.176	0.162	0.142	0.160	0.092	0.103	0.111	0.102
240	0.108	0.097	0.080	0.095	0.075	0.069	0.093	0.079	0.065	0.055	0.048	0.056
300	0.065	0.071	0.044	0.060	0.064	0.052	0.049	0.055	0.023	0.025	0.015	0.021
360	0.038	0.034	0.024	0.032	0.039	0.043	0.026	0.036				
420	0.030	0.024	0.021	0.025	0.024	0.023	0.013	0.020				

Frying time (s)	MR of MWVF (640W)			
	Sample 1	Sample 2	Sample 3	Average
0	1.000	1.000	1.000	1.000
30	0.563	0.541	0.540	0.548
60	0.368	0.374	0.380	0.374
120	0.186	0.180	0.174	0.180
180	0.082	0.071	0.075	0.076
240	0.031	0.029	0.024	0.028
300	0.021	0.017	0.019	0.019

MR, moisture ratio; MWVF, microwave-assisted vacuum frying.

Table A.4 Data of microwave-assisted vacuum frying durian at 110°C, 560W of various ripeness samples.

Frying time (s)	MR of durian Day 1				MR of durian Day 2				MR of durian Day 3			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
30	0.582	0.571	0.557	0.570	0.613	0.596	0.591	0.600	0.689	0.695	0.707	0.697
60	0.378	0.374	0.409	0.387	0.434	0.412	0.426	0.424	0.451	0.442	0.448	0.447
120	0.184	0.195	0.203	0.194	0.253	0.247	0.241	0.247	0.253	0.251	0.243	0.249
180	0.092	0.103	0.111	0.102	0.138	0.120	0.111	0.123	0.125	0.122	0.116	0.121
240	0.065	0.055	0.048	0.056	0.097	0.084	0.089	0.090	0.087	0.096	0.084	0.089
300	0.023	0.025	0.015	0.021	0.066	0.054	0.048	0.056	0.077	0.068	0.068	0.071
360					0.033	0.041	0.034	0.036	0.055	0.061	0.061	0.059
420					0.024	0.025	0.020	0.023	0.052	0.048	0.053	0.051
480									0.041	0.040	0.030	0.037

Frying time (s)	MR of durian Day 4			
	Sample 1	Sample 2	Sample 3	Average
0	1.000	1.000	1.000	1.000
60	0.778	0.792	0.740	0.770
120	0.544	0.533	0.516	0.531
240	0.286	0.279	0.296	0.287
360	0.134	0.126	0.133	0.131
480	0.092	0.089	0.104	0.095
600	0.076	0.082	0.067	0.075
720	0.065	0.059	0.065	0.063
840	0.054	0.053	0.052	0.053

MR, moisture ratio.

A.2 Shrinkage Data of durian chips during frying.

Table A.5 Shrinkage data of VF durian chips Day 1 at different frying temperatures.

Frying time (s)	%Shrinkage of VF (90°C)				%Shrinkage of VF (100°C)				%Shrinkage of VF (110°C)			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	18.36	18.58	19.10	0.38	13.22	13.32	13.84	0.33	14.12	14.66	13.97	0.36
60	23.55	23.42	23.47	0.07	22.28	21.81	22.06	0.24	24.55	24.64	24.58	0.05
120	23.63	24.02	23.57	0.24	23.32	23.15	23.10	0.12	22.88	22.78	23.25	0.25
180	24.25	24.16	24.04	0.11	23.89	23.42	23.37	0.29	22.11	22.23	22.56	0.23
240	24.18	24.56	23.77	0.40	23.21	22.79	23.30	0.27	22.55	22.58	22.49	0.05
300	24.06	23.98	24.11	0.07	23.26	23.17	23.47	0.15	21.72	21.94	22.13	0.21
360	24.43	24.36	24.80	0.24	23.39	23.22	23.14	0.13	22.35	22.12	22.28	0.12
420	24.31	24.17	24.36	0.10	23.31	23.75	23.47	0.22	22.16	22.36	22.23	0.10
480	24.33	24.45	23.91	0.28	22.85	23.16	23.02	0.16				
540	24.33	24.15	24.33	0.10								

VF, vacuum frying.

Table A.5 Shrinkage data of VF durian chips Day 1 at different frying temperatures (cont.).

Frying time (s)	%Shrinkage of VF (120°C)			
	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00
30	12.56	11.94	12.13	0.32
60	25.43	25.29	25.99	0.37
120	21.55	21.13	21.49	0.23
180	22.89	22.13	22.51	0.38
240	22.43	22.38	23.17	0.44
300	22.16	22.29	21.76	0.28
360	22.15	22.65	22.79	0.34
420	22.41	22.29	22.20	0.11

VF, vacuum frying.

Table A.6 Shrinkage data of fried durian chips Day 1 at different frying conditions (110°C).

Frying time (s)	%Shrinkage of VF				%Shrinkage of P+VF				%Shrinkage of MWVF			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	14.12	14.66	13.97	14.25	14.22	14.23	13.94	14.12	16.12	15.86	16.05	16.01
60	24.55	24.64	24.58	24.59	24.53	24.13	24.00	24.22	24.55	24.64	24.31	24.50
120	22.88	22.78	23.25	22.97	20.32	20.02	20.32	20.22	20.88	20.78	20.92	20.86
180	22.11	22.23	22.56	22.30	21.26	21.34	20.97	21.19	21.11	20.83	21.00	20.98
240	22.55	22.58	22.49	22.54	21.55	21.90	21.95	21.80	20.55	20.58	20.70	20.61
300	21.72	21.94	22.13	21.93	21.34	21.29	21.21	21.28	21.72	21.64	21.53	21.63
360	22.35	22.12	22.28	22.25	21.44	21.25	21.51	21.40				
420	22.16	22.36	22.23	22.25								

VF, vacuum frying; P+VF, pre-treatment prior to vacuum frying; MWVF, microwave-assisted vacuum frying.

Table A.7 Shrinkage data of MWVF durian chips Day 1 at different microwave power level (110°C).

Frying time (s)	%Shrinkage of MWVF (400W)				%Shrinkage of MWVF (480W)				%Shrinkage of MWVF (560W)			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	14.76	14.98	14.90	14.88	15.22	15.32	15.06	15.20	16.12	15.86	16.05	16.01
60	24.55	24.42	24.44	24.47	23.58	23.71	23.54	23.61	24.55	24.64	24.31	24.50
120	22.13	22.02	22.09	22.08	22.32	22.25	22.03	22.20	20.88	20.78	20.92	20.86
180	21.65	21.46	21.45	21.52	21.89	21.82	21.72	21.81	21.11	20.83	21.00	20.98
240	22.68	22.56	22.62	22.62	22.71	22.79	22.72	22.74	20.55	20.58	20.70	20.61
300	21.66	21.58	21.68	21.64	22.26	22.17	22.20	22.21	21.72	21.64	21.53	21.63
360	22.30	22.36	22.24	22.30	22.39	22.22	22.32	22.31				
420	22.71	22.70	22.81	22.74	22.81	22.75	22.69	22.75				

Frying time (s)	%Shrinkage of MWVF (640W)			
	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00
30	15.56	15.84	14.47	15.29
60	24.03	24.29	23.92	24.08
120	21.55	21.13	21.19	21.29
180	20.89	21.13	21.16	21.06
240	21.43	21.38	21.45	21.42
300	20.56	20.89	21.19	20.88

MWVF, microwave-assisted vacuum frying.

Table A.8 Shrinkage data of MWVF durian chips Day 1 at 110°C, 560W of different ripeness samples.

Frying time (s)	%Shrinkage of durian Day 1				%Shrinkage of durian Day 2				%Shrinkage of durian Day 3			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	16.12	15.86	16.05	16.01	16.18	16.15	15.94	16.09	12.24	12.15	12.12	12.17
60	24.55	24.64	24.31	24.50	25.18	25.12	25.03	25.11	22.78	22.68	22.85	22.77
120	20.88	20.78	20.92	20.86	22.46	22.36	22.47	22.43	20.18	20.26	20.16	20.20
180	21.11	20.83	21.00	20.98	21.35	21.41	21.23	21.33	19.78	19.66	19.72	19.72
240	20.55	20.58	20.70	20.61	20.65	20.54	20.55	20.58	19.06	19.03	18.94	19.01
300	21.72	21.64	21.53	21.63	21.66	21.45	21.57	21.56	19.44	19.52	19.48	19.48
360					21.12	21.03	21.15	21.10	20.16	20.01	20.01	20.06
420					21.50	21.44	21.53	21.49	19.64	19.63	19.59	19.62
480									19.22	19.30	19.32	19.28

Frying time (s)	%Shrinkage of durian Day 4			
	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00
60	10.65	10.72	10.64	10.67
120	18.95	18.77	19.10	18.94
240	17.85	17.74	17.81	17.80
360	17.67	17.53	17.78	17.66
480	17.67	17.85	17.76	17.76
600	17.23	17.34	17.06	17.21
720	16.83	16.74	16.89	16.82
840	17.59	17.44	17.50	17.51

A.3 Colorimetric data of fried durian chips

Table A.9 Lightness (L^*), redness (a^*), and yellowness (b^*) value of VF durian chips Day 1 at different frying temperatures.

Sample	Frying temperature (°C)	L^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (L_0)	-	90.36	90.53	90.13	90.34
VF durian chips	90	77.15	79.39	82.36	79.63
	100	78.32	75.58	75.69	76.53
	110	69.85	71.75	73.61	71.74
	120	61.47	62.78	65.64	63.30

Sample	Frying temperature (°C)	a^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (a_0)	-	0.66	0.59	0.49	0.58
VF durian chips	90	-1.24	-1.62	-1.53	-1.46
	100	-1.49	-1.12	-1.27	-1.29
	110	-1.58	-1.76	-1.51	-1.62
	120	3.63	3.71	4.82	4.05

Sample	Frying temperature (°C)	b^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (b_0)	-	27.26	27.17	27.08	27.17
VF durian chips	90	23.11	22.48	25.18	23.59
	100	26.95	23.41	21.24	23.87
	110	26.29	25.08	25.33	25.57
	120	28.41	27.57	29.64	28.54

VF, vacuum frying

L_0, a_0, and b_0 = the lightness value, red-green, and yellow-blue value of the fresh sample, respectively.

L^*, a^*, and b^* = the lightness value, red-green, and yellow-blue value of the fried sample, respectively.

Table A.10 Lightness (L^*), redness (a^*), and yellowness (b^*) value of P+VF durian chips Day 1 at different frying temperatures.

Sample	Frying temperature (°C)	L^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (L_0)	-	90.36	90.53	90.13	90.34
P+VF durian chips	90	76.91	81.33	80.34	79.53
	100	77.34	76.18	76.52	76.68
	110	70.14	71.22	73.02	71.46
	120	66.34	65.71	63.08	65.04

Sample	Frying temperature (°C)	a^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (a_0)	-	0.66	0.59	0.49	0.58
P+VF durian chips	90	-0.59	-0.68	-1.11	-0.79
	100	-1.14	-0.96	-0.67	-0.92
	110	0.44	-0.35	-1.14	-0.35
	120	2.34	2.99	3.15	2.83

Sample	Frying temperature (°C)	b^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (b_0)	-	27.26	27.17	27.08	27.17
P+VF durian chips	90	25.34	27.61	24.22	25.72
	100	25.91	22.04	26.22	24.72
	110	26.34	27.85	27.11	27.1
	120	27.63	29.14	29.26	28.68

VF, vacuum frying; P+VF, pre-treatment prior to vacuum frying; MWVF, microwave-assisted vacuum frying.

L_0, a_0, and b_0 = the lightness value, red-green, and yellow-blue value of the fresh sample, respectively.

L^*, a^*, and b^* = the lightness value, red-green, and yellow-blue value of the fried sample, respectively.

Table A.11 Lightness (L^*), redness (a^*), and yellowness (b^*) value of MWVF (560W) durian chips Day 1 at different frying temperatures.

Sample	Frying temperature (°C)	L^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (L_0)	-	90.36	90.53	90.13	90.34
MWVF durian chips	90	83.14	79.59	80.18	80.97
	100	77.61	78.24	75.94	77.26
	110	76.14	75.23	72.82	74.73
	120	64.72	65.25	67.59	65.85

Sample	Frying temperature (°C)	a^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (a_0)	-	0.66	0.59	0.49	0.58
MWVF durian chips	90	-1.66	-1.65	-1.73	-1.68
	100	-1.88	-0.74	-0.23	-0.95
	110	-1.84	-1.66	-1.54	-1.68
	120	3.16	2.83	3.28	3.09

Sample	Frying temperature (°C)	b^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (b_0)	-	27.26	27.17	27.08	27.17
MWVF durian chips	90	25.34	25.18	21.33	23.95
	100	25.19	24.17	28.36	25.91
	110	27.14	27.26	28.81	27.74
	120	27.83	27.58	28.84	28.08

MWVF, microwave-assisted vacuum frying.

L_0, a_0, and b_0 = the lightness value, red-green, and yellow-blue value of the fresh sample, respectively.

L^*, a^*, and b^* = the lightness value, red-green, and yellow-blue value of the fried sample, respectively.

Table A.12 Lightness (L^*), redness (a^*), and yellowness (b^*) value of MWVF durian chips Day 1 at different microwave power.

Sample	Microwave power (W)	L^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (L_0)	-	90.36	90.53	90.13	90.34
MWVF durian Day 1	400	73.11	72.34	74.52	73.32
	480	75.14	72.93	71.14	73.07
	560	76.14	75.23	73.82	75.06
	640	74.32	75.25	73.59	74.39

Sample	Microwave power (W)	a^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (a_0)	-	0.66	0.59	0.49	0.58
MWVF durian Day 1	400	-1.60	-0.44	-1.12	-1.05
	480	-1.84	-1.64	-1.74	-1.74
	560	-1.84	-1.66	-1.54	-1.68
	640	-1.86	1.63	1.48	0.42

Sample	Microwave power (W)	b^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (b_0)	-	27.26	27.17	27.08	27.17
MWVF durian Day 1	400	23.48	23.45	26.71	24.55
	480	26.31	23.14	24.22	24.56
	560	22.14	23.26	23.81	23.07
	640	24.33	23.58	24.14	24.02

MWVF, microwave-assisted vacuum frying.

L_0, a_0, and b_0 = the lightness value, red-green, and yellow-blue value of the fresh sample, respectively.

L^*, a^*, and b^* = the lightness value, red-green, and yellow-blue value of the fried sample, respectively.

Table A.13 Lightness (L^*), redness (a^*), and yellowness (b^*) value of MWVF durian chips Day 2 at different microwave power.

Sample	Microwave power (W)	L^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (L_0)	-	87.4	87.77	86.61	87.26
MWVF durian Day 2	400	69.31	70.52	70.25	70.03
	480	69.82	70.52	71.18	70.51
	560	71.34	71.10	70.18	70.87
	640	69.11	71.23	71.71	70.68

Sample	Microwave power (W)	a^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (a_0)	-	1.15	1.23	1.13	1.17
MWVF durian Day 2	400	-1.98	-1.03	-1.77	-1.59
	480	-1.28	-1.89	-1.79	-1.65
	560	-1.20	-1.13	-1.10	-1.14
	640	-1.11	1.14	-1.48	-0.48

Sample	Microwave power (W)	b^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (b_0)	-	30.12	30.51	30.66	30.43
MWVF durian Day 2	400	27.33	28.02	25.31	26.89
	480	25.26	30.14	27.02	27.47
	560	29.18	28.91	30.22	29.44
	640	27.14	30.25	28.74	28.71

MWVF, microwave-assisted vacuum frying.

L_0, a_0, and b_0 = the lightness value, red-green, and yellow-blue value of the fresh sample, respectively.

L^*, a^*, and b^* = the lightness value, red-green, and yellow-blue value of the fried sample, respectively.

Table A.14 Lightness (L^*), redness (a^*), and yellowness (b^*) value of MWVF durian chips Day 3 at different microwave power.

Sample	Microwave power (W)	L^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (L_0)	-	86.09	86.6	87.2	86.63
MWVF durian Day 3	400	69.04	66.21	69.16	68.14
	480	70.15	68.74	66.92	68.6
	560	67.61	70.36	68.18	68.72
	640	70.11	67.23	68.71	68.68

Sample	Microwave power (W)	a^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (a_0)	-	1.34	1.45	1.29	1.36
MWVF durian Day 3	400	-1.34	-0.96	-1.28	-1.19
	480	-1.24	-1.18	-1.20	-1.21
	560	-1.34	-1.15	-1.34	-1.28
	640	1.81	-1.14	-1.48	-0.27

Sample	Microwave power (W)	b^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (b_0)	-	33.71	33.85	33.45	33.67
MWVF durian Day 3	400	30.24	27.07	29.69	29.00
	480	30.24	27.35	26.16	27.92
	560	29.18	30.92	31.81	30.64
	640	31.14	31.25	34.74	32.38

MWVF, microwave-assisted vacuum frying.

L_0, a_0, and b_0 = the lightness value, red-green, and yellow-blue value of the fresh sample, respectively.

L^*, a^*, and b^* = the lightness value, red-green, and yellow-blue value of the fried sample, respectively.

Table A.15 Lightness (L^*), redness (a^*), and yellowness (b^*) value of MWVF durian chips Day 4 at different microwave power.

Sample	Microwave power (W)	L^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (L_0)	-	84.01	83.56	83.32	83.63
MWVF durian Day 4	400	52.42	56.82	55.57	54.94
	480	56.50	54.35	55.81	55.55
	560	59.92	53.64	55.15	56.24
	640	54.22	56.35	58.12	56.23

Sample	Microwave power (W)	a^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (a_0)	-	1.40	1.33	1.41	1.38
MWVF durian Day 4	400	1.90	1.13	1.93	1.65
	480	0.71	1.87	2.19	1.59
	560	0.62	1.13	0.76	0.84
	640	2.48	2.36	2.05	2.30

Sample	Microwave power (W)	b^*			
		Sample 1	Sample 2	Sample 3	Average
Fresh (b_0)	-	38.96	38.57	38.48	38.67
MWVF durian Day 4	400	37.49	36.11	36.31	36.64
	480	36.44	34.40	33.43	34.76
	560	36.26	37.89	36.86	37.00
	640	35.46	38.11	34.12	35.90

MWVF, microwave-assisted vacuum frying.

L_0, a_0, and b_0 = the lightness value, red-green, and yellow-blue value of the fresh sample, respectively.

L^*, a^*, and b^* = the lightness value, red-green, and yellow-blue value of the fried sample, respectively.

A.4 Oil content data of fried durian chips

Table A.16 Oil content data of durian chips Day 1 at different frying temperatures.

Sample	Frying temperature (°C)	%Oil content			
		Sample 1	Sample 2	Sample 3	Average
VF durian chips	90	9.38	9.65	9.38	9.47
	100	8.13	8.24	7.84	8.07
	110	6.33	6.17	6.34	6.28
	120	6.28	6.15	6.20	6.21

Sample	Frying temperature (°C)	%Oil content			
		Sample 1	Sample 2	Sample 3	Average
P+VF durian chips	90	8.55	8.43	8.46	8.48
	100	7.69	7.48	7.78	7.65
	110	6.31	6.17	6.12	6.20
	120	6.11	6.15	6.25	6.17

Sample	Frying temperature (°C)	%Oil content			
		Sample 1	Sample 2	Sample 3	Average
MWVF durian chips	90	8.65	8.44	8.38	8.49
	100	7.86	7.74	7.80	7.80
	110	5.36	5.48	5.30	5.38
	120	5.36	5.66	5.93	5.65

VF, vacuum frying; P+VF, pre-treatment prior to vacuum frying; MWVF, microwave-assisted vacuum frying.

Table A.17 Oil content data of MWVF durian chips Day 1 at different microwave power level (110°C).

Frying time (s)	%Oil content of 400W				%Oil content of 480W				%Oil content of 560W			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	0	0	0	0	0	0	0	0.00	0	0.00	0.00	0.00
30	3.25	3.02	3.18	0.12	2.89	2.70	2.75	0.10	1.89	2.23	2.24	0.20
60	3.28	3.16	3.10	0.09	3.56	3.42	3.01	0.29	2.89	2.80	2.59	0.15
120	4.19	4.23	3.85	0.21	3.80	3.64	3.66	0.09	3.47	3.65	3.59	0.09
180	5.01	4.80	4.80	0.12	4.36	4.65	4.76	0.21	4.23	4.29	3.99	0.16
240	5.28	5.44	5.30	0.09	5.44	5.49	5.06	0.24	4.77	4.79	4.90	0.07
300	6.13	5.88	5.96	0.13	5.60	5.78	5.96	0.18	5.56	5.29	5.29	0.16
360	6.48	6.68	6.46	0.12	6.18	6.12	5.97	0.11				
420	6.58	6.40	6.73	0.17	6.41	6.09	6.49	0.21				

Frying time (s)	%Oil content of 640W			
	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00
30	2.43	2.66	2.68	0.14
60	3.02	2.89	2.79	0.12
120	3.55	3.72	3.77	0.12
180	3.89	3.78	3.82	0.06
240	4.42	4.15	4.18	0.15
300	5.13	5.34	5.13	0.12

MWVF, microwave-assisted vacuum frying.

Table A.18 Oil content data of MWVF durian chips at 110°C, 560W of different ripeness samples.

Frying time (s)	%Oil content of durian Day 1				%Oil content of durian Day 2				%Oil content of durian Day 3			
	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	1.89	2.23	2.24	0.20	2.96	2.94	2.53	0.24	2.97	2.76	2.76	0.12
60	2.89	2.80	2.59	0.15	3.35	3.14	3.17	0.11	3.61	3.78	4.04	0.22
120	3.47	3.65	3.59	0.09	3.80	3.73	3.66	0.07	4.27	4.12	4.12	0.09
180	4.23	4.29	3.99	0.16	4.66	4.52	4.08	0.30	4.55	4.67	4.37	0.15
240	4.77	4.79	4.90	0.07	4.78	4.80	5.15	0.21	4.93	4.85	4.71	0.11
300	5.56	5.29	5.29	0.16	5.65	5.67	5.54	0.07	5.27	5.02	5.16	0.13
360					5.99	6.02	5.48	0.30	6.23	6.32	6.08	0.12
420					6.34	6.19	5.89	0.23	6.88	7.01	6.48	0.28
480									7.15	7.03	6.88	0.14

Frying time (s)	%Oil content of durian Day 4			
	Sample 1	Sample 2	Sample 3	Average
0	0.00	0.00	0.00	0.00
60	4.83	4.81	4.65	0.10
120	5.29	5.14	5.02	0.14
240	6.44	6.25	6.42	0.10
360	7.95	7.86	7.83	0.06
480	9.32	9.38	9.50	0.09
600	12.23	11.96	11.60	0.32
720	13.42	13.24	13.21	0.11
840	15.17	15.02	14.87	0.15

MWVF, microwave-assisted vacuum frying.

A.5 Hardness and crispness data of fried durian chips

Table A.19 Hardness and crispness data of VF durian Day 3 at different frying temperatures.

Number of samples	VF (90°C)		VF (100°C)		VF (110°C)	
	Hardness (N)	Crispness	Hardness (N)	Crispness	Hardness (N)	Crispness
1	5.55	1.00	6.53	1.00	5.45	2.00
2	6.88	1.00	5.90	1.00	6.98	1.00
3	4.63	2.00	5.61	2.00	4.43	1.00
4	7.42	1.00	6.44	1.00	7.62	2.00
5	6.10	1.00	6.10	1.00	6.10	2.00
6	4.86	2.00	4.86	2.00	4.86	2.00
7	3.55	2.00	3.55	2.00	3.55	1.00
8	6.08	1.00	6.08	2.00	6.08	3.00
9	3.88	2.00	3.88	2.00	3.88	3.00
10	3.48	2.00	3.48	2.00	3.48	3.00
11	6.29	1.00	6.29	1.00	6.29	1.00
12	4.22	2.00	4.22	2.00	4.22	2.00
13	7.24	1.00	7.24	1.00	7.24	3.00
14	5.05	1.00	5.05	1.00	5.05	2.00
15	7.12	1.00	7.12	1.00	7.12	1.00
16	3.72	2.00	3.72	1.00	3.72	2.00
17	7.17	1.00	7.17	1.00	7.17	1.00
18	5.39	1.00	5.39	1.00	5.39	2.00
19	5.54	3.00	5.54	3.00	5.54	3.00
20	5.13	2.00	5.13	2.00	5.13	1.00
21	4.11	2.00	4.11	1.00	4.11	2.00
22	4.35	2.00	4.35	2.00	4.35	2.00
23	4.51	2.00	4.51	2.00	4.51	2.00
24	4.08	2.00	4.08	2.00	4.08	1.00
25	6.37	2.00	5.38	2.00	6.37	2.00
26	6.11	2.00	6.11	2.00	4.15	1.00
27	4.96	2.00	4.96	2.00	4.96	2.00
28	5.39	2.00	5.39	2.00	5.39	2.00
29	4.68	2.00	4.68	2.00	4.68	1.00
30	4.27	1.00	4.27	1.00	4.27	1.00
31	5.24	2.00	5.24	2.00	5.24	1.00
32	5.35	2.00	5.35	2.00	5.35	2.00
33	5.40	1.00	5.40	3.00	5.40	2.00
34	4.84	2.00	4.84	2.00	4.84	1.00
Average	5.26	1.65	5.23	1.68	5.20	1.76

VF, vacuum frying.

Table A.19 Hardness and crispness data of VF durian Day 3 at different frying temperatures (cont.).

Number of samples	VF (120°C)	
	Hardness (N)	Crispness
1	4.76	2.00
2	5.90	1.00
3	5.61	1.00
4	6.44	1.00
5	5.11	2.00
6	4.86	2.00
7	5.51	2.00
8	5.10	2.00
9	3.88	1.00
10	3.48	1.00
11	6.29	1.00
12	4.22	2.00
13	7.24	1.00
14	5.05	1.00
15	7.12	1.00
16	3.72	2.00
17	7.17	2.00
18	5.39	2.00
19	5.54	3.00
20	5.13	2.00
21	4.11	2.00
22	4.35	2.00
23	4.51	2.00
24	4.08	2.00
25	6.37	3.00
26	5.13	2.00
27	4.96	2.00
28	5.39	2.00
29	4.68	2.00
30	4.27	2.00
31	5.24	1.00
32	5.35	2.00
33	5.40	3.00
34	4.84	2.00
Average	5.18	1.79

VF, vacuum frying.

Table A.20 Hardness and crispness data of P+VF durian Day 3 at 110°C.

Number of samples	Hardness (N)	crispness
1	5.21	1
2	4.86	2
3	3.51	2
4	4.88	2
5	3.94	2
6	5.09	1
7	4.17	2
8	5.64	1
9	6.95	1
10	3.59	2
11	4.63	2
12	6.68	1
13	3.93	3
14	5.44	2
15	4.12	3
16	4.63	2
17	6.39	2
18	4.52	2
19	3.52	2
20	3.74	2
21	4.41	2
22	4.34	2
23	4.38	2
24	5.25	2
25	4.84	2
26	4.98	2
27	3.54	2
28	3.43	3
29	7.19	2
30	3.69	2
Average	4.72	1.93

P+VF, pre-treatment prior to vacuum frying.

Table A.21 Hardness and crispness data of MWVF durian Day 3 at different microwave power level (110°C).

Number of samples	MWVF (400W)		MWVF (480W)		MWVF (560W)	
	Hardness (N)	crispness	Hardness (N)	crispness	Hardness (N)	crispness
1	5.85	1.00	4.57	1.00	6.93	1.00
2	6.65	2.00	5.90	2.00	5.30	1.00
3	5.35	1.00	5.61	1.00	4.76	3.00
4	5.66	1.00	5.45	1.00	6.48	2.00
5	4.14	1.00	6.10	1.00	5.02	2.00
6	4.45	2.00	4.86	2.00	4.56	2.00
7	6.40	2.00	3.55	2.00	7.51	1.00
8	6.57	1.00	6.08	1.00	4.41	2.00
9	5.21	1.00	3.88	1.00	4.34	2.00
10	6.09	1.00	5.44	1.00	6.09	1.00
11	4.59	2.00	6.29	2.00	4.59	3.00
12	4.16	1.00	4.22	1.00	4.26	2.00
13	5.76	2.00	6.26	2.00	4.78	3.00
14	6.36	2.00	6.03	2.00	6.36	1.00
15	4.60	1.00	7.12	1.00	4.60	1.00
16	4.80	3.00	3.72	3.00	7.84	1.00
17	4.49	2.00	7.17	2.00	4.49	3.00
18	4.52	2.00	5.39	2.00	4.43	1.00
19	5.28	1.00	5.54	1.00	5.47	3.00
20	6.47	2.00	5.13	2.00	5.49	2.00
21	5.21	2.00	4.11	2.00	6.19	3.00
22	5.20	3.00	4.35	3.00	5.20	2.00
23	4.89	2.00	4.51	2.00	3.91	2.00
24	5.40	1.00	5.06	1.00	4.41	2.00
25	5.47	2.00	6.07	2.00	4.49	3.00
26	5.23	2.00	5.13	2.00	6.02	1.00
27	5.19	3.00	4.96	3.00	6.17	2.00
28	5.33	2.00	5.39	2.00	4.55	2.00
29	4.67	2.00	4.68	2.00	3.79	2.00
30	4.33	2.00	4.27	2.00	5.33	1.00
31	5.12	2.00	5.24	2.00	3.54	2.00
32	4.39	1.00	5.35	2.00	4.29	2.00
33	5.08	1.00	5.40	1.00	4.98	1.00
34	4.12	3.00	4.84	3.00	4.20	1.00
Average	5.21	1.74	5.22	1.76	5.14	1.85

MWVF, microwave-assisted vacuum frying.

Table A.21 Hardness and crispness data of MWVF durian Day 3 (110°C) at different microwave power level (cont.).

Number of samples	MWVF (640W)	
	Hardness (N)	crispness
1	5.85	1.00
2	6.65	2.00
3	5.35	1.00
4	5.66	1.00
5	4.14	1.00
6	4.45	2.00
7	6.40	2.00
8	6.57	1.00
9	5.21	1.00
10	6.09	1.00
11	4.59	2.00
12	4.16	1.00
13	5.76	2.00
14	6.36	2.00
15	4.60	1.00
16	4.80	3.00
17	4.49	2.00
18	4.52	2.00
19	5.28	1.00
20	6.47	2.00
21	5.21	2.00
22	5.20	3.00
23	4.89	2.00
24	5.40	1.00
25	5.47	2.00
26	5.23	2.00
27	5.19	3.00
28	5.33	2.00
29	4.67	2.00
30	4.33	2.00
31	5.12	2.00
32	4.39	1.00
33	5.08	1.00
34	4.12	3.00
Average	5.21	1.74

MWVF, microwave-assisted vacuum frying.

Table A.22 Hardness and crispness data of MWVF durian at 560W of different ripeness samples (110°C).

Number of samples	MWVF of Day 1		MWVF of Day 2	
	Hardness (N)	crispness	Hardness (N)	crispness
1	4.60	1.00	4.46	1.00
2	6.44	2.00	7.71	1.00
3	4.85	1.00	5.94	1.00
4	6.63	2.00	6.57	1.00
5	4.78	2.00	5.38	1.00
6	5.94	2.00	4.89	3.00
7	5.98	2.00	4.30	1.00
8	4.70	2.00	6.07	1.00
9	4.40	1.00	3.95	2.00
10	6.16	1.00	3.64	2.00
11	4.15	1.00	4.04	2.00
12	4.01	2.00	5.18	3.00
13	5.08	1.00	3.85	1.00
14	5.92	1.00	3.87	2.00
15	4.73	1.00	5.50	1.00
16	4.08	1.00	6.75	1.00
17	6.35	1.00	5.21	2.00
18	5.76	1.00	3.54	1.00
19	6.22	3.00	6.24	1.00
20	5.19	2.00	5.84	2.00
21	5.57	2.00	4.98	2.00
22	4.67	2.00	3.63	2.00
23	5.99	2.00	4.54	1.00
24	5.48	2.00	4.60	1.00
25	6.01	2.00	5.36	3.00
26	4.13	2.00	6.50	1.00
27	6.63	2.00	4.87	1.00
28	5.16	2.00	6.66	1.00
29	4.41	2.00	7.05	3.00
30	4.85	1.00	5.79	3.00
31	6.84	2.00	6.33	1.00
32	4.73	2.00	6.03	2.00
33	6.37	3.00	3.85	3.00
34	4.43	2.00	5.53	2.00
35	4.35	2.00	6.21	2.00
36	4.90	1.00	3.59	1.00
37	5.29	1.00	6.44	3.00
38	4.04	1.00	3.51	1.00
39	4.97	1.00	4.93	3.00
40	4.25	1.00	7.49	1.00
Average	5.23	1.63	5.27	1.68

MWVF, microwave-assisted vacuum frying.

Table A.22 Hardness and crispness data of MWVF durian at 110°C, 560W of different ripeness samples (cont.).

Number of samples	MWVF of Day 4	
	Hardness (N)	crispness
1	13.84	12.00
2	21.75	12.00
3	12.33	12.00
4	19.77	13.00
5	10.50	10.00
6	13.68	10.00
7	14.57	10.00
8	11.96	12.00
9	11.42	7.00
10	13.62	9.00
11	15.32	10.00
12	17.32	10.00
13	21.25	8.00
14	17.16	10.00
15	12.57	11.00
16	10.43	11.00
17	15.41	7.00
18	14.07	6.00
19	16.34	6.00
20	10.59	8.00
21	12.99	11.00
22	23.36	11.00
23	16.82	10.00
24	18.93	6.00
25	18.65	8.00
26	10.11	7.00
27	15.10	9.00
28	16.78	7.00
29	16.35	6.00
30	18.41	7.00
31	15.74	11.00
Average	15.39	9.26

MWVF, microwave-assisted vacuum frying.

A.6 Sensory evaluation form

Name: Product:

Panelist No.: Date:

Instructions:

Taste the given samples, then place the point on the scale that best describes your feeling. The scale is as follows:

Score/Rating	Std. Hedonic Scale
7	Like very much
6	Like moderately
5	Like slightly
4	Neither like nor dislike
3	Dislike slightly
2	Dislike moderately
1	Dislike very much

Characteristics	Score/Rating			
	Sample A	Sample B	Sample C	Sample D
Color				
Appearance				
Aroma				
Texture				
Taste				
Overall acceptance				

A.7 Sensory data of fried durian chips

Table A.23 Sensory data of VF durian chips Day 3 at 110°C.

Characteristics	Number of consumers																														Avg. Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Color	5	4	5	7	6	6	5	4	5	6	5	7	6	6	4	7	4	6	4	5	6	6	5	6	6	6	6	7	6	6	5.57
Texture	6	7	6	7	5	7	7	6	7	6	5	6	6	6	7	6	5	6	4	5	6	6	4	5	7	5	5	7	7	5	5.90
Aroma	6	5	5	6	6	6	6	5	5	5	6	6	6	4	4	7	7	6	5	5	7	6	5	5	6	6	6	6	6	6	5.67
Appearance	5	3	6	6	5	6	6	5	5	6	6	5	7	5	5	7	6	6	5	5	7	5	5	4	6	6	6	6	5	5	5.50
Taste	5	4	6	6	4	5	5	6	6	6	6	3	5	5	6	6	6	6	6	6	6	5	5	5	7	5	6	6	7	5	5.50
Overall acceptance	5	5	6	6	5	6	6	5	5	6	6	5	7	5	6	7	7	6	6	6	7	6	5	6	6	5	6	7	6	5	5.83

VF, vacuum frying

Table A.24 Sensory data of P+VF durian chips Day 3 at 110°C.

Characteristics	Number of consumers																														Avg. Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Color	4	4	4	5	6	5	6	5	5	5	6	5	5	6	6	6	5	6	6	6	5	6	5	5	5	6	4	5	6	6	5.30
Texture	5	3	7	5	7	6	6	5	6	6	6	7	6	5	6	5	5	6	4	6	7	6	6	7	5	5	6	5	6	6	5.70
Aroma	4	5	6	6	5	7	6	6	6	4	5	7	4	6	5	6	6	7	6	6	7	5	5	6	7	4	5	6	5	7	5.67
Appearance	6	5	5	5	6	6	6	6	5	6	6	6	7	6	7	7	5	6	6	6	5	6	5	6	6	6	6	5	5	5	5.77
Taste	7	3	7	6	6	6	5	5	7	6	5	7	6	5	6	5	6	7	6	7	6	6	6	6	7	6	7	5	7	6	6.00
Overall acceptance	6	5	6	5	5	6	6	5	6	5	5	6	6	6	6	7	5	6	6	6	7	5	5	6	6	5	7	5	6	6	5.73

P+VF, pre-treatment prior to vacuum frying

Table A.25 Sensory data of MWVF durian chips Day 3 at 110°C, 560W.

Characteristics	Number of consumers																														Avg. Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Color	6	6	7	6	5	6	7	7	6	6	6	6	6	6	7	6	4	5	5	5	5	6	5	6	7	7	6	5	6	5	5.87
Texture	5	6	7	6	6	6	5	6	6	5	7	5	7	5	6	6	6	5	7	6	5	6	6	7	6	7	7	6	6	5	5.97
Aroma	6	7	6	5	6	7	4	7	6	6	6	6	6	6	6	5	4	6	4	6	6	5	4	6	6	7	6	5	6	6	5.73
Appearance	6	6	6	6	6	5	6	6	7	5	5	6	5	5	6	5	5	7	5	5	6	5	6	6	6	7	5	6	6	5	5.70
Taste	6	7	6	6	6	6	6	7	6	6	6	5	6	6	6	6	5	6	6	6	6	6	5	7	7	7	7	6	6	6	6.10
Overall acceptance	7	7	6	6	6	6	6	7	6	6	6	6	6	6	6	5	6	6	6	6	6	5	5	7	7	7	7	5	5	6	6.07

MWVF, microwave-assisted vacuum frying.

Table A.26 Sensory data of MWVF (560W) durian chips Day 1 at 110°C.

Characteristics	Number of consumers																														Avg. Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Color	5	6	5	6	5	5	5	7	5	5	5	5	5	5	6	4	4	5	5	5	6	7	6	6	7	7	5	5	4	5	5.37
Texture	7	6	6	6	5	5	5	5	6	5	5	5	5	5	6	4	4	5	6	5	5	6	6	5	6	4	5	4	4	5	5.20
Aroma	6	5	7	5	5	5	4	7	5	6	5	5	4	4	4	5	5	5	5	4	6	6	7	6	5	4	5	3	4	5	5.07
Appearance	7	6	6	7	6	5	6	4	6	7	6	5	6	6	6	5	6	7	6	6	6	7	5	7	5	5	6	6	6	6	5.93
Taste	6	6	7	7	6	5	5	7	5	6	5	5	4	5	5	7	6	4	5	4	6	6	6	5	6	4	5	4	4	4	5.33
Overall acceptance	6	5	7	6	6	5	5	6	5	5	6	5	5	5	5	6	5	5	5	4	5	5	5	5	6	3	5	3	4	5	5.10

MWVF, microwave-assisted vacuum frying.

Table A.27 Sensory data of MWVF (560W) durian chips Day 2 at 110°C.

Characteristics	Number of consumers																														Avg. Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Color	5	5	5	5	5	6	5	5	5	6	5	7	5	4	4	6	4	6	4	5	6	6	5	5	6	5	5	7	6	5	5.27
Texture	6	6	4	7	5	6	5	5	5	6	5	5	5	6	4	6	4	6	4	5	6	6	5	4	6	5	5	7	6	5	5.33
Aroma	5	5	5	5	4	6	6	5	7	5	5	7	3	5	4	6	4	6	3	5	7	6	4	4	6	5	6	7	6	5	5.23
Appearance	5	7	6	5	5	7	6	5	7	6	5	6	5	6	6	6	6	7	6	6	6	7	5	5	4	6	6	7	6	6	5.87
Taste	4	5	5	5	3	6	5	5	6	5	5	5	3	6	4	6	4	6	3	5	3	5	5	5	7	5	6	7	7	5	5.03
Overall acceptance	5	5	5	5	4	6	5	5	6	6	5	5	5	5	4	6	4	6	5	5	5	6	5	6	6	5	6	6	6	5	5.27

MWVF, microwave-assisted vacuum frying.

Table A.28 Sensory data of MWVF (560W) durian chips Day 3 at 110°C.

Characteristics	Number of consumers																														Avg. Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Color	6	6	7	6	5	6	5	7	6	6	5	5	5	5	7	4	4	5	5	5	5	4	5	5	7	7	6	5	4	5	5.43
Texture	5	6	7	6	6	6	5	6	6	5	7	5	7	5	6	6	6	5	7	6	5	6	6	7	6	7	7	6	6	5	5.97
Aroma	6	7	6	5	6	7	4	7	6	6	6	6	6	6	6	5	4	6	4	6	6	5	4	6	6	7	6	5	6	6	5.73
Appearance	6	7	7	6	6	5	5	6	5	5	5	6	5	5	6	5	5	6	5	6	6	5	5	6	6	7	5	6	6	5	5.63
Taste	6	6	6	6	6	6	6	7	6	6	6	5	6	6	6	4	5	5	5	6	6	6	5	7	7	7	6	6	6	6	5.90
Overall acceptance	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	6	7	7	5	5	5	6	5.70

MWVF, microwave-assisted vacuum frying.

Table A.29 Sensory data of MWVF (560W) durian chips Day 4 at 110°C.

Characteristics	Number of consumers																														Avg. Score
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Color	7	7	7	6	6	6	6	6	6	6	4	5	6	6	7	5	5	6	6	6	6	6	4	5	7	6	6	5	4	7	5.83
Texture	7	6	6	5	7	7	7	5	6	6	7	6	7	5	6	6	7	5	6	6	7	7	7	7	5	7	5	5	7	7	6.23
Aroma	6	6	7	7	7	7	6	4	7	6	6	7	7	6	6	4	6	7	6	7	7	6	3	5	5	7	7	6	7	7	6.17
Appearance	6	6	5	5	6	6	5	5	5	5	5	6	5	5	5	4	5	4	5	4	6	5	5	5	5	5	4	5	5	5	5.07
Taste	7	6	7	7	7	7	7	4	7	7	7	6	7	7	7	4	6	7	7	7	7	7	5	7	6	7	7	6	7	7	6.57
Overall acceptance	6	6	7	7	7	7	6	5	6	7	7	6	6	7	7	4	6	7	7	6	6	6	4	6	5	7	7	7	6	7	6.27

MWVF, microwave-assisted vacuum frying.

Appendix B

Economic Analysis

B.1 Electrical energy cost estimating for vacuum frying plant design

The limited information on the capacity and power of the electric equipment was used to calculate the cost of the electrical energy. The following is a summary of the electric power of the equipment used in this investigation.

A vacuum pump 0.7457 kW

A cooling tower 0.5593 kW

A water pump 0.7457 kW

A microwave power control (max. 0.8 kW)

Table B.1 Electricity charges for a small general service (applicable to businesses, commercial cum residential, industrial, government industrial institutions, state enterprises, or others, including its compound, with a maximum 15-minute integrated demand of less than 30 kW measured by a single Watt-hour meter) (PEA, 2022).

Rate (kWh)	Energy charge (THB per kWh)
First 150 kWh (0-150th)	3.2484
Nest 250 kWh (151st-400th)	4.2218
Over 400 kWh (401st-up)	4.4217

The cost of electricity of an item was calculated by Equation (50).

$$\text{Cost} = W \times C \tag{50}$$

where: C = the cost per unit of electricity (THB per kWh)

W = the electric power (kW).

Estimate the electricity cost for vacuum frying (VF) of durian Day 1 (un-ripened).

Project 1: Fried four times per day

The information for calculating the electricity cost is shown below.

7 hours 20 minutes of the vacuum pump for control of pressure in the vacuum fryer

7 hours 20 minutes of cooling tower for the cooling system in vacuum frying process

7 hours 20 minutes of water pump for the cooling system between cooling tower and vacuum pump

Calculation methods of the electricity cost for VF of durian Day 1

Firstly, total up the kilowatt hours per day for the items to get total kWh/day (Units/day) which is (0.746*440/60) + (0.559*440/60) + (0.746*440/60) = 15.039 Units per day. Secondly, the determined kilowatt per month for the value of this plan is 15.03925 = 375.975 Units per month (25 days per month shall constitute the normal work period for a full-time per diem employee). The kilowatt hours used each month are then used to calculate the project's average cost per year. The information is substituted in Eq. (50), which the calculation is shown below.

Table B.2 Electricity records for twelve times of frying per day of durian Day 1.

Rate (kWh)	Energy charge (THB/kWh)	Service charge (THB/month)
First 150 kWh (0-150th)	3.2484	150×3.2484 = 487.26
Nest 250 kWh (151st-400th)	4.2218	(375.975-150)×4.2218 = 954.02
Over 400 kWh (401st-up)	4.4217	-

The cost of this project per month is 487.26+954.02 = 1,441.28 THB, or the cost of this project per year is 1,441.28×12 = 17,295.36 THB.

Estimate the electricity cost for pre-treatment prior to vacuum frying (P+VF) of durian Day 1 (un-ripened).

Project 2: Fried four times per day

The information for calculating the electricity cost is shown below.

6 hours 40 minutes of the vacuum pump for control of pressure in the vacuum fryer

6 hours 40 minutes of cooling tower for the cooling system in vacuum frying process

6 hours 40 minutes of water pump for the cooling system between cooling tower and vacuum pump

24 hours at -18°C of freezing for pre-treatment prior to vacuum frying

Calculation methods of the electricity cost for P+VF of durian Day 1

Firstly, total up the kilowatt hours per day for the items to get total kWh/day (Units/day) which is (0.746*400/60) + (0.559*400/60) + (0.746*400/60) +

(0.22*1440/60) = 18.953 Units per day. Secondly, the kilowatt per month is calculated for the value of this plan is 18.953×25 = 473.825 Units per month (25 days per month shall constitute the normal work period for a full-time per diem employee). Finally, the average cost per year of this project is calculated from the kilowatt hours per month. The information is substituted in Eq. (50), which the calculation is shown below.

Table B.3 Electricity records for twelve times of frying per day of durian Day 1.

Rate (kWh)	Energy charge (THB/kWh)	Service charge (THB/month)
First 150 kWh (0-150th)	3.2484	150×3.2484 = 487.26
Nest 250 kWh (151st-400th)	4.2218	250×4.2218 = 1,055.45
Over 400 kWh (401st-up)	4.4217	(473.825-400) ×4.4217 = 326.43

The cost of this project per month is 487.26+1,055.45+326.43 = 1,869.14 THB, or the cost of this project per year is 1,869.14×12 = 22,429.68 THB.

Estimate the electricity cost for microwave assisted vacuum frying (MWVF) of durian Day 1 (un-ripened).

Project 3: Fried four times per day

The information for calculating the electricity cost is shown below.

6 hours of the vacuum pump for control of pressure in the vacuum fryer

6 hours of cooling tower for the cooling system in vacuum frying process

6 hours of water pump for the cooling system between cooling tower and vacuum pump

6 hours of microwave power control for emitting the microwave energy in the vacuum fryer

Calculation methods of the electricity cost for MWVF of durian Day 1

Firstly, total up the kilowatt hours per day for the items to get total kWh/day (Units/day) which is (0.746*360/60) + (0.559*360/60) + (0.746*360/60) + (0.56*360/60) = 15.666 Units per day. Secondly, the kilowatt per month is calculated for the value of this plan is 15.666×25 = 391.65 Units per month (25 days per month shall constitute the normal work period for a full-time per diem employee). Finally, the average cost per year of this project is calculated from the kilowatt hours per month. The information is substituted in Eq. (50), which the calculation is shown below.

Table B.4 Electricity records for twelve times of frying per day of durian Day 1.

Rate (kWh)	Energy charge (THB/kWh)	Service charge (THB/month)
First 150 kWh (0-150th)	3.2484	150×3.2484 = 487.26
Nest 250 kWh (151st-400th)	4.2218	(391.65-150)×4.2218 = 1,020.20
Over 400 kWh (401st-up)	4.4217	-

The cost of this project per month is 487.26+1,020.20= 1,507.46 THB, or the cost of this project per year is 1,507.46×12 = 18,089.52 THB.

Estimate the electricity cost for microwave assisted vacuum frying (MWVF) of durian Day 4 (ripened)

Project 4: Fried three times per day

The information for calculating the electricity cost is shown below.

7 hours 30 minutes of the vacuum pump for control of pressure in the vacuum fryer

7 hours 30 minutes of cooling tower for the cooling system in vacuum frying process

7 hours 30 minutes of water pump for the cooling system between cooling tower and vacuum pump

7 hours 30 minutes of microwave power control for emitting the microwave energy in the vacuum fryer

Calculation methods of the electricity cost for MWVF of durian Day 4

Firstly, total up the kilowatt hours per day for the items to get total kWh/day (Units/day) which is (0.746*450/60) + (0.559*450/60) + (0.746*450/60) + (0.56*450/60) = 19.583 Units per day. Secondly, the kilowatt per month is calculated for the value of this plan is 19.583×25 = 489.575 Units per month (25 days per month shall constitute the normal work period for a full-time per diem employee). Finally, the average cost per year of this project is calculated from the kilowatt hours per month. The information is substituted in Eq. (50), which the calculation is shown below.

Table B.5 Electricity records for twelve times of frying per day of durian Day 4.

Rate (kWh)	Energy charge (THB/kWh)	Service charge (THB/month)
First 150 kWh (0-150th)	3.2484	150×3.2484 = 487.26
Nest 250 kWh (151st-400th)	4.2218	250×4.2218 = 1,055.45
Over 400 kWh (401st-up)	4.4217	(489.575-400) ×4.4217 = 396.07

The cost of this project per month is 487.26+1,055.45+396.07= 1,938.78 THB, or the cost of this project per year is 1,938.78×12 = 23,265.36 THB.

B.2 Total fixed-capital investment

Table B.6 Total fixed-capital investment for vacuum frying.

Item	THB
1. Main equipment (includes auxiliary equipment) - Vacuum fryer (90 cm dia.×60 cm): 150,000THB - The basket for the vacuum fryer: 15,000THB - T reader, T controller, T indicator, T switch, Thermocouple: 25,000THB - Control box, breaker: 15,000THB - T gauge, P gauge, Valves, Fittings, Rubber seals, Bearing: 32,000THB - Electrical hoist system: 20,000THB - Gas fired heater: 5,000THB - Water condenser and trap: 40,000THB - Vacuum pump (water ring, 20 cu.ft/min): 150,000THB - Cooling tower (300L, T of water discharge is not over 45°C) - Inverter: 15,000THB - Centrifugal set: 15,000THB - Rotary vane pump: 10,000	547,000
2. Purchased-equipment installation (39% of main equipment)	213,330
3. Instrumentation and controls (installed) (26% of main equipment)	142,220
Total	902,550

Table B.7 Total fixed-capital investment for pretreatment prior to vacuum frying.

Item	THB
4. Main equipment (includes auxiliary equipment) - Vacuum fryer (90 cm dia.×60 cm): 150,000THB - The basket for the vacuum fryer: 15,000THB - T reader, T controller, T indicator, T switch, Thermocouple: 25,000THB - Control box, breaker: 15,000THB - T gauge, P gauge, Valves, Fittings, Rubber seals, Bearing: 32,000THB - Electrical hoist system: 20,000THB - Gas fired heater: 5,000THB - Freezer: 15,000THB - Water condenser and trap: 40,000THB - Vacuum pump (water ring, 20 cu.ft/min): 150,000THB - Cooling tower (300L, T of water discharge is not over 45°C) - Inverter: 15,000THB - Centrifugal set: 15,000THB - Rotary vane pump: 10,000	562,000
5. Purchased-equipment installation (39% of main equipment)	219,180
6. Instrumentation and controls (installed) (26% of main equipment)	146,120
Total	927,300

Table B.8 Total fixed-capital investment for microwave assisted vacuum frying.

Item	THB
7. Main equipment (includes auxiliary equipment) - Vacuum fryer (90 cm dia.×60 cm): 150,000THB - The basket for the vacuum fryer: 15,000THB - T reader, T controller, T indicator, T switch, Thermocouple: 25,000THB - Control box, breaker: 15,000THB - T gauge, P gauge, Valves, Fittings, Rubber seals, Bearing: 32,000THB - Electrical hoist system: 20,000THB - Gas fired heater: 5,000THB - Microwave system: 30,000THB - Magnetron, transformer (3 sets): 3,000THB - Water condenser and trap: 40,000THB - Vacuum pump (water ring, 20 cu.ft/min): 150,000THB - Cooling tower (300L, T of water discharge is not over 45°C) - Inverter: 15,000THB - Centrifugal set: 15,000THB - Rotary vane pump: 10,000	580,000
8. Purchased-equipment installation (39% of main equipment)	226,200
9. Instrumentation and controls (installed) (26% of main equipment)	150,800
Total	957,000

B.3 LPG cost estimating for vacuum frying plant design

The cost of the LPG was calculated from the specific energy consumption (SEC) of each frying and the cost of LPG/kg.

The weight of LPG used in each frying was calculated by Equation (51).

$$\text{Weight of LPG}=\frac{SEC\times(M_i-M_f)W_d}{HV} \quad (51)$$

where: SEC = Specific Energy consumption (kJ/kg)

M_i = Initial moisture content (%d.b.)

M_f = Final moisture content (%d.b.)

W_d = Solid weight (kg)

HV = Heating value (HV of LPG = 50,220 kJ/kg)

Table B.9 LPG rates for a 48 kg gas tank (EPPO, 2022) and cost of LPG of each frying conditions.

Conditions	Cost of LPG (THB/kg)	SEC (kJ/kg)	Weight of LPG used (kg)	Total cost of LPG (THB/month)
VF of Day 1 (frying 4 times per day)	29.31	22,031.08	2.092	1,532.91
P+VF of Day 1 (frying 4 times per day)	29.31	22,031.08	2.092	1,532.91
MWVF of Day 1 (frying 4 times per day)	29.31	22,031.08	2.092	1,532.91
MWVF of Day 4 (frying 3 times per day)	29.31	22,353.3	1.320	967.23

B.4 Cost estimating from the raw material costs

Calculation methods of the durian raw materials

Fresh durians were purchased from the local market with the price of 90 THB per kilograms.

In this study, the weight of the durian flesh (removed seed) is 30% the weight of the durian. So, the amount of the durian flesh in 1 kilogram of durian is 1000×0.30 = 300 grams. The result of the cost of the raw materials for the frying is 90 THB/300 grams of the durian flesh = 0.3 THB/grams of the flesh.

The raw material cost for four times of frying per day of durian Day 1 (un-ripened) was used to determine the economic feasibility. The feed rate of the fresh durian for frying once each day is 6,870 grams. So, the amount of the durian flesh for twenty times of frying per day is 6,870×4 = 27,480 grams. The result of the cost of the raw materials for frying is 0.3×27,480 = 8,244 THB per day or 8,244×300 days per year = 2,473,200 THB per year.

The raw material cost for three times of frying per day of durian Day 4 (ripened) was used to determine the economic feasibility. The feed rate of the fresh durian for frying once each day is 5,727 grams. So, the amount of the durian flesh for twenty times of frying per day is 5,727×3 = 17,181 grams. The result of the cost of the raw materials for frying is 0.3×17,181 = 5,154.3 THB per day or 5,154.3×300 days per year = 1,546,290 THB per year.

Each batch was made up of 6,870 g maximum of samples that were deep-fried in 115 liters of palm oil. To keep the palm oil fresh, it is replenished every day (Yamsaengsung et al, 2017). The result of the cost of palm oil used for frying is 115×45 = 5,175 THB/day or 5,175×300 days per year =1,552,500 THB per year.

B.5 Labor cost calculations of workers

The average time rate, which incorporates payroll costs, is used to express the labor cost for each process. The calculations of labor costs for each project are given below.

Estimating the labor cost for the VF of durian Day 1 (un-ripened)

Project 1: Fried four times per day

Calculation methods:

The minimum pay rate (THB per minute) and the worker's daily work time (minutes) are multiplied together to get the labor cost each day. The minimum pay rate in this study is 325 THB per day / 480 minutes per day (the worker's work time is 8 hours per day or 480 minutes per day), which equals 0.677 THB per minute. The labor cost of the worker in this study is 510 minutes per day ×0.677 THB per minute = 345.27 THB per day, or the labor cost of the worker per year is 345.27×300 days per year = 103,581 THB per year.

Estimating the labor cost for the P+VF of durian Day 1 (un-ripened)

Project 2: Fried four times per day

Calculation methods:

The minimum pay rate (THB per minute) and the worker's daily work time (minutes) are multiplied together to get the labor cost each day. The minimum pay rate in this study is 325 THB per day / 480 minutes per day (the worker's work time is 8 hours per day or 480 minutes per day), which equals 0.677 THB per minute. The labor cost of the worker in this study is 470 minutes per day ×0.677 THB per minute = 318.19 THB per day, or the labor cost of the worker per year is 318.19×300 days per year = 95,475 THB per year.

Estimating the labor cost for the MWVF of durian Day 1 (un-ripened)

Project 3: Fried four times per day

Calculation methods:

The minimum pay rate (THB per minute) and the worker's daily work time (minutes) are multiplied together to get the labor cost each day. The minimum pay rate in this study is 325 THB per day / 480 minutes per day (the worker's work time is 8 hours per day or 480 minutes per day), which equals 0.677 THB per minute. The labor cost of the worker in this study is 430 minutes per day ×0.677 THB per minute = 291.11 THB per day, or the labor cost of the worker per year is 291.11×300 days per year = 87,333 THB per year.

Estimating the labor cost for the MWVF of durian Day 4 (ripened)

Project 4: Fried three times per day

Calculation methods:

The minimum pay rate (THB per minute) and the worker's daily work time (minutes) are multiplied together to get the labor cost each day. The minimum pay rate in this study is 325 THB per day / 480 minutes per day (the worker's work time is 8 hours per day or 480 minutes per day), which equals 0.677 THB per minute. The labor cost of the worker in this study is 510 minutes per day ×0.677 THB per minute = 345.27 THB per day, or the labor cost of the worker per year is 345.27×300 days per year = 103,581 THB per year.

B.6 Profitable estimating from the sale price of the MWVF products

Calculation methods of the sale revenue of the fried durian Day 1 (un-ripened)

The price of commercial vacuum fried durian (Mr. Tong) is 99 THB per serving. The serving size of this product is 70 grams. So, the price of the commercial product is 99 THB per serving / 70 grams of the product = 1.41 THB per grams.

The product sales income for four times of durian frying each day on Day 1 was used to assess the economic feasibility. The rated operating capacity of the fried durian for frying once each day is grams of the fried product. So, the amount of fried durian for four times of frying per day is 2,382.52×4 = 9,530.06 grams. The product's sales income could then be calculated by multiplying the amount of fried durian by the price of commercial vacuum fried durian (Mr. Tong). The result of the sale revenue for the frying is 9,530.06×1.41 = 13,437.38 THB per day or 13,437.38×300 days per year = 4,031,214 THB per year.

Calculation methods of the sale revenue of the fried durian Day 4 (ripened)

The price of commercial vacuum freeze dried durian (Nature Vita) is 169 THB per serving. The serving size of this product is 100 grams. So, the price of the commercial product is 169 THB per serving / 100 grams of the product = 1.69 THB per grams.

The product sales income for four times of durian frying each day on Day 4 was used to assess the economic feasibility. The rated operating capacity of the fried durian for frying once each day is grams of the fried product. So, the amount of fried durian for three times of frying per day is 8,800.11×3 = 26,400.33 grams. Then, by multiplying the quantity of the fried durian and the cost of the commercial vacuum freeze-dried durian (Nature Vita), it is possible to calculate the products' sales income. The result of the sale revenue for the frying is 26,400.33×1.69 = 44,616.56 THB per day or ×300 days per year = 13,384,968 THB per year.

B.7 Net Present Value (NPV) Calculation

To compare the various options for obtaining the final product, the economic analysis is assessed. Both fixed and variable cost estimates are included in each project's cost estimate. The following diagram illustrates the approach used to determine the economic expenses. (Junlakan, 2014).

Estimating economic feasibility for VF of durian Day 1 (un-ripened) production

Project 1: Fried four times per day

Fixed costs:

(1) Total fixed-capital investment (Table B.6)

(2) Depreciation cost is the loss of value in an item over time. This study used the straight-line depreciation approach, whose straight-line depreciation is depicted here.

$$D=\frac{P-S}{L} \tag{51}$$

where: D = Depreciation (THB/year)

P = Purchase price (THB)

S = Salvage value (THB)

L = Service life (year)

Then the information is substituted in Eq. (51) or the depreciation can be calculated in 10% of fixed-capital investment (León et al., 2020), which the result of calculating the depreciation expense is 90,255 THB per year.

(3) The low interest rate on saving account at 0.50 percent per year (Bank of Thailand, 2022). The Minimum Attractive Rate of Return (MARR) is assumed to be 1% since it should be greater than the low interest return on savings.

(4) A Tax and the salvage value rate are not considered in evaluating the economic costs.

Variable costs:

(1) Maintenance cost from 6% of fixed-capital investment is 54,153 THB/year from mechanical seal of vacuum pump and water pump used in the system.

(2) Fuel cost is 18,394.92 THB/year

(3) Electricity cost is 17,295.36 THB/year

(4) Raw material cost is 2,473,200 +1,552,500 = 4,025,700 THB/year

(5) Labor cost is 103,581×2 = 207,162 THB/year

(6) Overhead costs (60% of labor cost and maintenance cost) = 156,789 THB/year

Total sales revenue:

The revenue from the sale of the VF durian Day 1 each of the frying is 3,359.35 THB. If the durians are fried 4 times per day, the revenue from the sale of the products is 13,437.38 THB per day or 4,031,214 THB per year.

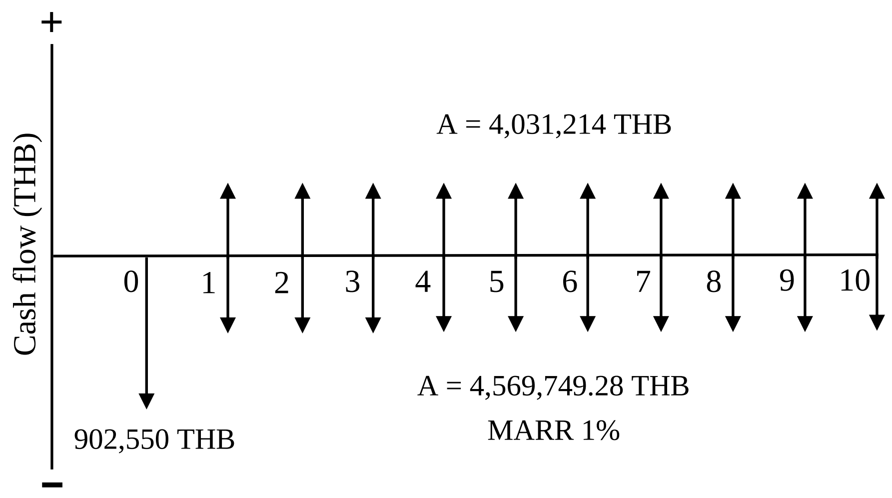
The Net Present Value, which is the difference between the present value of cash inflows and outflows, is then calculated using the aforementioned result. The NPV equation is shown below (Junlakan, 2014).

Net Present Value (NPV) = the present value of cash inflows – the present value of cash outflows (52)

The decision criteria

- If the NPV is positive, the project will be considered as an interesting investment.
- If the NPV is negative, the project will most likely be seen as an unappealing investment.

Solution



The present value of cash inflows = 4,031,214(P/A, 1%, 10)

= 4,031,214×9.4713

= 38,180,855.42

The present value of cash outflows = 902,550+[(90,255+54,153+18,394.92 +17,295.36+4,025,700+207,162+156,789)(P/A, 1%, 10)]

= 902,550+(4,569,749.28×9.4713)

= 44,184,037.06

Then substitute the values above into the Eq. (52):

The Net Present Value (NPV) = 38,180,855.42-44,184,037.06

= -6,003,181.64

The result shows the negative NPV, so the investment project is unattractive.

Estimating economic feasibility for P+VF of durian Day 1 (un-ripened) production

Project 2: Fried four times per day

Fixed costs:

(1) Total fixed-capital investment (Table B.6)

(2) The information is substituted in Eq. (51) or 10% of fixed-capital investment (León et al., 2020), which the result of evaluating the depreciation expense is 92,730 THB per year.

(3) The low interest rate on savings accounts at 0.5 percent per year (Bank of Thailand, 2022). The Minimum Attractive Rate of Return (MARR) is assumed to be 1% since it should be greater than the low interest return on savings.

(4) A tax and the salvage value are not considered in evaluating the economic costs.

Variable costs:

(1) Maintenance cost is 55,638 THB/year.

(2) Fuel cost is 18,394.92 THB/year.

(3) Electricity cost is 22,345.68 THB/year.

(4) Raw material cost is 4,025,700 THB/year.

(5) Labor cost is 95,475×2= 190,950 THB/year

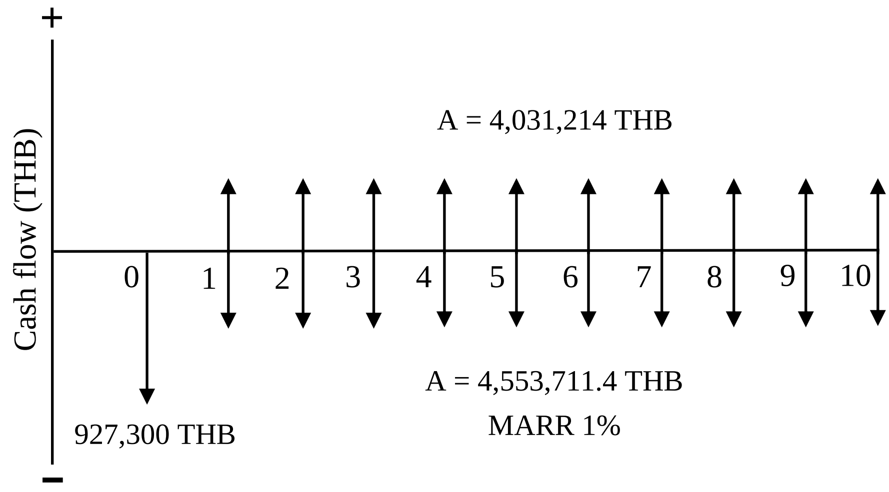
(6) Overhead costs = 147,952.8 THB/year.

Total sales revenue:

The revenue from the sale of the P+VF durian Day 1 each of the frying is 3,359.35 THB. If the durians are fried 4 times per day, the revenue from the sale of the products is 13,437.38 THB per day or 4,031,214 THB per year.

Then the result above is used to calculate the Net Present Value (Eq. (52))

Solution



The present value of cash inflows = 4,031,214 (P/A, 1%, 10)

= 4,031,214×9.4713

= 38,180,855.42

The present value of cash outflows = 927,300+[(92,730+55,638+18,394.92 +22,345.68+4,025,700+190,950+147,952.8)(P/A, 1%, 10)]

= 927,300+(4,553,711.4×9.4713)

= 44,056,866.78

Then substituted the values above into the Eq. (52):

The Net Present Value (NPV) = 38,180,855.42- 44,056,866.78

= -6,003,181.64

The result shows the negative NPV, so the investment project is unattractive.

Estimating economic feasibility for MWVF of durian Day 1 (un-ripened) production

Project 3: Fried four times per day

Fixed costs:

(1) Total fixed-capital investment (Table B.6)

(2) The information is substituted in Eq. (51) or 10% of fixed-capital investment (León et al., 2020), which the result of evaluating the depreciation expense is 95,700 THB per year.

(3) The low interest rate on savings accounts at 0.5 percent per year (Bank of Thailand, 2022). The Minimum Attractive Rate of Return (MARR) is assumed to be 1% since it should be greater than the low interest return on savings.

(4) A tax and the salvage value are not considered in evaluating the economic costs.

Variable costs:

(1) Maintenance cost is 57,420 THB/year.

(2) Fuel cost is 18,394.92 THB/year,

(3) Electricity cost is 18,089.52 THB/year.

(4) Raw material cost is 4,025,700 THB/year.

(5) Labor cost is 87,333×2 = 174,666 THB/year.

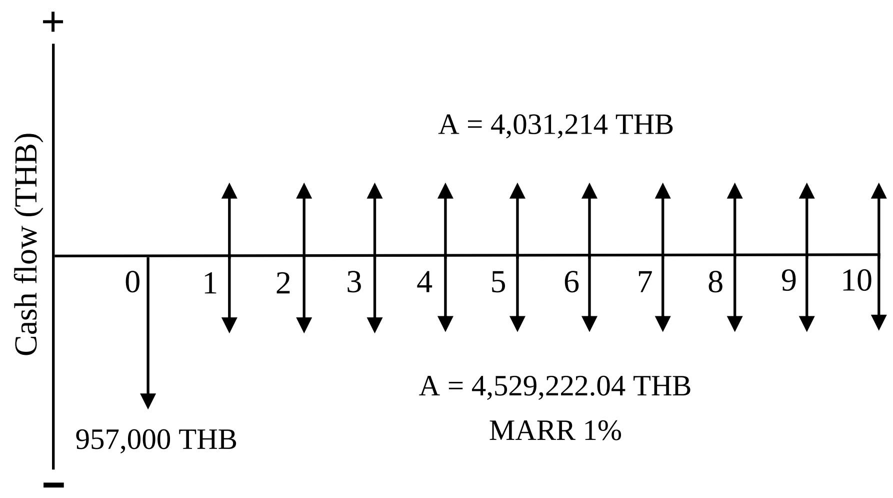
(6) Overhead costs = 139,251.6 THB/year.

Total sales revenue:

The revenue from the sale of the MWVF durian Day 1 each of the frying is 3,359.35 THB. If the durians are fried 4 times per day, the revenue from the sale of the products is 13,437.38 THB per day or 4,031,214 THB per year.

Then the result above is used to calculate the Net Present Value (Eq. (52)).

Solution



The present value of cash inflows = 4,031,214 (P/A, 1%, 10)

= 4,031,214×9.4713

= 38,180,855.42

The present value of cash outflows = 957,000+[(95,700+57,420+18,394.92 +18,089.52 +4,025,700 +174,666+139,251.6)(P/A, 1%, 10)]

= 957,000+(4,529,222.04×9.4713)

= 43,854,641.23

Then substituted the values above into the Eq. (52):

The Net Present Value (NPV) = 38,180,855.42-43,854,641.23

= -5,673,785.81

The result shows the negative NPV, so the investment project is unattractive.

Estimating economic feasibility for MWVF of durian Day 4 (ripened) production

Project 4: Fried three times per day

Fixed costs:

(1) Total fixed-capital investment (Table B.6)

(2) The information is substituted in Eq. (51) or 10% of fixed-capital investment (León et al., 2020), which the result of evaluating the depreciation expense is 95,700 THB per year.

(3) The low interest rate on savings accounts at 0.5 percent per year (Bank of Thailand, 2022). The Minimum Attractive Rate of Return (MARR) is assumed to be 1% since it should be greater than the low interest return on savings.

(4) A tax and the salvage value are not considered in evaluating the economic costs.

Variable costs:

(1) Maintenance cost is 57,420 THB/year.

(2) Fuel cost is 11,606.76 THB/year,

(3) Electricity cost is 23,265.36 THB/year.

(4) Raw material cost is 1,546,290 +1,552,500 = 3,098,790 THB/year.

(5) Labor cost is 103,581×2 = 207,162 THB/year.

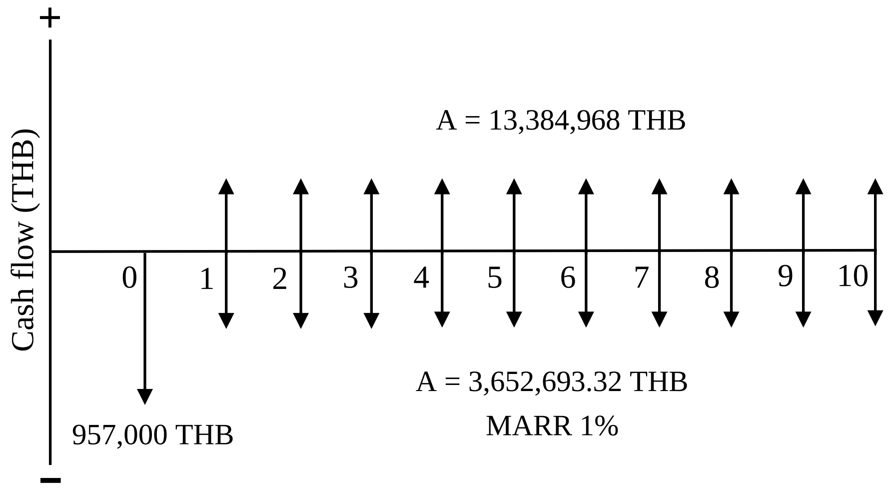
(6) Overhead costs = 158,749.2 THB/year.

Total sales revenue:

The revenue from the sale of the MWVF durian Day 4 each of the frying is 14,872.19 THB. If the durians are fried 3 times per day, the revenue from the sale of the products is 44,616.56 THB per day or 13,384,968 THB per year.

The result above is used to calculate the Net Present Value (Eq. (52)).

Solution



The present value of cash inflow = 13,384,968(P/A, 1%, 10)

= 13,384,968×9.4713

= 126,773,108.06

The present value of cash outflows = 957,000+[(95,700+57,420+11,606.76 +23,265.36+3,098,790+207,162+158,749.2)(P/A, 1%, 10)]

= 957,000+(3,652,693.32×9.4713)

= 35,552,770.79

Then substitute the values above into the Eq. (52):

The Net Present Value (NPV) = 126,773,108.06-35,552,770.79

= 91,220,337.27

The result shows the positive NPV, so the investment project is attractive.

CONFERENCE & JOURNAL PUBLICATIONS

International Conference on Engineering and Technology (ICET 2021) IOP Publishing
IOP Conf. Series: Materials Science and Engineering 1163 (2021) 012005 doi:10.1088/1757-899X/1163/1/012005

Physiochemical properties of vacuum fried durian (*Durio Zibethinus Murr.*) chips combined with microwave heating

C Thongcharoenpipat and R Yamsaengsung*

Department of Chemical Engineering, Faculty of Engineering, Prince of Songkla University, Hatyai, Songkla 90112, Thailand

*Corresponding author's e-mail: ram.y@psu.ac.th

Abstract. This research evaluated the effects of oil temperature, ripeness of durian (*Durio zibethinus Murr.*), and microwave combined heating (MCH) on the physiochemical properties of vacuum fried durian chips. The oil temperature was varied from 90, 100, 110, and 120°C, while the ripeness was determined in term of total sugar (base on day of ripening). In addition, the effect of pretreatment of durian chips by freezing overnight -18°C before vacuum frying (VF) was also investigated.

From this study, it was found that VF at 120°C with the ripeness of day 3 gave the lowest shrinkage, and using MCH produced a higher rate of moisture loss compared to the condition without MCH. Even though it was found that the ripeness of durian lead to more oil absorption, the addition of MCH resulted in decreasing the permeability of oil into the product. Finally, an increase in the frying temperature lead to a slight significant increase in color change ($p<0.05$), while the microwave power intensity did not have a significant effect on the color change ($p<0.05$).

1. Introduction

Durian (Durio zibethinus Murr.) is an attractive and high economic valuable tropical fruit grown widely in South-East Asia [1]. Due to its high nutrients and uniquely unpleasant odor, Durian is known as the "king of tropical fruit" [1]. One of the most important problem occurs in durian season, where there is excessive harvesting which floods the market making it impossible to sell all ripened durians even with high consumer demands. Therefore, it is more economical to process durian in order to extend its shelf-life and add value to the product. Presently, there are several methods including drying and deep-fat frying. Due to its high temperature and oil uptake, which detract the color and nutritive values of the product, alternative methods should be considered.

Drying of fruits and vegetables have been favored for centuries around the world. Not only can they be stored for a long period of time, but dried foods are convenient for carrying and appetizing to consumers. Moreover, drying of fruits and vegetables help to maintain the color and taste similar to the original fresh products meeting the demands of customers. One of the most efficient drying process is vacuum frying. Even though oil is used, the overall oil content is low compared to conventional frying process making it a feasible alternative for many fruit varieties in today's market.

During vacuum frying, products are dried under vacuum pressure, reducing the frying temperature required compared to traditional frying temperature (90-100oC versus 160-180°C), while maintaining high drying rate. The lower frying temperature leads to higher product qualities such as crispness, puffed

International Journal of Food Science +Technology

Institute of Food Science +Technology ifst

2862 International Journal of Food Science and Technology 2022, **57**, 2862–2871

Original article

Improving the drying kinetics and microstructure of vacuum-fried ripened durian chips

Chanoknate Thongcharoenpipat & Ram Yamsaengsung

Department of Chemical Engineering, Faculty of Engineering, Prince of Songkla University, Hatyai Songkla, 90110, Thailand

(Received 14 October 2021; Accepted in revised form 4 January 2022)

Summary This research evaluated the effects of process conditions on the physiochemical properties of vacuum-fried durian chips. Ripened durians were sliced and fried at 90, 100, 110 and 120°C under 8-kPa absolute pressure. From this study, microwave heating (MWH) during vacuum frying (VF) significantly reduced the frying time by 20% compared to VF ($P < 0.05$) with the effective moisture diffusivity for VF, pre-treatment before vacuum frying (P+VF) and VF+MWH at 110°C determined to be 3.63×10^{-09}, 4.30×10^{-09} and 4.84×10^{-09} $m^2 s^{-1}$, respectively. VF+MWH produced chips with significantly lower shrinkage, more yellowness ($P < 0.05$) and higher crispiness (consistent with the microstructure from scanning electron microscopy (SEM)). In addition, VF+MWH drastically decreased oil absorption by 10%, while P+VF yielded the lowest specific energy consumption (SEC). From sensory evaluation, the overall acceptability of VF+MWH chips rose from 5.83 to 6.07 (seven-point hedonic scale), thus making the product fall into the 'Good' to 'Very Good' range.

Keywords Drying kinetic, microwave, physiochemical property, pre-treatment, ripened durian, vacuum frying.

Introduction

Durian (*Durio zibethinus* Murr.) is one of the most popular tropical fruits in Southeast Asia and is widely claimed as the 'King of Fruits'. Due to its unique aromatic odour, specific taste and rich nutritional value and high antioxidants, it is one of Thailand's top exported fruits, especially to China. In 2020 alone, Thailand harvested more than one million tonne (OAE, 2020) with Montong (D159) being the most notable and harvested (Niponsak *et al*., 2020). During harvest season, un-ripened durians are harvested and deep-fat fried to produce durian chips in order to keep the market from over-flooding with ripened durian. But since fried durian chips have a high oil content of around 30%, they may not be desirable to health-conscious consumers (Bai-Ngew *et al*., 2011). Moreover, ripened durian chips are generally freeze-dried and sold commercially at a price up to three times higher than un-ripened fried durian chip due to its high energy consumption and high demand. Therefore, a less expensive process for ripened durian chips could meet demands and help alleviate the market surplus during durian season.

Many food businesses have also been pushed to produce fried products with lower oil content, as well as desirable texture and flavour (Su *et al*., 2017). One of the most efficient options for health-conscious food processors is vacuum frying (VF) (Su *et al*., 2016), which reduces oil uptake. By frying fruits and vegetables at reduced pressure (~ 8 kPa) and below the temperatures 160–180°C range, unacceptable chemical reactions, such as lipid oxidation can be diminished (Thongcharoenpipat & Yamsaengsung, 2021), and acrylamide formation and risk of cancer can be minimised (Banerjee & Kumar, 2017). Furthermore, many researchers have considered VF for improving the product appearance and texture, maintaining the fresh flavour and curtailing nutritional losses of vitamins in fried fruits, such as bananas (Yamsaengsung *et al*., 2011), potatoes (Su *et al*., 2016) and Chinese yam (Chitrakar *et al*., 2019). Moreover, in conjunction with freeze drying (FD), vacuum drying (VD) and VF, microwave-assisted heating has been shown to reduce the drying time, improve efficiency of the process, and improve the product attributes (Su *et al*., 2017).

The study of Paengkanya *et al*. (2015) found that the pros of microwave vacuum drying (MWVC) include increasing the dehydration process, minimizing energy consumption of drying and advancing the quality of durian chips, while Su *et al*. (2016) concluded that VF combined with microwave heating (VF+MWH) reduced oil absorption and could

*Correspondent: Fax: +66 7 455 8833; e-mail: ram.y@psu.ac.th

doi:10.1111/ijfs.15547

Food and Bioproducts Processing 138 (2023) 40–52

Available online at www.sciencedirect.com

Food and Bioproducts Processing

journal homepage: www.elsevier.com/locate/fbp

Microwave-assisted vacuum frying of durian chips: Impact of ripening level on the drying rate, physio-chemical characteristics, and acceptability

Chanoknate Thongcharoenpipat, Ram Yamsaengsung[*]

Department of Chemical Engineering, Faculty of Engineering, Prince of Songkla University, Hatyai, Songkla 90110, Thailand

ARTICLE INFO

Article history:
Received 1 April 2022
Received in revised form
21 December 2022
Accepted 4 January 2023
Available online 7 January 2023

Keywords:
Vacuum frying
Microwave
Durian
Ripening level
Drying rate
Acceptability

ABSTRACT

The microwave assisted vacuum frying (MWVF) of Durian cv. Monthong was performed to investigate the effect of microwave power levels (400, 480, and 560 W) and ripening stages (1 Day, 2 Days, 3 Days, and 4 Days after harvesting) on the kinetics of the durian chips. The physio-chemical properties, the specific energy consumption (SEC) and product acceptability using sensory evaluation were also determined at 110 °C and absolute pressure of 8 kPa. At the higher microwave power, the frying time was reduced leading to a lower SEC. Moreover, it also resulted in decreasing oil absorption, decreasing shrinkage, and increasing porosity. In addition, more ripeness in durians led to longer frying time, increased oil uptake, but also produced a more porous structure and higher crispiness. Furthermore, using the 7-point hedonic scale test, the sensory evaluation revealed that the chips from the more ripened durian had the higher overall acceptability score.

1. Introduction

In recent years, the most famous fruit cultivar in Thailand, Durian, has the potential to overflow the domestic market due to excessive cultivation by Thai farmers (Office of Agricultural Economics, Thailand. 2021) in order to increase export demands. Consequently, as the supply became increasingly abundant, the market price has been decreasing and orchard growers have resolved to preserving the values of durians by processing them into other products. One alternative is the crispy durian, made from deep-fat frying of un-ripened durian slices at atmospheric pressure. However, this product contains high amount of oil content (32.19–36.54%) that can lead to long term risk of heart diseases making it unsuitable for health-conscious consumers (Bai-Ngew et al., 2011; Paengkanya et al., 2015). Another option that has become increasingly popular among large food companies is freeze drying of ripened durian. Although this technique can produce crispy snacks and preserve the essential qualities of the product, the process required a much longer processing time resulting in high operating costs and investment (Giri and Prasad, 2007). Thus, the cost of freeze-dried durian is more than three times higher than its fried (un-ripened) counterpart.

Another viable alternative for durian preservation is vacuum frying (VF) which offers an efficient technique for achieving better product quality with reduced colour degradation, less oil uptake, enhanced texture, and preservation of original taste and essential nutritional values (Juvvi et al., 2016). Other important advantages include oil quality control (Yamsaengsung et al., 2017), reduction of toxic compound generation and higher overall acceptance of sensory characteristics (Santacatalina et al., 2016). In addition, microwave assisted vacuum frying (MWVF) has garnered much attention in recent years as an attractive method to generate rapid heat transfer at low processing temperature. A number of researchers have applied microwave combined heating to enhance the water evaporation rate and produce higher quality

[*] Corresponding author.
E-mail address: ram.y@psu.ac.th (R. Yamsaengsung).

https://doi.org/10.1016/j.fbp.2023.01.001
0960-3085/

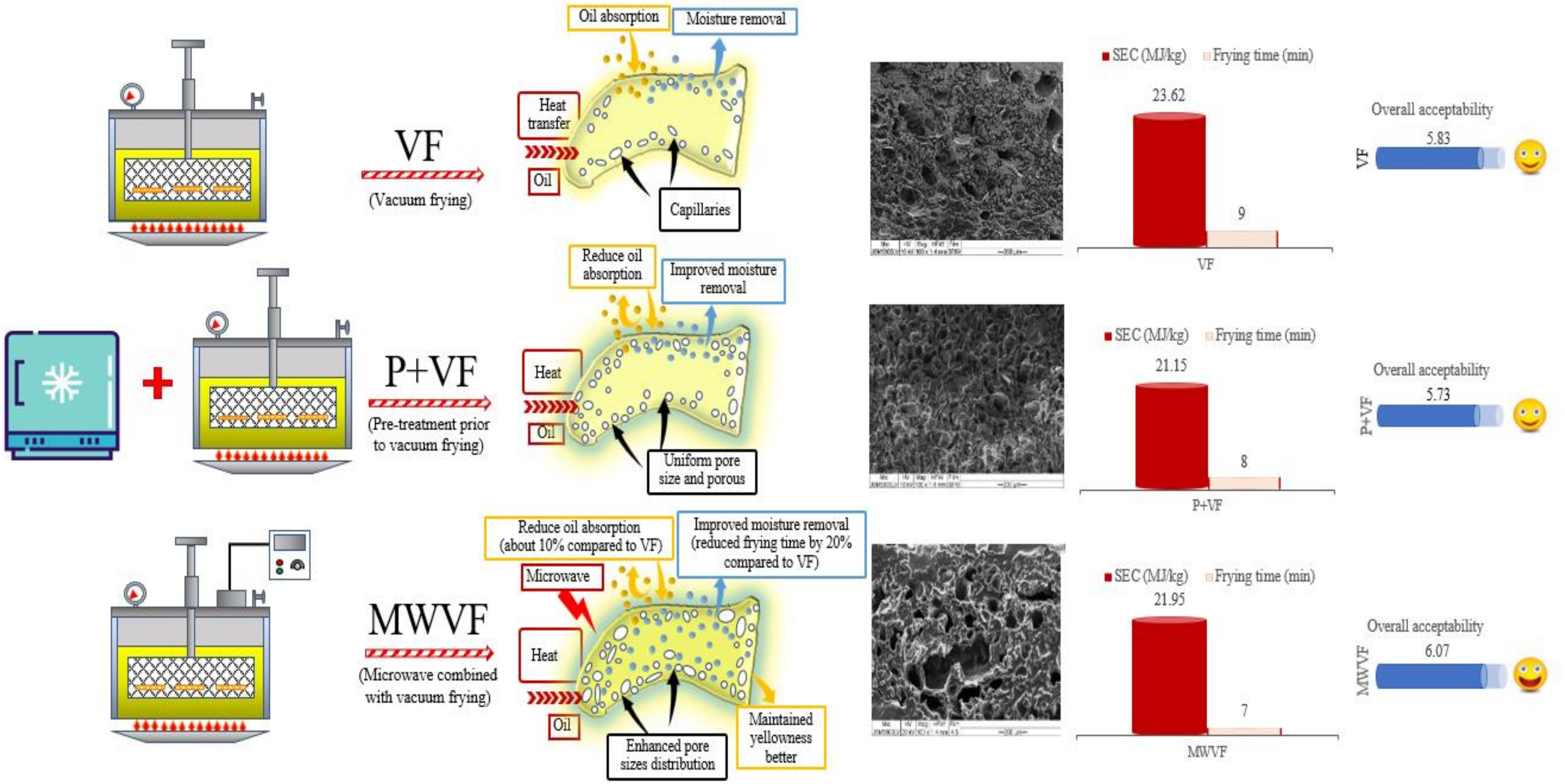


Figure C.1 Graphical abstract of different frying conditions for durian Day 3.

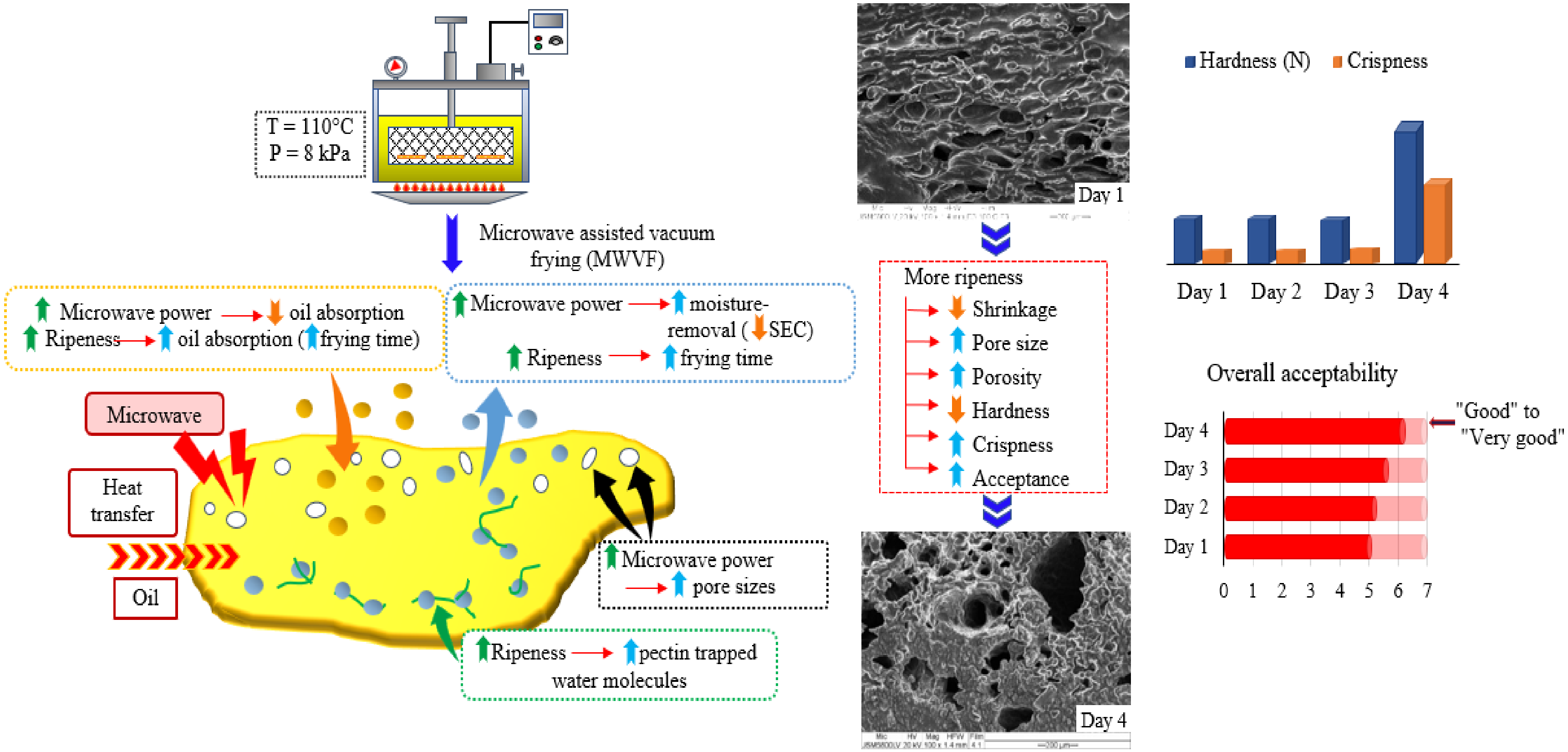


Figure C.2 Graphical abstract of MWVF for different ripening durian

VITAE

Name Chanoknate Thongcharoenpipat
Student ID 5810130008
Educational Attainment

Degree	Name of Institution	Year of Graduation
Bachelor of Engineering (Chemical Engineering)	Prince of Songkla University, Hatyai Campus	2015

Scholarship Awards during Enrolment

- The Graduate School Research Fund from Graduate School - Prince of Songkla University

- The Research and Researchers for Industries Fund from the Thailand Research Fund

List of Publication and Proceeding

Thongcharoenpipat, C., and Yamsaengsung, R. (2021). Physiochemical properties of vacuum fried durian (Durio Zibethinus Murr.) chips combined with microwave heating. 9th International Conference on Engineering and Technology. Krabi, Thailand.

Thongcharoenpipat, C., and Yamsaengsung, R. (2022). Improving the Drying Kinetics and Microstructure of Vacuum Fried Ripened Durian Chips. *International Journal of Food Science and Technology*, 57(5), 2862-2871.

Thongcharoenpipat, C., and Yamsaengsung, R. (2023). Microwave-assisted vacuum frying of durian chips: Impact of ripening level on the drying rate, physio-chemical characteristics, and acceptability. *Food and Bioproducts Processing*, 138, 40-52.