DRYING KINETICS AND QUALITY OF DRIED KEDONDONG FRUITS UNDERGOING HYBRID DRYING PROCESSES

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ABSTRACT

Kedondong fruit (*Spondias dulcis* Forst.) is an underutilized fruit that is gaining interest in many countries (Malaysia, India, Australia, Philippines and etc) as it is nutritious and can be planted easily. Kedondong fruit is rich in total polyphenols, vitamin C, carotenoids and vitamin A which may prevent degenerative diseases such as cancer, arthritis, arteriosclerosis, heart disease, inflammation, brain dysfunction and ageing. The objectives of this study were to investigate the drying kinetics of hot air, infrared and hybrid drying (freeze drying + hot air drying (FDHA) and freeze drying + infrared drying (FDIR)). Besides, the effects of hot air, infrared and hybrid drying on physical characteristics (colour and texture), chemical characteristics (total polyphenols content, vitamin C and antioxidant capacity) and sensory evaluation were also studied. Kedondong slices were first dried using hot air drying at 50˚C, 60˚C, 70˚C and 80˚C and infrared drying at 60˚C, 70˚C and 80˚C to study the drying kinetics, physical and chemical characteristics of dried kedondong samples. Two falling rate periods were detected in hot air drying at higher temperature (60˚C, 70˚C and 80˚C) whereas constant rate and falling rate periods were observed only at 50˚C. However, there was only one falling rate period detected in infrared drying. Effective diffusivities (D_{eff}) were obtained ranging from 8.56 x 10^{-10} m^2/s to 1.88 x 10^{-9} m^2/s and 1.30 x 10^{-9} m^2/s to 1.96 x 10^{-9} m^2/s as temperature increased for hot air and infrared drying, respectively. Activation energies (E_a) were determined for hot air and infrared drying at 25.28 kJ/mol and 20.13 kJ/mol, respectively. Both drying methods showed the lowest total colour change, lower hardness, higher total polyphenols content,

vitamin C and antioxidant capacity at drying temperature of 60˚C and this temperature was selected for hybrid drying.

In hybrid drying, first stage freeze drying at 6 hours and 12 hours were applied before second stage hot air or infrared drying. Drying rate curves of hybrid drying can be classified into three periods namely initial freeze drying, warming up when subjected to second stage drying and falling rate periods to remove remaining internal moisture. D_{eff} values for partially dried kedondong samples by freeze drying (first stage) at 6 and 12 hours were determined at 1.84×10^{-10} m^2/s and 1.98×10^{-10} m^2/s, respectively which is lower than single stage drying of HA60 and IR60. However, second stage hot air and infrared drying of hybrid drying were found to increase D_{eff} to the range between 1.23×10^{-9} m^2/s and 2.20×10^{-9} m^2/s. Partial dried kedondong samples by freeze drying in hybrid drying was found to lower total colour change of dried kedondong samples as compared to single stage drying (HA60 and IR60). Hardness results showed that hybrid drying with partial freeze dried kedondong samples at 12 hours was harder than that at 6 hours due to surface crust formation. In terms of chemical characteristics, hybrid drying was found to increase total polyphenols content but did not improve vitamin C retention. Pearson correlation showed that ABTS radical scavenging activity was found to have higher correlation to TPC (R^2 = 0.895) but moderate correlation to VC (R^2 = 0.662) whereas DPPH was observed to have higher correlation to VC (R^2 = 0.757) than TPC (R^2 = 0.698). Sensory evaluation analyzed by penalty analysis found that hybrid dried kedondong samples of FD6HA60 and FD12IR60 reduced the overall percentage of panel on penalty attributes as compared to HA60 and IR60 dried kedondong samples and some of the not-JAR attributes are preferred by sensory panel.

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DECLARATION

I hereby declare that the present work is prepared solely by me during my doctoral studies at the University of Nottingham (UNM). It has not been submitted anywhere for any awards. Works of other people are fully acknowledged according to standard referencing. This thesis complies fully with the regulations set by the University of Nottingham.

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LIST OF PUBLICATIONS

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NOMENCLATURES

A	Texture
AAC	Ascorbic acid content (mg/100g)
ABTS	2,2-azino-bis(3-ethylbenz-thiazoline-6-suflfonic acid) (μM Trolox equivalent/g dry solid)
AD	Hot air drying
AD-DIC	Instant controlled pressure drop assisted hot air drying
AEAC	Ascorbic acid equivalent antioxidant capacity (mg AA/100g dry sample)
a_0	a* colour parameter for reference sample
a*	Colour parameter (greenness to redness)
B	Browning
b_0	b* colour parameter for reference sample
b*	Colour parameter (blueness to yellowness)
C	Sweetness
D	Sourness
DCPIP	2,6-dichlorophenolindophenol
D_{eff}	Effective diffusivity (m^2/s)
D_0	Pre-exponential constant (m^2/s)
DPPH	1,1-diphenyl-2-picrylhydrazyl (mg AA/100g dry solid)
E	Kedondong notes
E_a	Activation energy (kJ/mol)

EO	Ethyl oleate
F	Kedondong aroma
FD	Freeze drying
FD-DIC	Instant controlled pressure drop assisted freeze drying
FDHA	Hybrid freeze drying and hot air drying
FDIR	Hybrid freeze drying and infrared drying
FD-MIRD	Combined freeze drying and mid-infrared radiation
FD6	Freeze drying (6 hours)
FD12	Freeze drying (12 hours)
FD24	Freeze drying (24 hours)
FD6IR60	Hybrid drying of freeze drying (6 hours) with infrared drying (60˚C)
FD12IR60	Hybrid drying of freeze drying (12 hours) with infrared drying (60˚C)
FD6HA60	Hybrid drying of freeze drying (6 hours) with hot air drying (60˚C)
FD12HA60	Hybrid drying of freeze drying (12 hours) with hot air drying (60˚C)
FIR	Far infrared
FRAP	Ferric reducing antioxidant power (μmol Fe(II)/g)
h	Hue angle (˚)
HA	Hot air
HA50	Hot air drying (50˚C)
HA60	Hot air drying (60˚C)
HA70	Hot air drying (70˚C)
HA80	Hot air drying (80˚C)
HP	Heat pump

IC_{50}	Concentration of the extract or standard solution that reduce absorbance value of DPPH solution by 50% (mg/ml)
IM&CD	Intermittent microwave-convection drying
IR	Infrared
IR60	Infrared drying (60˚C)
IR70	Infrared drying (70˚C)
IR80	Infrared drying (80˚C)
JAR	Just About Right
L	Half slab thickness (m)
L_0	L* parameter for reference sample
L*	Colour parameter (darkness to brightness)
$M_{bone\ dry}$	Bone dry weight (g dry solid)
MC	Moisture content (g H_2O/g dry solid)
MC_e	Equilibrium of moisture content (g H_2O/g dry solid)
MC_i	Initial moisture content (g H_2O/g dry solid)
MC_t	Moisture content after time t (g H_2O/g dry solid)
MD	Microwave drying
MIRD	Mid-infrared radiation
MIRD-FD	Combined mid-infrared radiation with freeze drying
MR	Moisture ratio
M_t	Weight of fruit slab at any time (g)
MW	Microwave
Na_2CO_3	Sodium carbonate

$Na_2S_2O_8$	Sodium persulfate
NIR	Near infrared
NPT	Non pre-treated
P	Pressure (kPa)
PPO	Polyphenol oxidase
R_g	Universal gas constant (8.3145 J/mol.K)
SIRFD	Sequential infrared radiation and freeze drying
SMIR	Short and medium-wave infrared radiation
T	Temperature (˚C)
T_{abs}	Absolute temperature (K)
TEAC	Trolox equivalent antioxidant capacity (µmol Trolox/100g dry solid)
TPC	Total polyphenols content (mg GAE/g dry sample)
t	Time (s)
V	Air velocity (m/s)
VC	Vitamin C (mg AA/100g dry solid)
VMW	Vacuum microwave
V_s	Volume of standard solution or filtrate (m^3)
V_f	Volume of extracted filtrate (m^3)
WB	Water blanching
ΔE	Total colour change
-	Too little
+	Too much

CHAPTER 1

INTRODUCTION

Background

Kedondong fruit (*Spondias dulcis* Forst.) (Figure 1.1) is an underutilized fruit currently planted in Malaysia but only in small quantity (around 46.5 ha). It has various local names such as ambarella, jew plum, june plum, golden apple, otaheite apple, caja-manga, pomme cythere, hogplum, ma-kok-farang, mokak and so on, according to the origins of the plant. The fruit belongs to Anarcardiacea family which includes mango (*Mangifera indica* L.) and cashew (*Anarcardium occidentale* L.) (Mohammed, 2011). Kedondong is gaining interest in many countries like Malaysia, India, Ceylon, Queensland, Australia, Philippines, Gabon and Zanzibar as it is nutritious and can be planted easily (Ishak *et al*., 2005).

Figure 1.1: (a) Kedondong fruit and (b) kedondong plant

Kedondong fruit is oval in shape with dimensions 2.5 - 3.5 cm in width and 3 - 5 cm in length. In mature green stage, it can be eaten raw and it has a flavor mix between green

mango and pineapple. It can also be made into fresh juice or can be preserved as pickles using vinegar, sugar and salt. Besides, the fruit can be cooked with water and sugar, and then made into sauce similar to apple sauce. Other than that, the fruit can also be cooked into thick concentrate with cinnamon and other spices (Mohammed, 2011).

Kedondong fruit is rich in total polyphenols, vitamin C, carotenoids and vitamin A. Besides, it also consists of small amount of protein, minerals like phosphorus, calcium, magnesium, sodium and zinc (Ishak *et al*., 2005). All of these nutrients may prevent degenerative disease such as cancer, arthritis, arteriosclerosis, heart disease, inflammation, brain dysfunction and ageing process.

Kedondong fruit is highly perishable especially at storage temperature above 25˚C. Drying is one of the potential methods to extend the shelf life and preserve its nutrients by removing the moisture within the fruit that assures microbial stability and minimizes chemical and physical changes of the dried products during storage. According to World Integrated Trade Solution (WITS), amount of dried fruit that were imported and exported in Malaysia were 160,220 kg and 21,524 kg, respectively, in year 2018. To date, studies on drying of kedondong fruits are quite scarce and not widely available in literatures. Recently, local government agency have initiated program to promote planting of underutilized fruits and improve farmers' revenue by diversifying product range including production of dried fruit chips (CFF, 2014). Therefore, it is desirable to carry out this research to investigate the drying characteristics of kedondong fruits for commercial production. Various technologies are available in the market for fruit drying such as hot air drying, vacuum drying, infrared drying, microwave drying, freeze drying, sun drying, solar drying and so on. However, hot air drying (convective drying) is the oldest and commonly

used drying method to preserve food. The technology is simple and operating cost is low (Salehi *et al*., 2017), however, the major disadvantages of hot air drying are such as low energy/thermal efficiency, low product quality and case hardening (Pan *et al*., 2008; Adak *et al*., 2017). Moreover, dried product quality are also inferior in terms of appearance (color/shrinkage), rehydration capacity, texture and nutritional content (Horuz *et al*., 2017a).

Recently, infrared drying has been studied by researchers due to its inherent advantages over conventional drying under similar drying conditions. Infrared radiation impinges on the exposed area of the food product could penetrate to create internal heating with molecular vibration and the radiation energy is then converted into heat to conduct the drying process. Infrared drying has better energy efficiency because infrared energy is transferred directly onto the product's surface without heating the surrounding air unlike in hot air drying. Therefore, this drying method offer advantages such as high energy efficiency, reduced drying time, high quality dried products and more uniform product temperature during drying.

Freeze drying is one of the most sophisticated drying methods that is known for producing high quality dehydrated food products. It can produce dried products that resemble the fresh products in terms of appearance (no shrinkage/colour change) and nutritional quality due to the vacuum (oxygenless) and low temperature sublimation process. However, freeze drying is costly and usually requires long drying time and it also requires pre-freezing prior to drying. Therefore, freeze drying is mainly used for highly priced medicinal or herbal plant products but commercially it has also been used in manufacturing of freeze dried durian, jackfruit, rambutan and mangosteen fruit snacks.

Problem Statement

Hot air drying is not conducive in producing high quality dried fruit products. On the other hand, freeze drying requires long drying time and incur high operating cost. Therefore, in order to speed up the drying process and reduce its overall cost of drying as well as to improve product quality of hot air dried products, hybrid drying methods were attempted in this research by combining freeze drying with either hot air or infrared drying. Hybrid drying has been reported able to maximize the benefit of the chosen drying methods and resulted in better quality dried products (Wang *et al*., 2015; Horuz *et al*., 2017b; Nathakaranakule *et al*., 2010).

Research Objectives

In this research, the main objective is to investigate the effects of hybrid drying on the drying kinetics and product quality of dried kedondong fruits. Specific objectives of the research are as follow:

- To investigate the drying kinetics of hot air, infrared and hybrid drying methods.
- To investigate the effect of hot air, infrared and hybrid drying methods on preservation of the bioactive compounds and nutrients in kedondong fruits.
- To investigate the effect of hot air, infrared and hybrid drying methods on physical and sensory quality attributes.

Contribution of Research

Research studies on kedondong fruits are very scarce to date and current research in drying aspects for this fruit are perhaps only the very few available in published literatures and none has been reported for hybrid drying. Production of premium dried tropical fruit snacks is starting to gain popularity in America, Europe and Middle East. Therefore, knowledge gained in conducting this research is able to provide information on the drying kinetics which are essential in design of dryers optimal for dried kedondong fruit snacks. In addition, investigation on product quality is able to provide information that are essential in ensuring only premium quality product is produced and with good shelf life.

CHAPTER 2

LITERATURE REVIEW

2.1 Nutritional Content of Kedondong

Kedondong fruits contain nutrients that can contribute positively to human health as reported in several published literatures (Table 2.1). Most studies show that kedondong contains total polyphenols content and vitamin C in the range of 33 - 686.5 mg/100g and 4.65 – 42 mg/100g, respectively (Ishak *et al*., 2005; Luximon-Ramma *et al*., 2003**;** Lim *et al*., 2007; Morton, 1987; Janick and Paull, 2008; Bhuiyan, 2012). Polyphenols and vitamin C can act as antioxidants to overcome free radicals in human body subsequently lowering incidence of degenerative disease such as cancer, arthritis, arteriosclerosis, heart disease, inflammation, brain dysfunction and ageing process (Hii *et al*., 2009). Besides, kedondong also contains 157.30 of calories, 0.20 – 2.33 % of protein, 0.28 – 1.79 % of fat, 8.05 – 10.54 % of sugar (sucrose), 0.85 – 3.60 % of crude fiber, 0.40 – 6.78 % of ash, 67.00 - 4.52 x 10^3 mg/100g of phosphorus, 29.88 – 56.00 mg/100g of calcium, 10.34 - 11.76 mg/100g of magnesium, 1.00 – 4.36 mg/100g of sodium, 0.24 – 0.29 mg/100g of zinc, 1.56 – 2.13 g Ca pectate/100g of pectin, 0.38 - 0.56 mg/100g of chlorophyll content, 309 µg/100g of cryptoxanthin, 364 µg/100g of lycopene, 201 µg/100g of β-carotene, 12.4 % of carbohydrate, 0.3 mg of iron, 95 mg/100g of potassium, 0.05 mg/100g of thiamine, 0.2 mg/100g of riboflavin, 1.4 mg/100g of niacin and 205 IU mg/100g of vitamin A (Morton, 1987; Ishak *et al*., 2005; Luximon-Ramma *et al*., 2003**;** Lim *et al*., 2007; Setiawan *et al*., 2000; Janick and Paull, 2008; Bhuiyan, 2012).

Table 2.1: Summary of nutritional value of kedondong from several studies

Food value	Morton (1987) Per 100g of edible portion*	Ishak *et al.* (2005)	Luximon-Ramma *et al.* (2003)	Lim *et al.* (2007)	Setiawan *et al.* (2000)	Janick and Paull (2008)	Bhuiyan (2012)
Calories	157.30	-	-	-	-	-	-
Total Solids (%)	14.53 – 40.35	-	-	-	-	-	-
Moisture (%)	59.63 – 85.47	89.0 – 90.0	-	-	-	86.9	-
Protein (%)	0.50 – 0.80	1.76 – 2.33	-	-	-	0.2	-
Fat (%)	0.28 – 1.79	0.34 – 0.53	-	-	-	-	-
Sugar (sucrose) (%)	8.05 – 10.54	-	-	-	-	-	-
Acid (%)	0.47	-	-	-	-	-	-
Crude Fiber (%)	0.85 – 3.60	-	-	-	-	1.1	-
Ash (%)	0.44 – 0.65	6.23 – 6.78	-	-	-	0.4	-
Phosphorus (mg/100g)	-	3.93×10^3 – 4.52×10^3	-	-	-	67.0	-
Calcium (mg/100g)	-	29.88 – 35.05	-	-	-	56.0	-
pH	-	3.59 – 3.87	-	-	-	-	-
Magnesium (mg/100g)	-	10.34 – 11.76	-	-	-	-	-

Table 2.1: Summary of nutritional value of kedondong from several studies (continue)

Food value	Morton (1987) Per 100g of edible portion*	Ishak *et al.* (2005)	Luximon-Ramma *et al.* (2003)	Lim *et al.* (2007)	Setiawan *et al.* (2000)	Janick and Paull (2008)	Bhuiyan (2012)
Sodium (mg/100g)	-	4.13 – 4.36	-	-	-	1.0	-
Zinc (mg/100g)	-	0.24 – 0.29	-	-	-	-	-
Titratable acidity (%)	-	0.81 – 0.88	-	-	-	-	-
Insoluble matter (%)	-	8.80 – 13.50	-	-	-	-	-
Soluble solid (Brix)	-	4.00 – 6.00	-	-	-	-	-
Pectin (g Ca pectate/ 100g)	-	1.56 – 2.13	-	-	-	-	-
Total phenolic content (mg/100g)	-	171.20 – 686.50	105.0	33.0	-	-	-
Vitamin C (mg/ 100g)	42.0	4.65 – 5.86	24.4	30.0	-	36.0	30.9
Total dietary fibre (% dry basis)	-	17.20 – 20.25	-	-	-	-	-
Chlorophyll content, (mg/100g)	-	0.38 – 0.56	-	-	-	-	-

Table 2.1: Summary of nutritional value of kedondong from several studies (continue)

Food value	Morton, (1987) Per 100g of edible portion*	Ishak *et al.* (2005)	Luximon-Ramma *et al.* (2003)	Lim *et al.* (2007)	Setiawan *et al.* (2000)	Janick and Paull (2008)	Bhuiyan (2012)
Cryptoxanthin (µg/100g)	-	-	-	-	309.0	-	-
Lycopene (µg/100g)	-	-	-	-	364.0	-	-
β-carotene (µg/100g)	-	-	-	-	201.0	-	-
Vitamin A (mg/100g)	-	-	-	-	-	205 IU	-
Energy (kcal)	-	-	-	-	-	46.0	-
Lipid (%)	-	-	-	-	-	0.1	-
Carbohydrate (%)	-	-	-	-	-	12.4	-
Iron (mg)	-	-	-	-	-	0.3	-
Potassium (mg/100g)	-	-	-	-	-	95.0	-
Thiamine (mg/100g)	-	-	-	-	-	0.05	-
Riboflavin (mg/100g)	-	-	-	-	-	0.2	-
Niacin (mg/100g)	-	-	-	-	-	1.4	-

Polyphenols, proanthocyanidins, flavonoids and vitamin C may contribute to antioxidant activities (Luximon-Ramma *et al*., 2003). Table 2.2 shows the total polyphenols content (TPC) of kedondong reported by Luximon-Ramma *et al*. (2003) at 1050 µg/g which is higher than pineapple, banana, avocado, jamalac, passion fruit, mango, papaya, litchi and longanberry (Range 118 - 576 µg/g in these fruits) whereas Lim *et al*. (2007) found that TPC of kedondong was only 330 µg/g which is higher than papaya and dragon fruit. Great difference in TPC values between the two findings could be due to different methods of measuring TPC where Luximon-Ramma *et al*. (2003) used both fruit pulp and skin whereas Lim *et al*. (2007) used only fruit pulp. Besides, flavonoids content of kedondong (183 µg/g) is higher than starfruit, pink guava, pineapple, banana, avocado, jamalac, jamblon, passion fruit, litchi and longanberry (Range 21 - 159 µg/g in these fruits). Proanthocyanidins content of kedondong (167 µg/g) is higher than pink guava, pineapple, banana, avocado, jamalac, passion fruit, litchi and longanberry (Range 7 - 109 µg/g in these fruits), whereas vitamin C of kedondong (244 µg/g) is also higher than starfruit, chinese guava, banana, avocado, jamalac, passion fruit, and litchi (Range 8 - 242 µg/g in these fruits). Trolox equivalent antioxidant capacity (TEAC) and Ferric reducing antioxidant power (FRAP) are the methods used to determine the radical scavenging ability. Kedondong (6 µmol Trolox/g) was found higher than pineapple, banana, avocado, jamalac, passion fruit, mango, litchi and longanberry (Range 1 – 5 µmol Trolox/g in these fruits). Therefore, kedondong can be recommended as nutritional supplement in daily food intake.

Table 2.2: Total polyphenols, flavonoid, proanthocyanidin, vitamin C contents and antioxidant activities as assessed by TEAC and FRAP assays of commonly consumed Mauritian fruits (Luximon-Ramma *et al*., 2003)

Scientific name	Common name	Fruit type	Total phenolics[a] (µg/g)	Flavonoids[b] (µg/g)	Proanthocyanidins[c] (µg/g)	Vitamin C[d] (µg/g)	TEAC[e] (µmol Trolox/g)	FRAP[f] (µmol Fe(II)/g)
Averrhoa carambola	Starfruit	Acid	1429 ± 71	103 ± 11	896 ± 23	190 ± 15	11 ± 2	9 ± 0
		Sweet	2099 ± 104	148 ± 9	1321 ± 61	144 ± 3	17 ± 4	22 ± 1
-	Starfruit		1310 ± 540*	-	-	-	-	-
Psidium cattleianum	Chinese guava	Red	5638 ± 364	712 ± 32	2561 ± 101	242 ± 15	47 ± 5	34 ± 1
		Yellow	5372 ± 186	308 ± 13	2409 ± 89	200 ± 3	45 ± 3	25 ± 0
Psidium guajava	Guava	Pink	1264 ± 60	110 ± 21	109 ± 14	722 ± 6	7 ± 1	8 ± 0
		White	2473 ± 45	209 ± 10	263 ± 31	1426 ± 26	17 ± 2	14 ± 1
-	Guava	Seeded	1380 ± 310*	-	-	-	-	-
-		Seedless	1790 ± 440*	-	-	-	-	-
Spondias dulcis	Hogplum	-	1050 ± 43	183 ± 7	167 ± 13	244 ± 0	6 ± 1	7 ± 0
-	Kedondong	-	330 ± 50*	-	-	-	-	-
Ananas comosus	Pineapple	Bourgault	479 ± 14	159 ± 8	14 ± 0	275 ± 0	2 ± 1	3 ± 0
Musa acuminata	Banana	Gingeli	118 ± 4	56 ± 0	51 ± 7	8 ± 1	1 ± 0	3 ± 0

Table 2.2: Total polyphenols, flavonoid, proanthocyanidin, vitamin C contents and antioxidant activities as assessed by TEAC and FRAP assays of commonly consumed Mauritian fruits (Luximon-Ramma *et al*., 2003) (continue)

Scientific name	Common name	Fruit type	Total phenolics[a] (µg/g)	Flavonoids[b] (µg/g)	Proanthocyanidins[c] (µg/g)	Vitamin C[d] (µg/g)	TEAC[e] (µmol Trolox/g)	FRAP[f] (µmol Fe(II)/g)
-	Banana	Mas	510 ± 70*	-	-	-	-	-
Persea americana	Avocado	-	242 ± 19	21 ± 0	7 ± 0	11 ± 1	2 ± 0	1 ± 0
Litchi chinensis	Litchi	-	288 ± 17	94 ± 6	100 ± 9	138 ± 15	5 ± 1	3 ± 1
Syzygium samarangense	Jamalac	-	320 ± 14	31 ± 4	33 ± 9	151 ± 20	2 ± 0	2 ± 0
-	Water apple	-	350 ± 40*	-	-	-	-	-
Syzygium cumini	Jamblon	-	2359 ± 47	135 ± 7	453 ± 85	319 ± 0	15 ± 2	16 ± 0
Passiflora edulis	Passion fruit	Orange	574 ± 107	121 ± 17	12 ± 1	86 ± 15	3 ± 0	3 ± 1
-	Orange	-	750 ± 100*	-	-	-	-	-
Mangifera indica	Mango	Maison Rouge	560 ± 21	281 ± 28	168 ± 11	605 ± 15	5 ± 1	5 ± 0

Table 2.2: Total polyphenols, flavonoid, proanthocyanidin, vitamin C contents and antioxidant activities as assessed by TEAC and FRAP assays of commonly consumed Mauritian fruits (Luximon-Ramma *et al*., 2003) (continue)

Scientific name	Common name	Fruit type	Total phenolics[a] (µg/g)	Flavonoids[b] (µg/g)	Proanthocyanidins[c] (µg/g)	Vitamin C[d] (µg/g)	TEAC[e] (µmol Trolox/g)	FRAP[f] (µmol Fe(II)/g)
Carica papaya	Papaya	Exotica	576 ± 41	376 ± 15	208 ± 21	929 ± 19	10 ± 0	2 ± 0
-	Papaya	Solo	280 ± 60*	-	-	-	-	-
Euphoria longan	Longanberry	-	154 ± 23	79 ± 5	109 ± 12	266 ± 15	3 ± 1	0.3 ± 1
-	Dragon fruit	-	210 ± 60*	-	-	-	-	-
-	Langsat	-	1000 ± 290*	-	-	-	-	-

[a] µg gallic acid g^{-1} fresh weight; [b] µg quercetin g^{-1} fresh weight; [c] µg cyaniding chloride g^{-1} fresh weight; [d] µg ascorbic acid g^{-1} fresh weight; [e] µmol Trolox g^{-1} fresh weight; [f] µmol Fe(II) g^{-1} fresh weight;
* TPC value were found by Lim *et al*., 2007

Table 2.3 shows that orange is rich in ascorbic acid and Lim *et al*. (2007) reported only guava and papaya has ascorbic acid value higher than orange. Kedondong has moderate amount of ascorbic acid (30 mg/100g) as compared to orange as shown in Table 2.3. IC_{50} is the amount of fruit sample extracted into 1 ml solution necessary to decrease by 50 % the initial DPPH concentration. The lower IC_{50}, the better it is in scavenging the radicals, particularly peroxy radiclas which are propagator of the autoxidation of lipid molecules and thereby break the free radical chain reaction (Lim *et al*., 2007). Kedondong recorded IC_{50} at 9.9 which has a higher ability to scavenge the radical compare to banana, dragon fruit, langsat, mangosteen and water apple.

Table 2.3: The total polyphenols and ascorbic acid contents, IC_{50} and AEAC of tropical fruits (orange is included for comparison) (Lim *et al*., 2007)

Fruits	AAC (mg/100g)	IC_{50} (mg/ml)	AEAC (mg/100g)
Guava (seeded)[8]	144 ± 60	1.71 ± 0.61	218 ± 79
Guava (seedless)[6]	132 ± 46	2.11 ± 0.63	176 ± 54
Banana (mas)[6]	4.9 ± 0.6	13.4 ± 2.5	27.8 ± 5.5
Dragon fruit[3]	8.0 ± 1.6	27.5 ± 3.9	13.5 ± 2.1
Kedondong[7]	30 ± 5	9.9 ± 1.9	37.6 ± 7.6
Langsat[3]	3.9 ± 1.0	25.4 ± 7.3	14.6 ± 4.3
Mangosteen[5]	5.8 ± 0.8	11.5 ± 3.6	32.3 ± 10.3
Papaya (Solo)[3]	108 ± 16	3.5 ± 0.9	106 ± 28
Star fruit[7]	5.2 ± 1.9	3.8 ± 2.1	98 ± 55
Water apple[4]	4.1 ± 2.1	12.0 ± 3.8	31 ± 10
Orange[5]	67 ± 9	5.4 ± 1.3	69 ± 17

The superscript numerals are the number of samples studied.

2.2 Drying Methods

Most fruit products can be dried using various methods such as hot air drying, vacuum drying, infrared drying, microwave drying, freeze drying, hybrid drying, sun drying, solar drying and so on to reduce the moisture content within the fruit in order to minimize spoilage and increase shelf life of the dried products. It is important not only to successfully dry the fruit product but also able to have quality attributes acceptable by consumers.

2.2.1 Hot air drying

Hot air drying is the most common and oldest drying method used in food industry where more than 85 % of industrial dryers are the air convective type (Zarein *et al*., 2015) and the cost of drying is low (Salehi *et al*., 2017). In other word, hot air is used to supply heat for evaporation of moisture and convection air is used to carry away the evaporated moisture from the product. During drying, samples are exposed to the drying air under constant temperature and air velocity. Temperature gradient between drying air and the samples causes heat and mass transfer to occur. Due to the inefficient heat transfer mechanism and poor thermal conductivity of the food sample, heat transfer is therefore not that efficient to penetrate to the inner section of the sample (Pan *et al*., 2008) and usually results in prolonged drying time. Disadvantages of hot air drying are such as increase in energy consumption, nutrition degradation due to longer exposure time to oxygen, inferior quality such as darkening and hardening of the dried sample and lower rehydration ability. Figure 2.1 shows schematic diagram of conventional type hot air cabinet dryer. The system essentially consists of an air inlet, fan, electrical heater, product tray and air outlet. Air inlet is heated to the required temperature by electric heater and channeled to the samples placed

on the tray by fan (Kassem *et al*., 2011). Heat is supplied to the surface of the sample by convection from the circulating hot air (Sakai and Hanzawa, 1994). Other examples of hot air convective dryer are such as tunnel dryer and conveyor belt dryer (Sabarez, 2016).

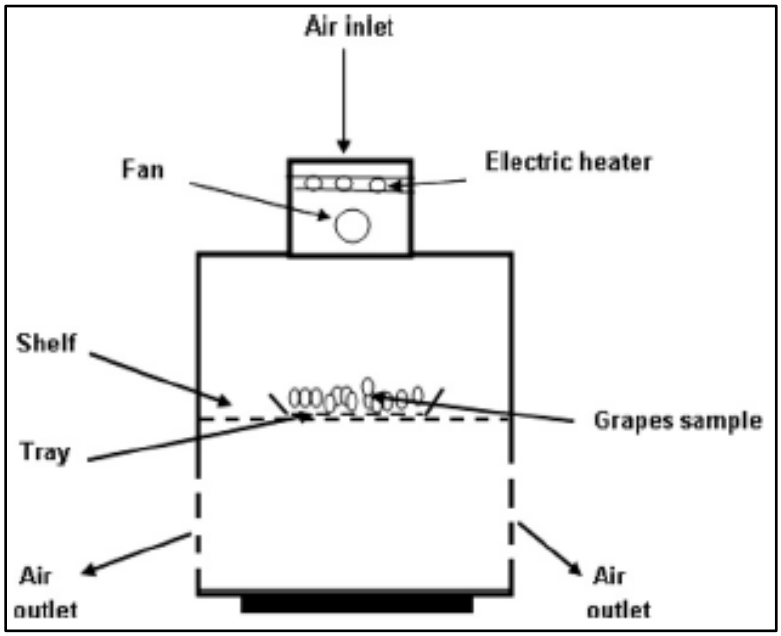


Figure 2.1: Schematic diagram of conventional oven (Kassem *et al*., 2011)

2.2.2 Infrared drying

Infrared drying generates interest over hot air drying due to its inherent advantages such as higher energy efficiency, shorter drying time and better product quality (Wang *et al*., 2015). This drying method heats up sample by infrared radiation which is a form of electromagnetic energy located between visible light (wavelength = 0.38 μm - 0.78 μm) and microwave (radio wave) (wavelength = 1 mm – 1000 mm) as shown in Figure 2.2 (Herschel, 2020). Infrared can be further classified into three classes namely near infrared (NIR = 0.78 μm – 1.4 μm), mid-infrared (mid-IR = 1.4 μm - 3 μm) and far infrared (FIR 3 μm - 1000 μm). Hashimoto *et al*. (1991) found that drying rate of granular bed of products (alumina, silver and stainless steel powder) irradiated by far infrared is higher than near infrared. During infrared drying, the radiation that impinges on the samples' surface penetrates the sample and heat up the moisture within the inner part of the samples (Togrul, 2005; Hebbar *et al*., 2004). Depth of penetration is depending on the wavelength (Pan *et al*., 2008) and this creates molecular vibration that subsequently generates heat both at surface and inner layers that dry the samples (Hebbar *et al*., 2004). This heating method reduces the necessity for air flow across the samples thus it is more efficient than hot air drying. Furthermore, the heating method is more uniform than hot air drying as irregular surface of sample has lesser effect on heat transfer (Sakai and Hanzawa, 1994). Figure 2.3 shows schematic diagram of an infrared oven. Heat is supplied by the infrared heater in the form of electromagnetic wave that passes through the air and it is readily absorbed by the food through conduction. The rate of energy transfer depends on the temperature different between the heater and the food. This drying method is normally used in food industries for baking (roasting), drying, pasteurization and thawing (Sakai and Hanzawa, 1994).

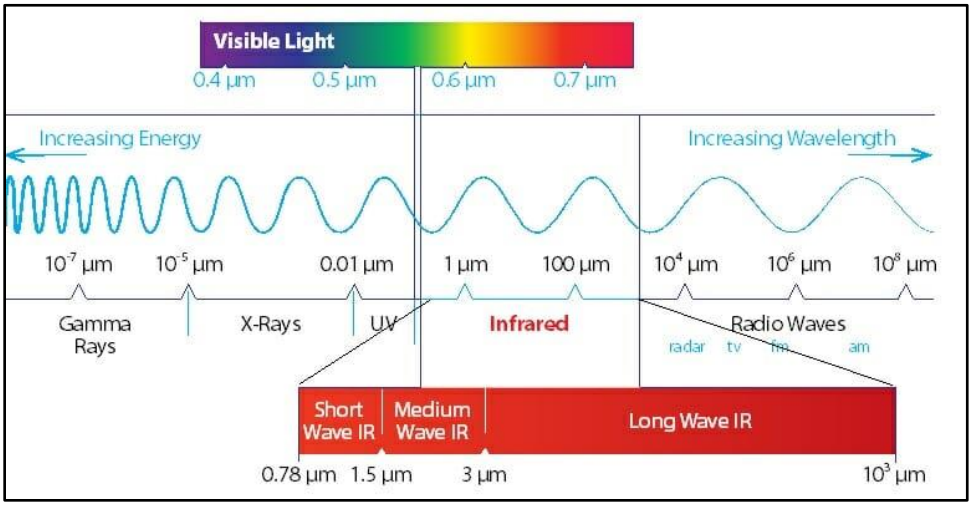


Figure 2.2: Types of infrared radiations

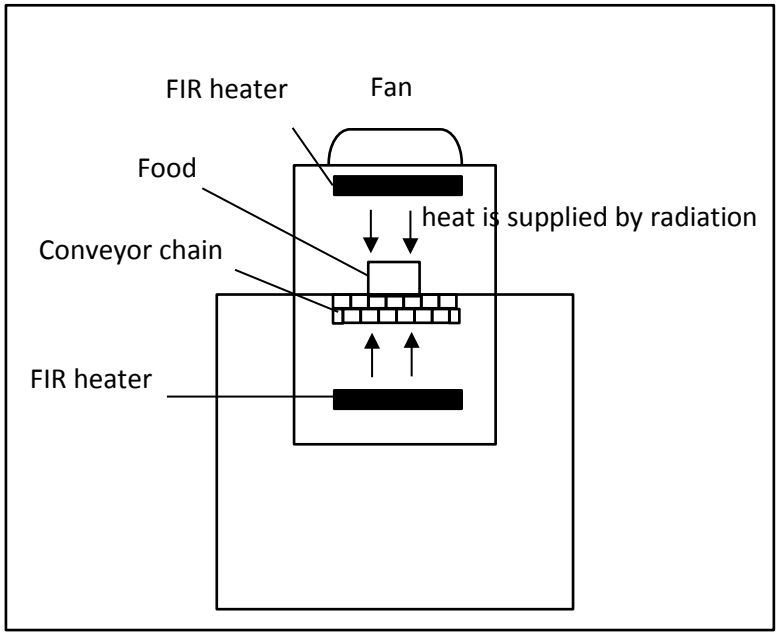


Figure 2.3: Schematic diagram of far infrared dryer (Sakai and Hanzawa, 1994)

2.2.3 Freeze drying

Freeze drying is generally known as the best method in preserving food nutrients, appearance and flavor close to the fresh products. This is mainly due to the operation under vacuum, low/mild temperature and oxygenless condition. The drying process removes moisture from the frozen sample by sublimation where moisture in solid state (ice) is directly transformed into vapour without passing through a liquid state (Serna-Cock *et al*., 2015). This can be carried out when the operating temperature and pressure are adjusted to below the triple point of water (0.01˚C, 0.612 kPa) as indicated in the phase diagram of water in Figure 2.4 (Duan *et al*., 2007; Serna-Cock *et al*., 2015; Berk, 2018). Figure 2.5 shows schematic diagram of a freeze dryer and the steps involved in freeze drying namely (i) freezing, (ii) primary drying and (iii) secondary drying. Moisture within the sample was frozen prior entering the dryer for primary drying process. In primary drying, the samples are placed on shelves inside the drying chamber and a vacuum pump is used to lower the pressure for sublimation process to occur. The shelves can be heated to accelerate the sublimation process. Then, the evaporated vapour is removed by a low temperature condenser plates through freezing. The concentration gradient of water vapour between the drying front and condenser is the main driving force for moisture removal during freeze drying (Nireesha *et al*., 2013). Upon completion of primary drying, all ice crystals have sublimed yet bound moisture are still present in the samples. Therefore, the shelves temperature are increased in secondary drying which is a desorption process to further remove the bound moisture in the sample. Typically, the drying time of secondary drying is about 1/3 or 1/2 of the drying time of primary drying.

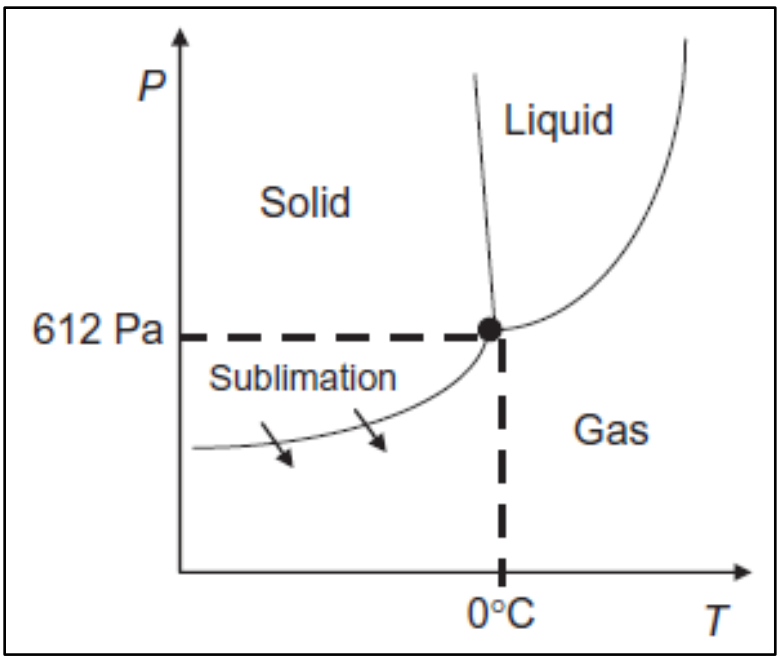


Figure 2.4: Phase diagram of water (Berk, 2018)

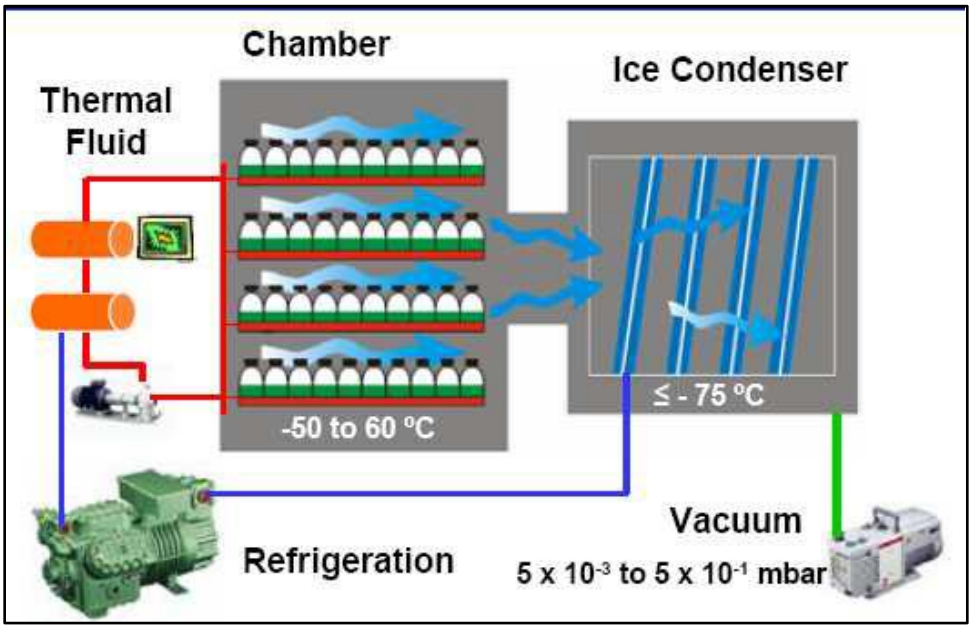


Figure 2.5: Freeze dryer design (Nireesha *et al*., 2013)

Freeze drying is able to protect the primary structure and shape of the products, hence, the resultant product has high porosity, low bulk density and better rehydration capability (Wang *et al*., 2015; Cui *et al*., 2008). However, a major disadvantage of this drying method is the long drying time, low throughput and high energy consumption. In addition, sample freezing, heating of the frozen sample to assist sublimation and operation under vacuum also increase energy consumption and operating cost (Pei *et al*., 2014b). Therefore, freeze drying is mainly used for higher value added food products (e.g. herbal and medicinal products) that can be sold at a much higher price in the market. Freeze dried sample is also used as a benchmark to compare dried products produced from other drying methods.

2.2.4 Hybrid drying

Hybrid drying is a combined drying method that takes the benefit of each drying method and packaged it into a cost and energy efficient drying process. Table 2.4 shows examples of hybrid drying studies carried out by researchers. In general, hybrid drying has advantages such as shorter drying time and faster drying rate which subsequently reduce energy consumption as compared to conventional drying (Horuz *et al*., 2017a; Wang *et al*., 2015; Sharma and Prasad, 2001; Nathakaranakule *et al*., 2010; Horuz *et al*., 2017b; Hebbar *et al*., 2004). Besides, it also has advantages such as lower drying temperature (Salehi *et al*., 2017), crispier product (Pan *et al*., 2008; Yi *et al*., 2016), better colour retention (Wang *et al*., 2015; Sharma and Prasad, 2001; Hebbar *et al*., 2004; Yi *et al*., 2016), higher retention of flavor (Sharma and Prasad, 2001), lesser shrinkage (Nathakaranakule *et al*., 2010), higher rehydration capacity (Nathakaranakule *et al*., 2010; Horuz *et al*., 2017b; Yi *et al*., 2016), lower hardness (Nathakaranakule *et al*., 2010; Hebbar *et al*., 2004), lesser total polyphenols degradation (Horuz *et al*., 2017b), higher antioxidant capacity (Horuz *et al*., 2017b) and lower moisture content (Yi *et al*., 2016). However, hybrid drying also has few disadvantages such as shrinkage or crust formation of products in hybrid freeze drying and infrared drying (Pan *et al*., 2008; Wang *et al*., 2015), product browning in shiitake mushroom (Wang *et al*., 2015; Nathakaranakule *et al*., 2010), degradation of total polyphenols and lower antioxidant capacity in jackfruit (Yi *et al*., 2016).

Table 2.4: Advantages and disadvantages of hybrid drying

Sample	Hybrid drying	Advantages	Disadvantages	Sources
Button Mushroom	Infrared + vacuum drying	Low temperature		Salehi *et al*. (2017)
Banana	Sequential infrared radiation and freeze drying (SIRFD)	Product crispier than freeze drying product	-SIRFD did not reduce drying time -shrinkage/ crust formation in SIRFD due to exposed to heat	Pan *et al*. (2008)
Apricot	Microwave + conventional drying	Reduce drying time		Horuz *et al*. (2017a)
Shiitake Mushroom	Freeze drying + mid-infrared (FD-MIRD) Mid-infrared + freeze drying	-Reduce drying time -Energy saving -Colour parameter of FD-MIRD close to FD	-Browning at MIRD-FD -MIRD-FD greater shrinkage	Wang *et al*. (2015)
Garlic	Microwave + hot air dryer	-Reduce drying time -Increase drying rate -Lighter in colour -Higher retention of flavor		Sharma and Prasad (2001)
Longan	Hot air in combination with far-infrared radiation Heat pump in combination with far-infrared radiation	-Increase drying rate -Reduce energy consumption -Reduce drying time -Less shrinkage -Increase percentage rehydration -Reduce hardness and toughness	-Acceleration of non-enzymatic browning reaction	Nathakaranakule *et al*. (2010)

Table 2.4: Advantages and disadvantages of some hybrid drying combination (continue)

Sample	Hybrid drying	Advantages	Disadvantages	Sources
Sour Cherries	Microwave + conventional drying	-Reduce drying time -Reduce energy consumption -Lesser loss of total polyphenols content -Higher antioxidant capacities -Higher rehydration capacity		Horuz *et al*. (2017b)
Carrot and Potato	Infrared + hot air drying	-Reduce drying time -Lesser total colour change -Minimum case hardening -Lowest energy consumption		Hebbar *et al*. (2004)
Jackfruit	Instant control pressure drop (DIC) – assisted freeze drying (FD-DIC) Instant control pressure drop (DIC) – assisted hot air drying (AD-DIC)	-Lower moisture content as compared to freeze drying -total colour change of FD-DIC no significant different compare to freeze drying -FD-DIC higher crispness -No significant rehydration capacity between freeze drying and FD-DIC	-Lower total polyphenols, total carotenoid and antioxidant capacity compare to freeze drying	Yi *et al*. (2016)

2.3 Drying Kinetics

Table 2.5 shows the comparison of different drying methods on the effect of drying kinetics which includes drying time, effective diffusivity and activation energy.

2.3.1 Drying time

Aghbashlo *et al*. (2008), Babalis and Belessiotis (2014), Aral and Bese (2016), Lule and Koyuncu (2015), Horuz *et al*. (2017b) and Xiao *et al*. (2010) reported that drying at high temperatures resulted in reduction of total drying time due to increase in vapor pressure of the sample that speed up the moisture migration process from the inner part of the sample to the surface layer. For example, Aral and Bese (2016), Horuz *et al*. (2017b) and Xiao *et al*. (2010) found that average drying time reduced by 87 %, 76 % and 60 % for hawthorn fruits, sour cherry, and manuka grape, respectively, as drying temperature increased from 50˚C to 70˚C. On the other hand, an increase in air velocity was found to decrease the drying time due to the reduction in moisture barrier on the surface which facilitate the heat and mass transfer processes. Aral and Bese (2016) reported that drying time of hawthorn reduced by 15.7 %, 30.6 % and 37 % at constant drying temperature of 50˚C, 60˚C and 70˚C, respectively, as air velocity increased from 0.5 m/s to 1.3 m/s. Similar observation was observed by Xiao *et al*. (2010) in drying of manuka grape where the drying time decreased from 39 hours to 31 hours as air velocity increased from 3 m/s to 9 m/s.

Similar to hot air drying, by increasing the power of infrared and microwave drying results in reduced drying time due to formation of higher vapor pressure within the products. For example, reduced drying time had been observed in studies carried out by Wang *et al*. (2007) in microwave drying (150 W to 600 W) of apple pomace, Salehi *et al*. (2017) in

infrared drying (150 W to 375 W) of button mushroom, Lule and Koyuncu (2015) in microwave drying (90 W to 350 W) of sorbus and Togrul (2005) in infrared drying (50˚C to 80˚C) of apple. However, the drying time required for infrared and microwave drying are relatively shorter than hot air drying. For example, Hebbar *et al*. (2004) reported that total drying time of infrared heating for potato and carrot was 285 minutes which was faster than hot air drying (345 minutes). This is mainly attributed to the direct penetration of infrared and microwave that induces intense heating within the entire product (from inside to outside) in a quick and uniform manner. Subsequently, this leads to rapid evaporation of moisture whereas hot air drying only transfer heat from the drying air to the surface and formation of surface crust on product's surface further impedes the moisture migration process and thus longer drying time is needed (Pei *et al*., 2014b).

Freeze drying is known to require long drying time due to the mild temperature environment and also the slow sublimation process. Pei *et al*. (2014b) observed that combined freeze drying with microwave vacuum drying of button mushroom reduced total drying time by 35 %. Wang *et al*. (2015) found that combined mid-infrared radiation with freeze-drying (MIRD @25 min – FD) and freeze-drying with mid-infrared radiation (FD @2h – MIRD) reduced drying time of shiitake mushroom by 43 % and 59 %, respectively, as compared to freeze drying alone. Nevertheless, some combinations did not reduce the total drying time such as in sequential infrared radiation and freeze drying of banana (Pan *et al*., 2008), combined freeze drying and vacuum drying and combined freeze drying and hot air drying of button mushroom (Pei *et al*., 2014b). This is mainly due to the formation of surface crust in infrared radiation and hot air drying and this impeded the moisture migration from the inner part of the sample to the surface.

On the other hand, some other combinations were found able to reduce drying time as compared to single stage drying. For example, infrared combined with hot air drying of carrot and potato reduced drying time to 180 minutes as compared to hot air drying (345 minutes) and infrared drying (285 minutes) (Hebbar *et al*., 2004). Microwave (120 W) combined with hot air drying (50˚C) of sour cherry reduced drying time to 1680 minutes as compared to hot air drying at 50˚C (2940 minutes) (Horuz *et al*., 2017b). Heat pump (55˚C) combined with infrared drying (250 W) of longan reduced drying time to 12 hours as compared to heat pump drying at 55˚C (15.5 hours) (Nathakaranakule *et al*., 2010).

2.3.2 Effective diffusivity

Effective moisture diffusivity (D_{eff}) is the overall mass transport properties of the food products during drying. Food drying highly depends on internal diffusion of moisture to the food surface and this can be described using the Fick's second law equation. General solution of Fick's second law is as shown in Equation 2.1 (e.g. slab geometry) and it is frequently used to determine the effective diffusivity of food products. The general solution can be derived from the Fick's unsteady state diffusion equation (Rastogi and Raghavarao, 1997).

$$\text{Slab: } MR = \frac{8}{\pi^2}\sum_{n=0}^{n=\infty}\frac{1}{(2n+1)^2}\exp[\frac{-(2n+1)^2\pi^2 D_{eff}t}{4L^2} \quad (2.1)$$

where MR is the moisture ratio, D_{eff} is the effective moisture diffusivity (m^2/s), L is the half slab thickness (m) when evaporation occurs on both sides of the slab and t is the drying time (s).

In many cases, effective moisture diffusivity is estimated by using only the first term of the solution (n = 0) for long drying period. The equation can be simplified as shown in Equation 2.2. The equation can be linearized by multiplying natural log t both sides of the equation. Subsequently, by plotting natural log of the moisture ratio (lnMR) versus drying time (t), the slope can be obtained from the graph for calculation of effective moisture diffusivity.

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4L^2} t \quad (2.2)$$

The increase in the rate of moisture diffusion as affected by drying parameters such as drying temperature, air velocity and power could increase the effective diffusivity values. As shown in Table 2.5, the D_{eff} values of berberis increase from 8.19 $x10^{-10}$ m^2/s to 9.00 $x10^{-9}$ m^2/s (Aghbashlo *et al*., 2008), figs from 7.77 x 10^{-10} m^2/s to 2.43 x 10^{-9} m^2/s (Babalis and Belessiotis, 2004) and hawthorn from 2.341 x 10^{-10} m^2/s to 1.295 x 10^{-9} m^2/s at constant air velocity of 0.5 m/s (Aral and Bese, 2016), mango from 1.74 x 10^{-10} m^2/s to 3.00 x 10^{-10} m^2/s at constant air velocity of 1.8 m/s (Corzo *et al*., 2008) and manuka grape from 1.82 x 10^{-10} m^2/s to 5.84 x 10^{-10} m^2/s at constant air velocity of 5 m/s (Xiao *et al*., 2010) as affected by an increase in hot air temperature.

Increasing air velocity under constant air temperature in hot air drying also enhances effective diffusivity values (D_{eff}). Corzo *et al*. (2008) observed that D_{eff} of mango increased from 1.74 x 10^{-10} m^2/s to 2.23 x 10^{-10} m^2/s whereas Aral and Bese (2016) reported D_{eff} of hawthorn increased from 2.341 x 10^{-10} m^2/s to 2.708 x 10^{-10} m^2/s. However, some of the findings showed that D_{eff} values decreased with increasing air velocity such as berberis

from 8.19 x10^{-10} m^2/s to 3.32 x10^{-10} m^2/s (Aghbashlo *et al*., 2008) and figs from 7.77 x 10^{-10} m^2/s to 6.48 x 10^{-10} m^2/s (Babalis and Belessiotis, 2004) as air velocity increased from 0.5 m/s to 2 m/s and 0.5 m/s to 3 m/s, respectively. This is in agreement with the observation reported by Kumar and Prasad (2010) where higher air velocity on okra drying prolonged the drying process due to the cooling effect on the product surface that reduced the temperature gradient (driving force) that could assist the mass transfer process.

Wang *et al*. (2007) reported that an increase in microwave power during drying of apple pomace increased D_{eff} values from 1.05 x 10^{-8} m^2/s to 3.69 x 10^{-8} m^2/s. Salehi *et al*. (2017) observed similar trend on infrared drying of button mushroom where an increase in power increased D_{eff} values from 1.1 x 10^{-9} m^2/s to 2.3 x 10^{-9} m^2/s. Furthermore, Wang *et al*. (2007) reported that hybrid drying (combined hot air and microwave) of apple pomace was able to increase D_{eff} values from 1.047 x 10^{-8} m^2/s - 3.69 x 10^{-8} m^2/s to 2.99 x 10^{-8} m^2/s - 9.15 x 10^{-8} m^2/s.

2.3.3 Activation energy

Activation energy (E_a) is known as the minimum amount of energy require to initiate diffusion of moisture from the inner vicinity to the surface of the drying product. It can be determined by using the Arrhenius equation as shown in Equation 2.3 (Aghbashlo *et al*., 2008).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R_g T_{abs}}\right) \quad (2.3)$$

where D_0 is the pre-exponential constant (m^2/s), E_a is the activation energy (kJ/mol), R_g is the universal gas constant (8.3143 J/(mol.K)), and T_{abs} is the absolute temperature (K). By applying natural log at both sides of Equation 2.3, this gives Equation 2.4.

$$\text{Ln } D_{eff} = \text{Ln } D_0 - \frac{E_a}{R_g} . \frac{1}{T_{abs}} \quad (2.4)$$

By plotting Ln D_{eff} versus $1/T_{abs}$, the slope can be used to determine the activation energy (E_a). As shown in Table 2.5, activation energies of various fruit products show ranges of values. For example, green mango shows activation energies at 22.3 kJ/mol - 11.4 kJ/mol and half ripe mango at 9.3 kJ/mol - 8.7 kJ/mol at air velocity of 1.8 m/s and 1.91 m/s, respectively (Corzo *et al*., 2008). In figs drying, air velocity showed an impact on activation energies at 37.27 kJ/mol, 30.81 kJ/mol, 45.81 kJ/mol and 48.47 kJ/mol at air velocity range of 0.5 m/s – 3 m/s (Babalis and Belessiotis, 2004). However, activation energies of berberis are much higher at 110.837 kJ/mol, 118.910 kJ/mol, 130.610 kJ/mol and 124.356 kJ/mol (air velocity range of 0.5 m/s - 2 m/s) which could be due to the high moisture diffusion resistance skin layer (Aghbashlo *et al*., 2008).

2.4 Product Quality

Drying processes may affect partially or totally the quality of the final dried products and several process parameters have been identified able to impact product quality. These are summarized as shown in Table 2.6 (physical changes) and Table 2.7 (chemical changes).

Table 2.5: Summary of drying kinetics for different drying methods

Sample	Drying method	Drying parameter					Drying time (hour)	Effective diffusivity, D_{eff} (m^2/s)	Activation energy, E_a (kJ/mol)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)				
Berberis	HA	50	0.5				-	8.190×10^{-10}	110.837	Aghbashlo *et al*. (2008)
		60	0.5				-	4.545×10^{-9}		
		70	0.5				-	9.000×10^{-9}		
		50	0.7				-	5.984×10^{-10}	118.910	
		60	0.7				-	2.125×10^{-9}		
		70	0.7				-	7.921×10^{-9}		
		50	1.0				-	4.010×10^{-10}	130.610	
		60	1.0				-	1.799×10^{-9}		
		70	1.0				-	6.830×10^{-9}		
		50	2.0				-	3.320×10^{-10}	124.356	
		60	2.0				-	1.261×10^{-9}		
		70	2.0				-	4.944×10^{-9}		
Apple pomace	Microwave			150			77	1.047×10^{-8}		Wang *et al*. (2007)
				300			37	2.213×10^{-8}		
				450			29	2.716×10^{-8}		
				600			21	3.685×10^{-8}		
	HA + Microwave	105		150			23	2.992×10^{-8}		
		105		300			11.5	5.372×10^{-8}		
		105		450			8.5	7.515×10^{-8}		
		105		600			6.5	9.154×10^{-8}		
Button mushroom	Infrared vacuum drying			5	150		1.83	1.1×10^{-9}		Salehi *et al*. (2017)

Table 2.5: Summary of drying kinetics for different drying methods (continue)

Sample	Drying method	Drying parameter					Drying time (hour)	Effective diffusivity, D_{eff} (m^2/s)	Activation energy, E_a (kJ/mol)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)				
				5	250		1.50	1.7×10^{-9}		
				5	375		1.00	2.3×10^{-9}		
				5	150		-	1.1×10^{-9}		
				10	150		-	9.6×10^{-10}		
				15	150		-	8.3×10^{-10}		
				5	250		-	1.7×10^{-9}		
				10	250		-	1.4×10^{-9}		
				15	250		-	1.0×10^{-9}		
				5	375		-	2.3×10^{-9}		
				10	375		-	1.5×10^{-9}		
				15	375		-	1.5×10^{-9}		
Figs	HA	55	0.5				-	7.70×10^{-10}	37.27	Babalis and Belessiotis (2004)
		65	0.5				-	1.13×10^{-9}		
		75	0.5				-	1.68×10^{-9}		
		85	0.5				-	2.43×10^{-9}		
		55	1.0				-	1.33×10^{-9}	30.81	
		65	1.0				-	1.79×10^{-9}		
		75	1.0				-	2.59×10^{-9}		
		85	1.0				-	3.36×10^{-9}		
		55	2.0				-	1.23×10^{-9}	45.81	
		65	2.0				-	2.01×10^{-9}		
		75	2.0				-	3.05×10^{-9}		
		85	2.0				-	5.13×10^{-9}		
		55	3.0				-	6.48×10^{-10}	48.47	
		65	3.0				-	8.40×10^{-10}		

Table 2.5: Summary of drying kinetics for different drying methods (continue)

Sample	Drying method	Drying parameter					Drying time (hour)	Effective diffusivity, D_{eff} (m^2/s)	Activation energy, E_a (kJ/mol)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)				
		75	3.0				-	1.64×10^{-9}		
		85	3.0				-	2.73×10^{-9}		
Green mango	HA	50	1.80				-	1.74×10^{-10}	22.3	Corzo *et al*. (2008)
		60	1.80				-	2.09×10^{-10}		
		70	1.80				-	2.49×10^{-10}		
		80	1.80				-	3.00×10^{-10}		
		50	1.91				-	2.23×10^{-10}	11.4	
		60	1.91				-	2.71×10^{-10}		
		70	1.91				-	3.07×10^{-10}		
		80	1.91				-	3.15×10^{-10}		
Half ripe mango		50	1.80				-	2.30×10^{-10}	9.3	
		60	1.80				-	2.47×10^{-10}		
		70	1.80				-	2.80×10^{-10}		
		80	1.80				-	3.13×10^{-10}		
		50	1.91				-	2.52×10^{-10}	8.7	
		60	1.91				-	2.91×10^{-10}		
		70	1.91				-	3.08×10^{-10}		
		80	1.91				-	3.28×10^{-10}		
Longan	Heat pump	55					15.5			Nathakaranakule *et al*. (2010)
	Heat pump + IR	55			250		12			
		55			350		11			

Table 2.5: Summary of drying kinetics for different drying methods (continue)

Sample	Drying method	Drying parameter					Drying time (hour)	Effective diffusivity, D_{eff} (m^2/s)	Activation energy, E_a (kJ/mol)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)				
		55			450		9.5			
	HA	65					11			
	HA + IR	65			250		10.5			
		65			350		9			
		65			450		8			
Shiitake mushroom	FD	50					13			Wang *et al*. (2015)
	IR + FD	60				10	9.17			
						15	9.17			
						25	7.42			
	FD + IR	50				120	5.33			
						240	6.83			
						360	8.67			
Hawthorn	HA	50	0.5				140	2.341×10^{-10}	78.74	Aral and Bese (2016)
		60	0.5				49	7.071×10^{-10}		
		70	0.5				27	1.295×10^{-9}		
		50	0.9				135	2.381×10^{-10}	82.617	
		60	0.9				46	7.504×10^{-10}		
		70	0.9				22	1.486×10^{-9}		
		50	1.3				118	2.708×10^{-10}	91.54	
		60	1.3				34	1.043×10^{-9}		
		70	1.3				17	2.089×10^{-9}		

Table 2.5: Summary of drying kinetics for different drying methods (continue)

Sample	Drying method	Drying parameter					Drying time (hour)	Effective diffusivity, D_{eff} (m^2/s)	Activation energy, E_a (kJ/mol)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)				
Sorbus	HA	50					22			Lule and Koyuncu (2015)
		70					12			
	Microwave				90		15			
					160		6			
					350		3			
Sour cherry	HA	50					49			Horuz *et al*. (2017b)
		60					20			
		70					12			
Monukka grape	Air impinge hot air drying	50	5				51	1.82×10^{-10}	67.29	Xiao *et al*. (2010)
		55	5				45	2.92×10^{-10}		
		60	5				37	3.65×10^{-10}		
		65	5				21	5.84×10^{-10}		
		60	3				39			
		60	7				34			
		60	9				31			
Carrot	HA	80	1				5.75			Hebbar *et al*. (2004)
	IR	80					4.75			
	HA+IR	80	1				3			
Potato	HA	80	1				5.75			
	IR	80					4.75			

Table 2.5: Summary of drying kinetics for different drying methods (continue)

Sample	Drying method	Drying parameter					Drying time (hour)	Effective diffusivity, D_{eff} (m^2/s)	Activation energy, E_a (kJ/mol)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)				
	HA+IR	80	1				3			
Bananas	IR 20% + FD						23			Pan *et al*. (2008)
	IR 40% + FD						38			
	FD						21.1			
Button mushroom	FD						8			Pei *et al*. (2014b)
	FD 38% + HA						9			
	FD 38% + Vacuum drying						10.5			
	FD 38% + Microwave vacuum drying						5			

Table 2.6: Summary of physical characteristics of different drying method

Sample	Drying method	Drying parameter					Colour (ΔE)	Shrinkage (%)	Hardness (N)	Rehyd-ration ratio	Density (kg/dm^3)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)						
Button mushroom	Infrared vacuum drying			5	150		27.33	-	-	-	-	Salehi *et al*. (2017)
				10	150		37.44	-	-	-	-	
				15	150		38.92	-	-	-	-	
				5	250		30.99	-	-	-	-	
				10	250		37.52	-	-	-	-	
				15	250		40.79	-	-	-	-	
				5	375		33.10	-	-	-	-	
				10	375		38.27	-	-	-	-	
				15	375		60.40	-	-	-	-	
Longan	HP	55					-	88.7^{g}	19.56^{e}	-	-	Nathaka ranakule *et al*. (2010)
	HP+IR	55			250		-	85.1^{e}	16.02^{d}	-	-	
		55			350		-	79.0^{c}	15.84^{c}	-	-	
		55			450		-	76.9^{b}	13.26^{b}	-	-	
	HA	65					-	86.5^{f}	17.99^{de}	-	-	
	HA+IR	65			250		-	83.9^{d}	15.74^{bc}	-	-	
		65			350		-	83.8^{d}	14.67^{bc}	-	-	
		65			450		-	75.4^{a}	10.45^{a}	-	-	
Shiitake mushroom	FD (half dried)	50				120	5.77^{a}	-	-	-	-	Wang *et al*. (2015)
						240	5.71^{a}	-	-	-	-	
						360	3.00^{c}	-	-	-	-	

Table 2.6: Summary of physical characteristics of different drying method (continue)

Sample	Drying method	Drying parameter					Colour (ΔE)	Shrinkage (%)	Hardness (N)	Rehyd-ration ratio	Density (kg/dm^3)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)						
	MIRD (half dried)	60				10	5.04^{b}	-	-	-	-	
						15	4.78^{b}	-	-	-	-	
						25	6.90^{a}	-	-	-	-	
	FD	50					4.60^{c}	-	-	5.45^{a}	0.2854^{d}	
	MIRD (10min) - FD	60+ 50				10	10.00^{b}	-	-	4.95^{b}	0.3362^{c}	
	MIRD (15min) - FD	60+ 50				15	8.05^{b}	-	-	4.77^{bc}	0.3586^{b}	
	MIRD (25min) - FD	60+ 50				25	15.00^{a}	-	-	4.60^{c}	0.3715^{a}	
	FD (2h) - MIRD	50+ 60				120	7.99^{b}	-	-	4.62^{c}	0.3140^{c}	
	FD (4h) - MIRD	50+ 60				240	8.39^{b}	-	-	4.91^{bc}	0.2950^{d}	
	FD (6h) - MIRD	50+ 60				360	7.74^{b}	-	-	5.29^{a}	0.2905^{d}	
Hawthorn	HA	50	0.5				35.93	-	-	-	-	Aral and Bese (2016)
		60	0.5				25.47	-	-	-	-	
		70	0.5				17.11	-	-	-	-	

Table 2.6: Summary of physical characteristics of different drying method (continue)

Sample	Drying method	Drying parameter					Colour (ΔE)	Shrinkage (%)	Hardness (N)	Rehyd-ration ratio	Density (kg/dm^3)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)						
		50	0.9				33.78	-	-	-	-	
		60	0.9				24.16	-	-	-	-	
		70	0.9				11.92	-	-	-	-	
		50	1.3				32.13	-	-	-	-	
		60	1.3				17.98	-	-	-	-	
		70	1.3				11.05	-	-	-	-	
Monukka grape	Air impinge HA	50	5				-	-	9.53^{c}	-	-	Xiao *et al.* (2010)
		55	5				-	-	11.27^{c}	-	-	
		60	5				-	-	14.52^{b}	-	-	
		65	5				-	-	17.16^{a}	-	-	
		60	3				-	-	15.21^{b}	-	-	
		60	7				-	-	13.98^{b}	-	-	
		60	9				-	-	14.83^{b}	-	-	
	Fresh						-	-	0.62^{d}	-	-	
Jackfruit	FD		25	0.1			7.6^{a}	-	34^{a}	-	-	Yi *et al.* (2016)
	FDDIC						6.5^{a}	-	42^{b}	-	-	
	ADDIC	60	1.2				9.8^{b}	-	48^{c}	-	-	
Carrot	VMW				3000 1000 500	19 4 10	-	-	11.0	-	0.55	Lin *et al.* (1998)
	AD	70					-	-	18.1	-	1.13	
	FD	20					-	-	5.5	-	0.17	

Table 2.6: Summary of physical characteristics of different drying method (continue)

Sample	Drying method	Drying parameter					Colour (ΔE)	Shrinkage (%)	Hardness (N)	Rehyd-ration ratio	Density (kg/dm^3)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)						
Button mushroom	FD	40					-	-	1.74[a]	5.61[a]	0.11[a]	Pei *et al*. (2014b)
	FD 85% + AD						-	-	-	2.22[e]	1.36[c]	
	FD 38% + AD	40					-	-	2.26[b]	3.98[c]	0.12[a]	
	FD 20% + AD						-	-	-	4.04[c]	0.12[a]	
	FD 85% + VD						-	-	-	2.74[d]	0.31[b]	
	FD 38% + VD	40		-90			-	-	2.01[ab]	4.87[b]	0.11[a]	
	FD 20% + VD						-	-	-	5.02[b]	0.11[a]	
	FD85% + MVD						-	-	-	4.87[d]	0.11[b]	
	FD38% + MVD	40		-90	60 W/g		-	-	2.07[ab]	5.02[b]	0.11[a]	
	FD20% + MVD						-	-	-	2.68[b]	0.34[a]	
Murta berries	HA	40	1.5				23.3[de]	-	-	-	-	Puente-Diaz *et al*. (2012)
		50	1.5				25.8[def]	-	-	-	-	
		60	1.5				30.8[ef]	-	-	-	-	
	HA+IR	40	1.5		400		25.5[def]	-	-	-	-	
		40	1.5		800		32.7[f]	-	-	-	-	

Table 2.6: Summary of physical characteristics of different drying method (continue)

Sample	Drying method	Drying parameter					Colour (ΔE)	Shrinkage (%)	Hardness (N)	Rehyd-ration ratio	Density (kg/dm^3)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)	Time (min)						
		50	1.5		400		24.9^{def}	-	-	-	-	
		50	1.5		800		20.5^{d}	-	-	-	-	
		60	1.5		400		26.6^{def}	-	-	-	-	
		60	1.5		800		28.2^{def}	-	-	-	-	
Jujube	HA	60					12.91^{c}	-	-	-	-	Chen *et al*. (2015)
		70					13.40^{b}	-	-	-	-	
		80					12.50^{cd}	-	-	-	-	
		90					15.65^{a}	-	-	-	-	
	SMIR	60					7.57^{f}	-	-	-	-	
		70					12.27^{de}	-	-	-	-	
		80					12.12^{de}	-	-	-	-	
		90					12.76^{c}	-	-	-	-	

*T refer to temperature, V refer to air velocity, P refer to pressure

Table 2.7: Summary of chemical characteristics of different drying method

Sample	Drying method	Drying parameter				TPC (mg GAE/100g)	Antioxidant (%inhibition)	DPPH (mM TE g^{-1})	FRAP (mM TE g^{-1})	ABTS (mM TE g^{-1})	VC (mg AA/100g)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)							
Sour cherries	HA	50				239.67	12.21	-	-	-	58.13	Horuz *et al*. (2017b)
		60				235.22	14.97	-	-	-	56.99	
		70				225.52	17.89	-	-	-	54.98	
	MW+ HA	50			120	285.56	22.51	-	-	-	38.02	
		50			150	327.41	25.57	-	-	-	32.98	
		50			180	359.00	28.87	-	-	-	38.85	
		60			120	293.03	26.32	-	-	-	45.81	
		60			150	305.66	27.84	-	-	-	56.37	
		60			180	379.10	32.04	-	-	-	57.87	
		70			120	316.85	27.32	-	-	-	52.66	
		70			150	346.49	29.64	-	-	-	52.75	
		70			180	385.85	33.23	-	-	-	76.07	
	Fresh					1234.3	48.2	-	-	-	203.19	
Monukka grape	Air impinge HA	50	5			-	-	-	-	-	2.25	Xiao *et al*. (2010)
		55	5			-	-	-	-	-	1.48	
		60	5			-	-	-	-	-	0.94	
		65	5			-	-	-	-	-	0.57	
		60	3			-	-	-	-	-	0.86	
		60	7			-	-	-	-	-	0.79	
		60	9			-	-	-	-	-	1.03	
	Fresh					-	-	-	-	-	5.72	

Table 2.7: Summary of chemical characteristics of different drying method (continue)

Sample	Drying method	Drying parameter				TPC (mg GAE/100g)	Antioxidant (%inhibition)	DPPH (mM TE g^{-1})	FRAP (mM TE g^{-1})	ABTS (mM TE g^{-1})	VC (mg AA/100g)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)							
Strawberry	HA+IR	80	2		100	3517.1	-	-	-	-	-	Adak *et al*. (2017)
		80	2		200	3006.7	-	-	-	-	-	
		80	2		300	4499.3	-	-	-	-	-	
		60	2		200	4691	-	-	-	-	-	
		80	2		200	3006.7	-	-	-	-	-	
		100	2		200	3883.2	-	-	-	-	-	
		80	1.0		200	4744.6	-	-	-	-	-	
		80	1.5		200	4762.6	-	-	-	-	-	
		80	2.0		200	3006.7	-	-	-	-	-	
Jackfruit	FD	25				160	-	0.38	0.72	0.43	-	Yi *et al*. (2016)
	FDDIC					120	-	0.27	0.64	0.35	-	
	ADDIC	60	1.2			89	-	0.21	0.51	0.26	-	
	Fresh					180	-	0.50	1.00	0.54	-	
Murta berries	HA	40	1.5			2.17[b]	-	-	-	-	-	Puente-Diaz *et al*. (2012)
		50	1.5			1.40[e]	-	-	-	-	-	
		60	1.5			0.96[h]	-	-	-	-	-	
	HA+IR	40	1.5		400	3.27[c]	-	-	-	-	-	
		40	1.5		800	3.74[d]	-	-	-	-	-	
		50	1.5		400	2.93[f]	-	-	-	-	-	
		50	1.5		800	3.41[c]	-	-	-	-	-	

Table 2.7: Summary of chemical characteristics of different drying method (continue)

Sample	Drying method	Drying parameter				TPC (mg GAE/100g)	IC_{50} (mg/mL extract)	DPPH (mg AA g^{-1})	FRAP (g VC g^{-1})	ABTS (mM TE g^{-1})	VC (mg AA/100g)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)							
		60	1.5		400	1.77^{i}	-	-	-	-	-	
		60	1.5		800	2.22^{b}	-	-	-	-	-	
Ginger	Fresh					1197^{b}	1.11^{c}	3.49^{c}	19.37^{d}	64.45^{d}	-	An *et al*. (2016)
	AD	60				969^{d}	1.15^{a}	3.37^{d}	17.41^{e}	62.22^{e}	-	
	IR				225	1135^{c}	1.09^{d}	3.55^{b}	22.14^{a}	66.79^{c}	-	
	FD	25				1383^{a}	1.05^{e}	3.69^{a}	20.88^{c}	68.65^{b}	-	
	MD					841^{e}	1.13^{b}	3.42^{d}	15.66^{f}	60.06^{f}	-	
	IM&CD	60			700	1128^{c}	1.08^{d}	3.58^{b}	21.91^{b}	71.68^{a}	-	
Jujube	Fresh					-	-	-	-	-	1382^{a}	Chen *et al*. (2015)
	HA	60				-	-	-	-	-	746^{c}	
		70				-	-	-	-	-	524^{d}	
		80				-	-	-	-	-	479^{d}	
		90				-	-	-	-	-	477^{d}	
	SMIR	60				-	-	-	-	-	959^{b}	
		70				-	-	-	-	-	742^{c}	
		80				-	-	-	-	-	727^{c}	
		90				-	-	-	-	-	477^{d}	
Pepper	HA	50	1.5			-	-	-	-	-	69.1	Veras *et al*. (2012)
		60	1.5			-	-	-	-	-	80.0	
		70	1.5			-	-	-	-	-	86.0	
	FD					-	-	-	-	-	324.50	

Table 2.7: Summary of chemical characteristics of different drying method (continue)

Sample	Drying method	Drying parameter				TPC (mg GAE/100g)	IC_{50} (mg/mL extract)	DPPH (mg AA g^{-1})	FRAP (g VC g^{-1})	ABTS (mM TE g^{-1})	VC (mg AA/100g)	Source
		T (˚C)	V (m/s)	P (kPa)	Power (W)							
Strawberry	Fresh					-	-	-	-	-	528.42[a]	Orak *et al.* (2012)
	NPT+AD	65				-	-	-	-	-	246.95[e]	
	EO+AD	65				-	-	-	-	-	265.49[d]	
	WB+AD	65				-	-	-	-	-	192.56[f]	
	NPT+FD	30				-	-	-	-	-	396.46[b]	
	EO+FD	30				-	-	-	-	-	388.56[b]	
	WB+FD	30				-	-	-	-	-	362.65[c]	
Pineapple	HA	45	1.5			-	-	-	-	-	93.9%	Ramallo and Mascheroni (2012)
		60	1.5			-	-	-	-	-	79.7%	
		75	1.5			-	-	-	-	-	73.3%	

*T refer to temperature, V refer to air velocity, P refer to pressure

2.4.1 Colour

Colour is an important parameter that may affect consumer acceptance visually. This parameter indicates the nutrient retention of dried sample with the least colour change indicates the lowest deterioration in nutrient (e.g. lesser browning). Generally, colour change can be affected by enzymatic browning, non-enzymatic browning and pigment degradation. Enzymatic browning is an oxidation reaction of phenolic compounds with the presence of oxygen and polyphenol oxidase to produce dark brown melanin pigment as shown in Figure 2.6 (Whitaker and Lee, 1995; Marshall *et al*., 2000). This reaction is quite common especially in cut fruits that subject to air drying as the samples are exposed to oxygen rich environment. On the other hand, non-enzymatic browning can be classified as caramelization and Maillard reaction where caramelization is a sugar pyrolysis and oligomerization process while undergoes heat treatment as shown in Figure 2.7 (Aguiar *et al*., 2015). On the other hand, Maillard reaction is the reaction between carbonyl group (reducing sugar) and amino acid to form dark pigmentation that is known as melanoidin as shown in Figure 2.8 (Martins *et al*., 2001).

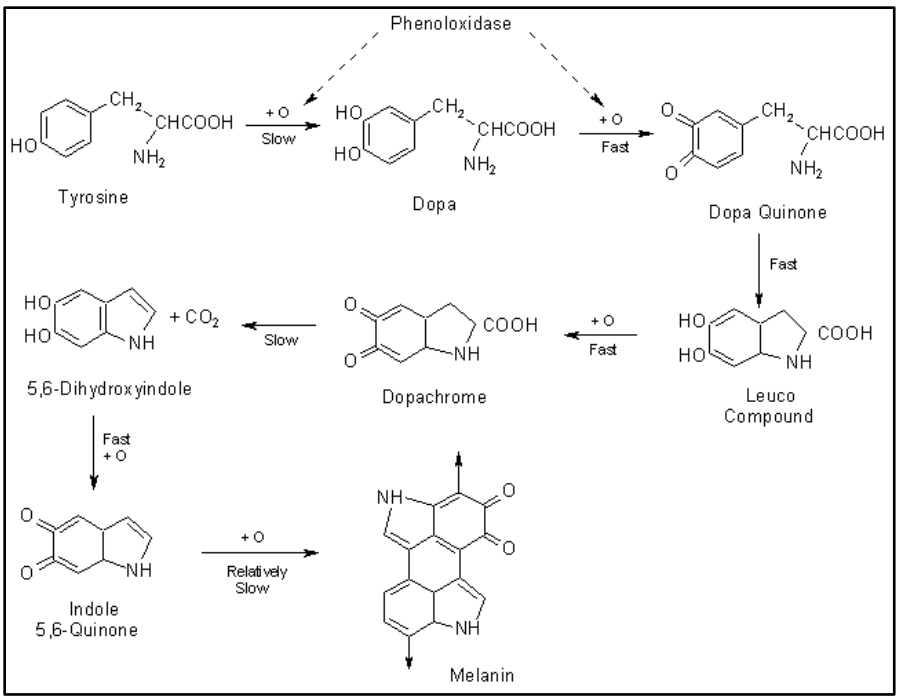


Figure 2.6: Example enzymatic browning of tyrosine (Marshall *et al*., 2000)

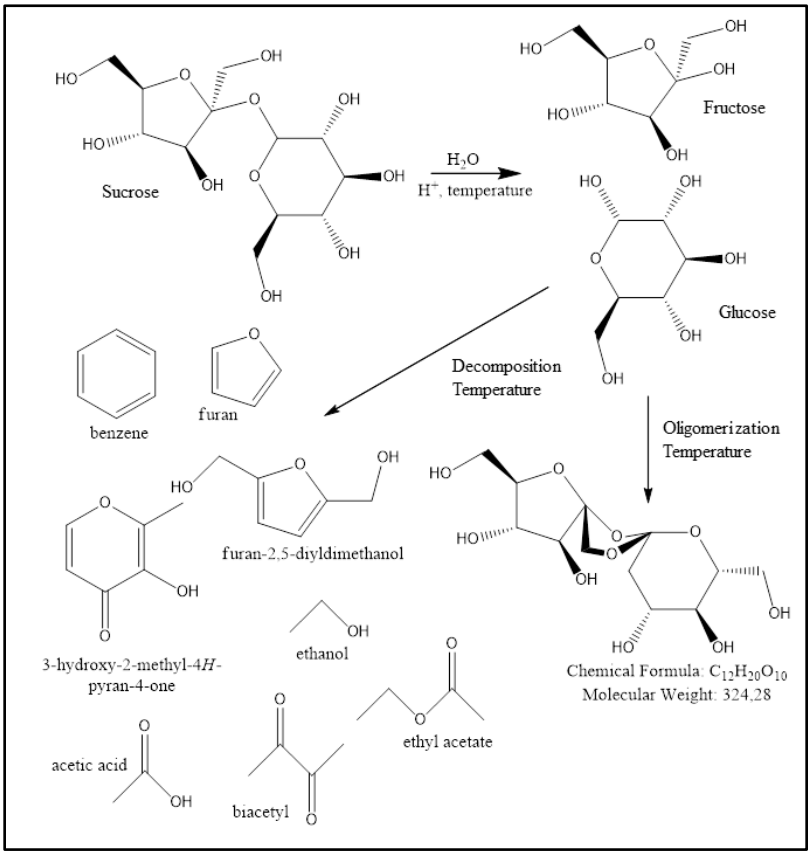


Figure 2.7: Example of caramelization (Aguiar *et al*., 2015)

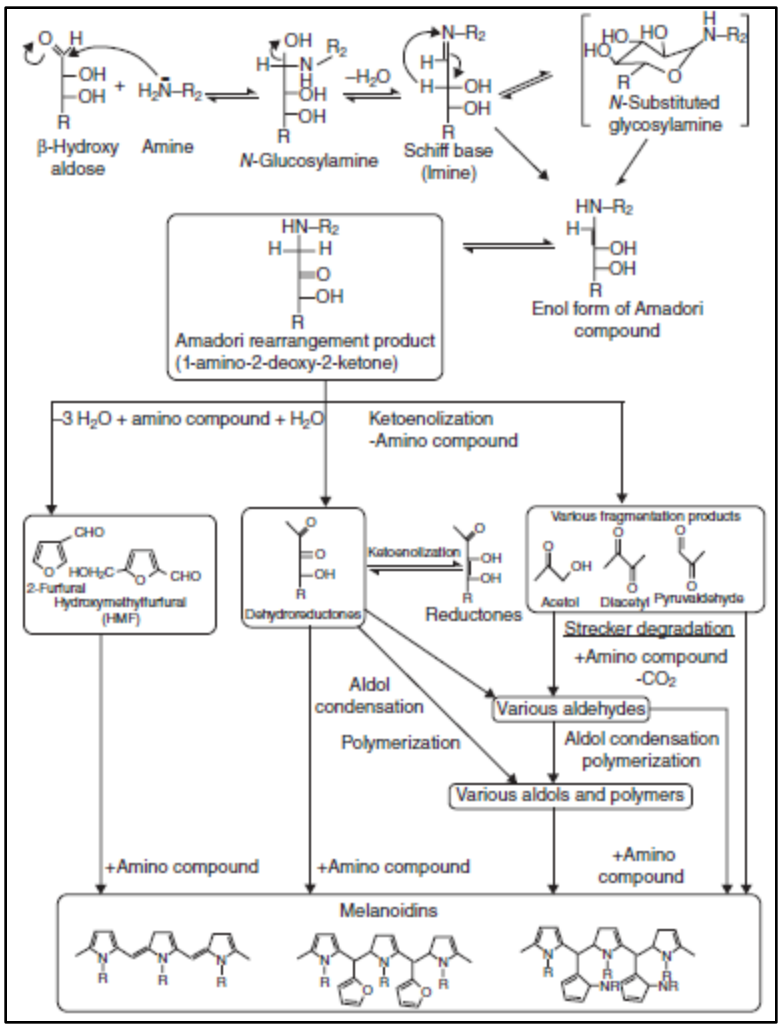


Figure 2.8: Example of Maillard reaction (Perez-Locas *et al*., 2010)

Total colour change (ΔE) of dried samples depend on many process variables such as temperature, drying time and oxygen during drying (Aral and Bese, 2016). As shown in Table 2.6, Puente-Diaz *et al*. (2012), Chen *et al*. (2015) and Salehi *et al*. (2017) reported that an increase in drying temperature or infrared power that subsequently raise the temperature of the sample resulted in higher total colour change. This is attributed to the increase in the reaction rate of the browning reaction where higher temperature promotes the hydrolysis of sucrose to glucose and fructose which subsequently react with amino acid

to form brown pigment. Similar observation had been reported by Borompichaichartkul *et al*. (2009) on hybrid drying of macadamia nut. However, Aral and Bese (2016) reported opposite observation in convective drying of hawthorn. The lowest temperature shows higher total colour change due to the longer drying time (8400 min, 2940 min and 1620 min at drying temperature 50˚C, 60˚C and 70˚C at air velocity of 0.5 m/s, respectively) which exposed the samples longer to heat. Also, by reducing the air velocity from 1.3 m/s to 0.5 m/s resulted in longer drying time (8400 min @ 0.5 m/s, 8100 min @ 0.9 m/s and 7080 min @ 1.3 m/s) hence higher total colour change was detected (Aral and Bese, 2016). On the other hand, Chen *et al*. (2015) found that total colour change of jujube dried using hot air drying is higher due to the longer drying time (580 min - 270 min at 60˚C - 90˚C) as compared to infrared drying (480 min - 90 min at 60˚C - 90˚C, respectively). It is noteworthy that increasing infrared power combined infrared and hot air drying of murta berry resulted in lower total colour change attributed to the reduction in drying time. However, this result was not observed at lower hot air temperature combination (40˚C) as longer time associated with lower temperature would intensify the effect of higher radiation on browning effect (Puente-Diaz *et al*., 2012). Wang *et al*. (2015) reported that freeze drying time play an important role in total colour change of combined freeze drying and mid-infrared drying. By setting 6 hours of freeze drying in this combined technique, it showed total colour change closer to the freeze dried sample as compared to the shorter period setting (2 hours and 4 hours freeze drying in combined technique) due to presence of lesser free water that could promote enzymatic browning reaction. Besides, the sequence used in combined drying is also important where mid-infrared drying before freeze drying was found having higher total colour change as compared to the reverse sequence. Yi *et al*.

(2016) reported that total colour change of combined freeze drying and instant control pressure drop (FD-DIC) was lower than combined air drying and instant control pressure drop (AD-DIC) because of lower color deterioration at the initial freeze drying stage that impeded browning.

2.4.2 Shrinkage, rehydration ratio, hardness and density

Shrinkage, rehydration ratio, hardness and density are directly related to the structure of the dried samples. Xiao *et al*. (2010) reported that drying temperature significantly affect the hardness of dried manuka grape by increasing the drying temperature from 50˚C to 65˚C and resulted in increase in product hardness from 9.53 N to 17.16 N. This is mainly due to case hardening as the removal of surface moisture is faster than internal moisture diffusion thus a hard crusty layer was formed on the surface due to precipitation of dissolve solutes. However, by increasing the power of far infrared radiation from 250 W to 450 W in combined drying of longan, this caused a reduction in hardness from 16.02 N to 13.26 N (Nathakaranakule *et al*., 2010). This is because of the in-situ vaporization of moisture due to direct penetration of IR radiation that generated heat within the sample. Therefore, moisture diffused from the inner part of the sample without carrying solutes to the surface (Lin *et al*., 1998) and at the same time vapour pressure generated within the sample resulted in puffing effect (Nathakaranakule *et al*., 2010). Similar observation was reported by Lin *et al*. (1998) when comparing vacuum microwave, hot air drying and freeze drying of carrot where internal heating of vacuum microwave was found to show lesser case hardening than that in hot air drying. Thus, hardness of dried products from vacuum microwave (11 N) is lesser than hot air drying (18.1 N) and freeze drying shows the lowest (5.5N) which could

be due the porous structure of the product. Pei *et al*. (2014b) observed much higher hardness for dried products from combined freeze drying and hot air drying (230.43 g) as compared to freeze drying alone (177.58 g) which could be due to the extreme shrinkage and surface hardening caused by second stage hot air drying. On the other hand, the hardness of products from combined freeze drying and vacuum drying (204.46 g) and combined freeze drying and microwave vacuum drying (211.37 g) show no significant difference as compared to freeze drying (177.58 g).

Nathakaranakule *et al*. (2010) observed that longer drying time during heat pump drying resulted in higher percentage of shrinkage (88.7 %) as compared to hot air drying (86.5 %). However, the percentage of shrinkage reduced when combined with far-infrared drying due to the puffing effect from 85.1 % to 76.9 % using combined heat pump drying and far-infrared drying and from 83.9 % to 75.4 % for combined hot air drying and far infrared drying as the power increased from 250 W to 450 W, respectively.

Pore size distribution within the sample is a major factor affecting rehydration ratio and density of final product. Lin *et al*. (1998) found that void present in freeze drying of carrot resulted in the lowest density (0.17 g/ml) followed by vacuum microwave drying (0.55 g/ml) due to high internal vapour pressure generated and caused structural expansion and puffing of carrot while hot air drying showed the highest density (1.13 g/ml). Pei *et al*. (2014b) reported that inadequate freeze drying time of button mushroom at 85 % moisture content resulted in collapse of the microstructure at subsequent drying process, thus lowering rehydration ratio and higher density were obtained. In other word, sufficient freeze drying time to achieve moisture content of less than 38 % was able to maintain the internal structure of the sample, subsequent drying resulted in lesser structural collapse

thus better rehydration ratio and density that was comparable to freeze dried products. Wang *et al*. (2015) also observed that mid-infrared drying before freeze drying caused formation of crust on the surface which restricted the moisture from diffusing out. This resulted in much higher shrinkage at the surface layer that reduced rehydration capability and increased the density of final product. On the other hand, freeze drying before mid-infrared drying produced final product with larger pores due to the puffing effect and sufficient freeze drying time (6 hour) resulted in final product having rehydration ratio (5.29) and density (0.2905 kg/dm^3) that had no significant difference as compared to freeze drying alone (rehydration ratio of 5.45 and density of 0.2854 kg/dm^3) (Wang *et al*., 2015).

2.4.3 Total polyphenols content

Total polyphenols content (TPC) is mainly affected by drying time and drying temperature. According to Horuz *et al*. (2017b), by increasing the drying temperature from 50˚C to 70˚C this would increase the deterioration of TPC from 80.5 % to 81.7 % attributed to the long exposure to oxygen and thermal degradation of phenolic compounds (Table 2.7). Similar observation was observed by Adak *et al*. (2017) on strawberry where TPC decreased from 46910 mg GAE/kg to 38832 mg GAE/kg as drying temperature increased from 60˚C to 100˚C. Puente-Diaz *et al*. (2012) also observed that polyphenolic compound is highly dependent on drying rate where higher drying rate at 60˚C resulted in reduction of TPC to 0.96 mg GA/g dry matter as compared to 2.17 mg GA/g dry matter at 40˚C. However, by increasing microwave power from 120 W to 180 W (Horuz *et al*., 2017b), infrared from 100 W to 300 W (Adak *et al*., 2017) and infrared from 400 W to 800 W (Puente-Diaz *et al*., 2012) were found able to increase TPC within these reported range of

microwave and infrared power. This is mainly due to the faster drying rate and shorter heating time that lead to inactivation of phenolic enzymes and promotes better preservation of phenolic compounds. Puente-Diaz *et al*. (2012) also postulated that disruption of sample cell wall caused the release of phenolic compounds but the high drying temperature inactivated the enzyme and resulted in higher TPC as power increased. Hybrid drying of sour cherries using combined microwave drying and hot air (Horuz *et al*., 2017b) and combined infrared drying and hot air drying led to reduction in drying time which subsequently reduced the exposure time to oxygen and prevent oxidation of phenolic compounds as compared to hot air drying alone. An *et al*. (2016) compared effects of different drying methods on TPC of ginger and found that freeze drying showed higher retention of TPC as compared to the fresh sample while hot air drying, infrared drying, intermittent microwave-convection drying and microwave drying were found to reduce TPC by 19.05 %, 5.17 %, 5.76 % and 29.74 %, respectively. Possible explanation for the highest losses of microwave dried sample could be due to the intense heating and rapid drying that cause severe degradation of phenolic compounds (Lim and Murtijaya, 2007). Yi *et al*. (2016) also found that combined freeze drying and instant control pressure drop (FD-DIC) showed higher TPC as compared to combined air drying and instant control pressure drop (AD-DIC) due to the higher antioxidant activity.

2.4.4 Vitamin C

Degradation of vitamin C (VC) depends on several factors which include pH, moisture content, metallic ion catalysis, oxygen, light, and temperature (Veras *et al*., 2012; Erenturk *et al*., 2005). As shown in Table 2.7, an increase in drying temperature of hot air and infrared drying of sour cherries, monukka grape, jujube, pepper, rosehip and pineapple (Horuz *et al*., 2017b; Xiao *et al*., 2010; Chen *et al*., 2015; Veras *et al*., 2012; Erenturk *et al*., 2005; Ramallo and Mascheroni, 2012) has a negative effect on the retention of vitamin C. This is attributed to the irreversible oxidation and thermo-sensitivity of vitamin C (Veras *et al*., 2012; Xiao *et al*., 2010; Chen *et al*., 2015). Oxidation of vitamin C (Figure 2.9) resulted in the formation of dehydroascorbic acid (DHA) which can be further oxidized to wide range of products. Besides, high drying temperature could also increase the degradation rate due to the high water solubility properties (Ramallo and Mascheroni, 2012; Erenturk *et al*., 2005).

Orak *et al*. (2012) and Horuz *et al*. (2017b) found that pretreatment by ethyl oleate (EO) and hybrid microwave drying shortened the total drying time of strawberry and sour cherries and increased the retention of vitamin C. However, Ramallo and Mascheroni (2012) observed that 73.3 % of vitamin C was retained at shorter drying time (45min) and higher temperature (75˚C) as compared to 93.9 % retention at longer drying time (115min) and lower temperature (45˚C). This proved that temperature effect is more important as compared to drying time. Erenturk *et al*. (2005) reported that chopped rosehip with greater surface area exposed to oxygen increased the loss of vitamin C. Therefore, vacuum condition is more conducive in inhibiting the oxidation of vitamin C, thus Veras *et al*.

(2012) and Orak *et al*. (2012) reported that freeze dried samples showed the highest amount of vitamin C retained under the oxygenless and mild temperature conditions.

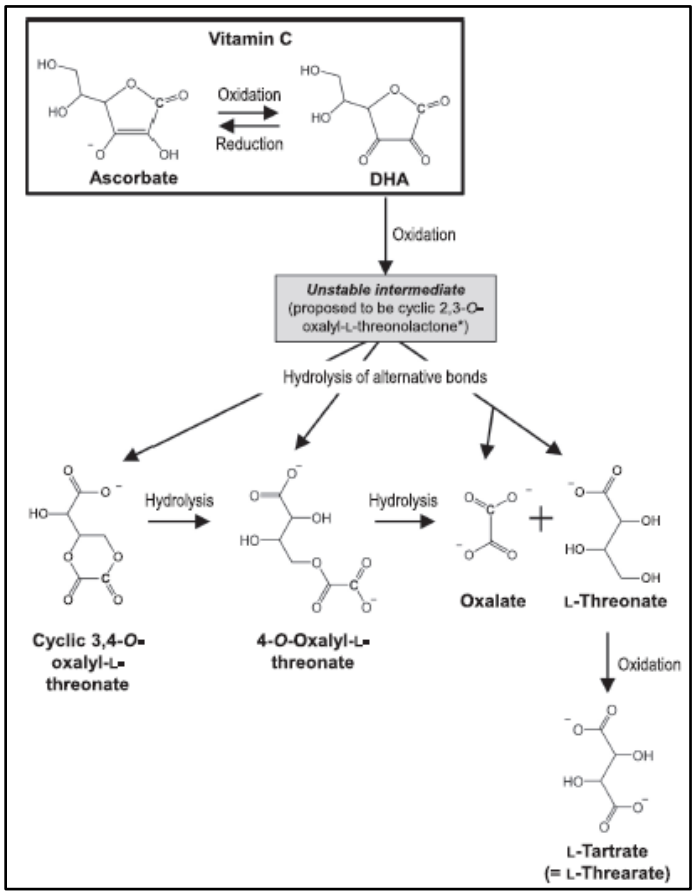


Figure 2.9: Oxidation degradation of vitamin C

2.4.5 Antioxidant capacity

Free radicals are generated within human body from normal essential metabolic process or from external sources such as exposure to industrial chemicals, cigarette smoking, X-rays, air pollutants and ozone (Lobo *et al*., 2010). A balance between free radicals and antioxidant is important to maintain human health where excessive free radicals will alter lipids, proteins, and DNA thus trigger number of human diseases. Hence, consuming food that are rich in antioxidant may help to prevent the oxidative stress. 1,1-diphenyl-2-picrylhydrazyl (DPPH), Ferric reducing/ antioxidant power (FRAP) and 2,2-azino-bis(3-ethylbenz-thiazoline-6-suflfonic acid) (ABTS) are the common methods used to evaluate the antioxidant capacities of food products. As shown in Table 2.7, Horuz *et al*. (2017b) found that antioxidant capacity of sour cherries dried at convective drying and hybrid drying increased with drying temperature and microwave power due to the reduction in total drying time that prevent losses of bioactive compounds. Similar observation was also observed by Orak *et al*. (2012) where pretreatment of ethyl oleate (EO) on strawberry caused reduction in total drying time (8.5 hours) as compared to hot air drying (12 hours) thus resulted in higher DPPH scavenging activity. It was also reported that pretreatment using water blanching at high temperature (80˚C) resulted in loss of bioactive compounds (total phenolic content at 4.05 μg GAE/g extract and ascorbic acid at 192.56 mg/100g DM) and resulted in the lowest DPPH value. On the other hand, the low temperature and oxygenless condition of freeze drying without any pretreatment resulted in the highest retention in total phenolic content (11.67 μg GAE/g extract) and ascorbic acid (396.46 mg/100g DM) as well as the highest DPPH (93.52 % inhibition). Yi *et al*. (2016) reported that freeze drying showed the highest DPPH, FRAP and ABTS values as compared to

instant controlled pressure drop assisted freeze drying (FD-DIC) and instant controlled pressure drop assisted hot air drying (AD-DIC). This is mainly attributed to the higher amount of total phenolic content that are preserved in the freeze dried samples as compared to FD-DIC and AD-DIC. An *et al*. (2016) reported that FRAP and ABTS of ginger showed higher correlation with total polyphenols content (R^2 = 0.741 and 0.848, respectively) and total flavonoid content (R^2 = 0.850, and 0.848, respectively) but DPPH only showed high correlation with total polyphenols content (R^2 = 0.866) but not with total flavonoid content (R^2 = 0.594)

2.5 Sensory Evaluation

Sensory evaluation is usually carried out before the food product is released to the market with the aim to get a better understanding on the product acceptance as required by the consumers. Visual appearance, colour, texture, taste and odour are some of the quality attributes tested during sensory evaluation. Ratings on these attributes are carried out to determine the level of acceptance by trained sensory panel or general consumers.

Drying is a product transformation process whereby the fresh product is converted into dried product through moisture removal (e.g. by hot air) and this would affect the sensory attributes of the final dried products. Aktas *et al*. (2013) reported that sensory scores for untreated apples in terms of appearance, texture, taste and overall acceptance were not as good as the osmotic pre-treated apples. Wojdylo *et al.* (2016) reported that panels rated freeze dried jujube had the lightest appearance whereas convective dried samples resulted in darker appearance. Similar observation was reported by Politowicz *et al*. (2018) where panels rated that freeze drying preserved better colour, lesser shrinkage, mushroom identity

and sponginess. However, convective drying showed acceptance close to freeze dried samples while vacuum microwave dried samples deviated greatly from the freeze dried samples. Calin-Sanchez *et al*. (2013) also found that convective drying showed better colour score than vacuum microwave drying. Wojdylo *et al*. (2016) reported that vacuum microwave drying of jujube produced dried product with the highest hardness at the highest microwave power (480 W) and this resulted in significant bitter taste due to the burning owing to excessive heating. Bagheri *et al*. (2019) reported similar finding on infrared drying of peanut where high infrared power (450 W) was rated at a lower score as compared to that at low infrared power (350 W) due to the burnt, rancid flavor and darker appearance. Freeze drying, low temperature convective drying (50˚C) and vacuum microwave drying (480 W - 120 W) resulted in final products with stronger jujube identity, vegetal/fruity notes and longer pleasant after taste. In addition, freeze drying and vacuum microwave drying (480 W - 120 W) produced final products with higher crunchiness, juiciness and lower hardness (Wojdylo *et al*., 2016). Calin-Sanchez *et al*. (2013) reported that an increase in drying temperature and microwave power were found to increase the crispness of the final samples as drying temperature increased to 70˚C and microwave power increased to 480 W.

Penalty analysis or mean drop analysis is an emerging sensory data analysis method used in food industry to identify the potential direction for product development and optimization (Zhi *et al*., 2016). This analysis combines scores from "Just-about-right (JAR) scales" and "hedonic scales". JAR scale is a bipolar measurement that consists of 5 points where one end point labelled as having too little of the characteristics, another end as having too much of the characteristics and midpoint as having just about right (Xiong and

Meullenet, 2006). Hedonic scale is a measurement of likeability of the characteristics that consists of 9 points ranging from dislike extremely (point 1) to like extremely (point 9) (Narayanan *et al*., 2014). Therefore, maximum hedonic score is assumed to occur at the JAR point. The percentage respondents of the group that is not-JAR (too much or too little) and JAR were calculated, also the mean of liking scores were calculated for each group in order to identify the mean drop by subtracting the mean of JAR group to the mean of not-JAR. Penalty analysis represent graphically by plotting mean drop (y-axis) against percentage of respondents (x-axis) of not-JAR group as shown in Figure 2.10 to identify the potential directions for product improvement. Twenty percent was used as a cutoff point as respondents below 20% are too small and not reliable (Estiaga, 2015). Attributes that located at lower left quadrant in the graph is known as high acceptability attributes where low mean drop and low percentage of respondents are obtained. Whereas attributes located at upper right quadrant is known as most penalized attributes and should be improved first (higher mean drop). For the attributes that are located at lower right quadrant means that higher percentages of the respondents claim the attributes is not right however respondents tend to prefer the not-JAR taste. Sometimes, both not-JAR (too much and too little) show percentage of respondents more than 20% and the difference between too much and too little is less than 12%, this is known as the candidate for penalty analysis due to the bipolar condition of personal preference. Figure 2.11 shows the penalty analysis of liquid milk where higher penalties were found at sweetness (too little), fresh milk flavor (too little), smoothness (too little), thickness (too little) and sourness (too much) whereas highly preferred attributes include fresh milk flavor (too much), thickness (too much) and sweetness (too much). Even though more than 20% of respondents claimed smoothness

was too much yet the respondents still preferred thick smoothness more than the JAR group.

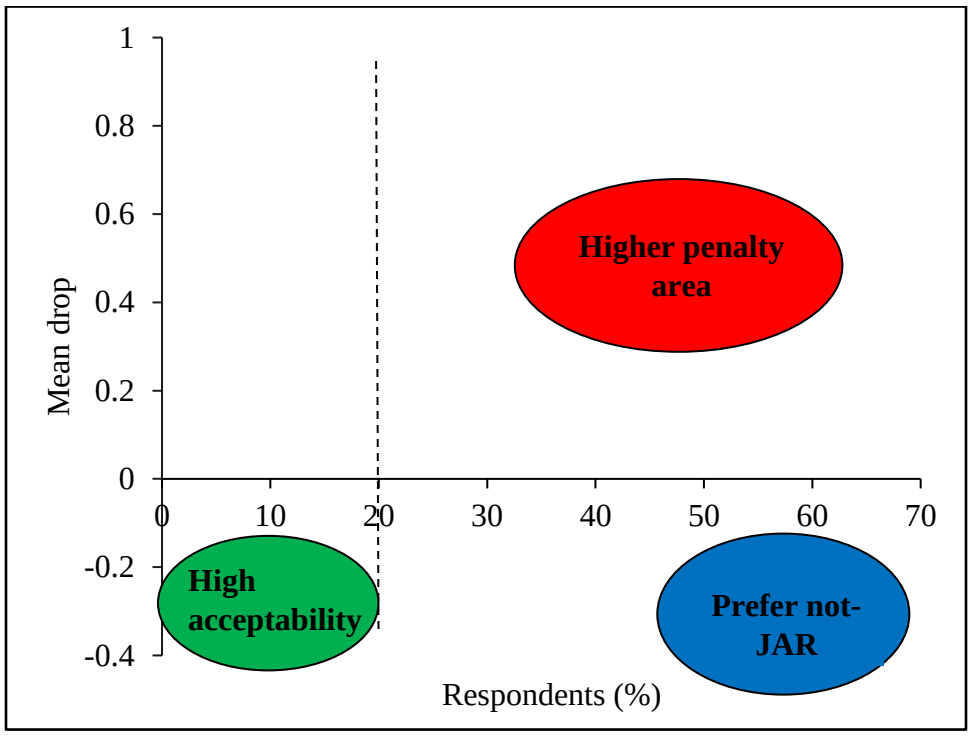


Figure 2.10: Penalty analysis plot

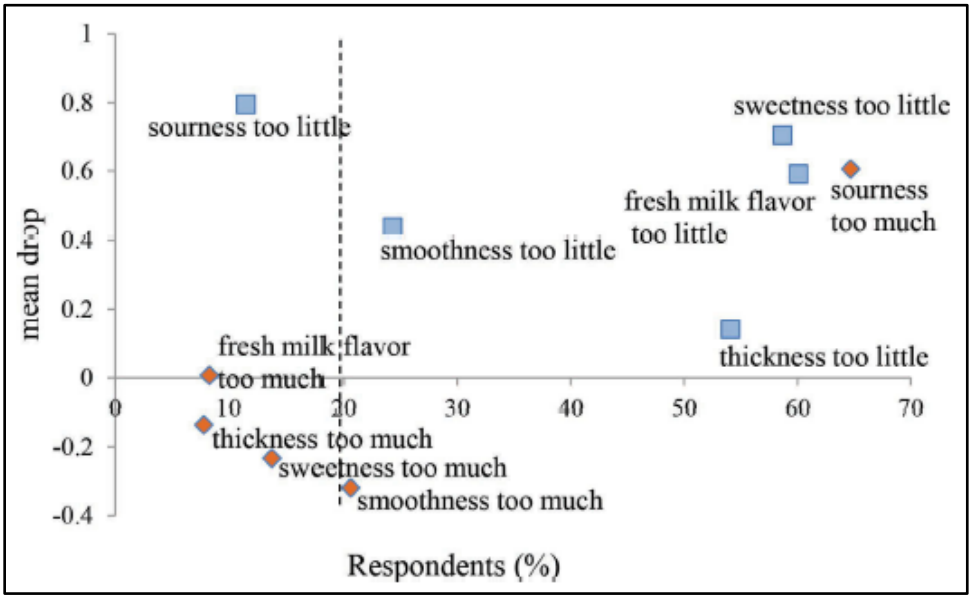


Figure 2.11: Penalty analysis of liquid milk (Zhi *et al*., 2016)

CHAPTER 3

METHODOLOGY

3.1 Drying Procedures

3.1.1 Sample preparation (General)

Kedondong fruits were purchased from a local supermarket and stored in refrigerator (2°C). Only firm, disease free and green kedondong (as measured by colorimeter with L* = 76 – 78, a*=1 – 4 and b* = 15 – 20) was chosen for the drying experiments. Around twenty kedondong fruits were hand peeled and sliced crosswise into circular shapes of approximately 1 cm thick, 2.5 cm – 3 cm diameter and 8 g – 10 g weight as shown in Figure 3.1. The fruit slices were weighed by electronic balance (Metler Toledo, USA) to record the initial fresh weights.

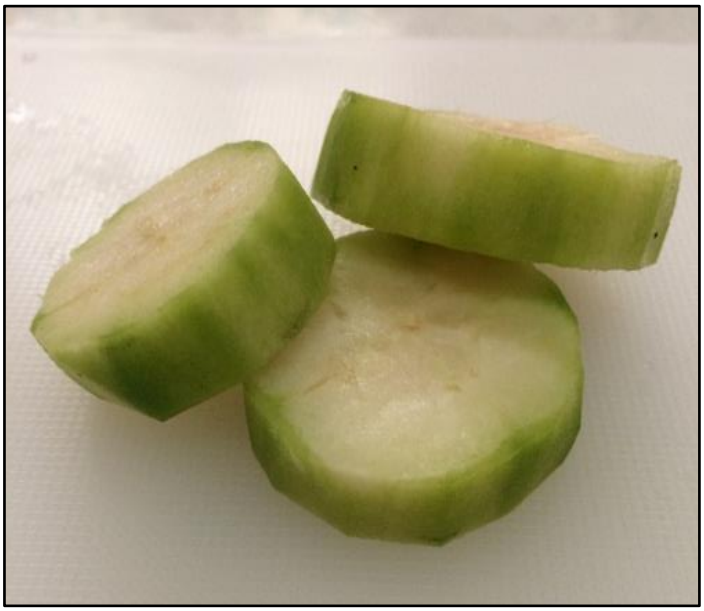


Figure 3.1: Kedondong slices

3.1.2 Hot air (HA) drying

The hot air oven (Memmert, Germany) (Figure 3.2) was preheated to the required temperature and humidity before putting in the samples. The relative humidity was fixed at 30 % and four drying temperatures were tested at 50˚C, 60˚C, 70˚C and 80˚C. The fruit slices were placed on a meshed tray as shown in Figure 3.3 and placed in the oven for drying. The samples were weighed every hour during drying until the samples reached constant weight (equilibrium moisture content). The dried fruit samples were examined for the drying kinetics, physical and chemical properties. The best temperature setting that showed optimal results in terms of physical and chemical quality attributes were chosen for hybrid drying. The experiments were conducted in triplicate.

Figure 3.2: Hot air dryer

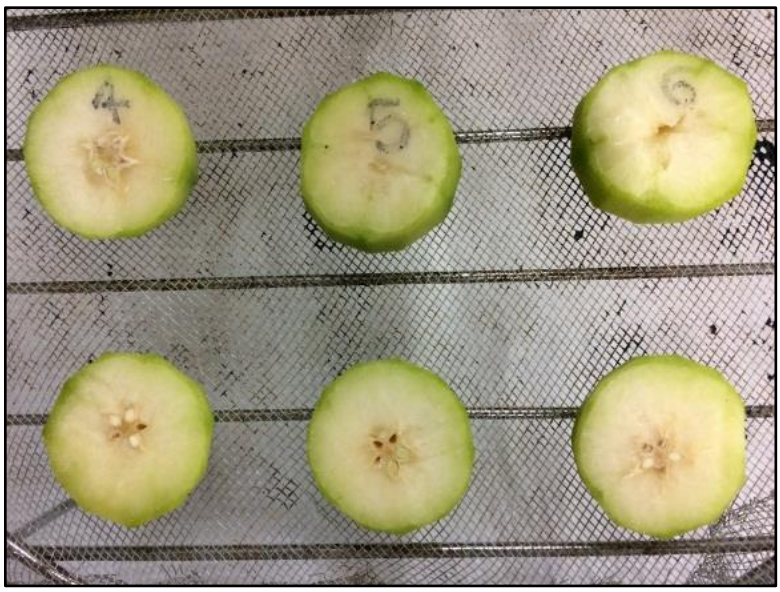


Figure 3.3: Kedondong slices on drying tray

3.1.3 Infrared (IR) drying

Infrared dryer (I Lab Instrument, Malaysia) (Figure 3.4) was preheated to the required temperature and rotation speed before putting in the samples. The rotation speed was fixed at 50 rpm and three drying temperatures were used at 60˚C, 70˚C and 80˚C. Kedondong fruit slices were placed on a rotating tray in the lower section of the drying compartment. The infrared radiators were fitted at the top and bottom sections of the compartment. The samples were weighed every hour until it achieved constant weight (equilibrium moisture content). The dried samples were examined for the drying kinetics, physical and chemical properties. The best temperature setting from infrared drying that showed optimal results in terms of physical and chemical quality attributes were chosen for hybrid drying. The experiments were conducted in triplicate.

Figure 3.4: Infrared dryer

3.1.4 Sample preparation (Hybrid drying)

Selected temperature settings from hot air drying and infrared drying were used for hybrid drying. The kedondong fruits were cleaned, peeled, cut and weighed using the same procedure as mentioned in section 3.1.1. The samples were then stored in the freezer (-80˚C) for one day to solidify the moisture inside the sample into ice prior to freeze drying.

3.1.5 Hybrid drying (FDHA and FDIR)

Freeze dryer (Christ Alpha 1–2 Ldplus, Germany) was warmed up for 30 minutes prior to drying (Figure 3.5). The frozen kedondong slices were immediately put on petri dishes as shown in Figure 3.6 and placed in the freeze dryer to commence drying. The pressure was set at 0.12 mbar and subject to drying in two stages. In first stage drying, the samples were dried for 6 hours or 12 hours in the freeze dryer (FD). Thereafter, the partially dried samples were transferred to hot air dryer (HA) or infrared dryer (IR) for second stage drying based on the selected temperature settings from section 3.1.2 and 3.1.3. The fruit samples were weighed every hour during second stage drying until the samples achieved constant weight (equilibrium moisture content). Besides FDHA and FDIR samples, the fully dried (24 hours) and partially dried (6 hours and 12 hours) freeze dried samples were also assessed for physical and chemical properties. Drying kinetics were determined throughout the hybrid drying process. The experiments were conducted in triplicate.

Figure 3.5: Freeze dryer

Figure 3.6: Frozen kedondong slices

3.2 Drying Kinetics

3.2.1 Bone dry weight

After drying, the kedondong samples were further dried overnight inside a hot air oven at 105˚C for 24 hours until constant weight to obtain the bone dry weight (Hii *et al*., 2013).

3.2.2 Moisture content

Moisture content is the ratio of the weight of water to the weight of solids in the sample and it was calculated based on Equation 3.1(Hii *et al*., 2016).

$$\text{Moisture content, MC} = \frac{M_t - M_{\text{bone dry}}}{M_{\text{bone dry}}} \quad (3.1)$$

where M_t refers to weight of fruit sample at any time (g), $M_{\text{bone dry}}$ is the bone dry weight (g dry solid) and the unit for moisture content is g H_2O/g dry solid.

3.2.3 Moisture ratio

Moisture ratio was determined according to Equation 3.2(Hii *et al*., 2016).

$$\text{Moisture Ratio, MR} = \frac{(MC_t - MC_e)}{(MC_i - MC_e)} \quad (3.2)$$

where MC_t is the moisture content at time t (g H_2O/g dry solid), MC_e is the equilibrium moisture content (g H_2O/g dry solid) and MC_i is the initial moisture content (g H_2O/g dry solid).

3.2.4 Drying rate

Drying rate is defined as the rate of change in moisture content at a specific time which was calculated based on Equation 3.3 (Horuz *et al*., 2017a).

$$\text{Drying rate} = \frac{MC_{(t+dt)} - MC_{(t)}}{dt} \quad (3.3)$$

where t is the drying time (h) and MC is the moisture content (g H_2O/g dry solid).

3.2.5 Effective moisture diffusivity (D_{eff})

By plotting the natural log of the moisture ratio (lnMR) versus the drying time (t) as shown in Equation 2.2 (Chapter 2), the gradient from the graph was used to calculate the effective moisture diffusivity as shown in Equation 3.4.

$$\text{Gradient} = -\frac{\pi^2 D_{eff}}{4L^2} \quad (3.4)$$

where L is the half thickness of the fruit (m).

Relationship between temperature and effective moisture diffusivity can be expressed in Arrhenius type equation as shown in Equation 3.5.

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (3.5)$$

where D_0 is the constant (m^2/s), E_a is the activation energy for moisture diffusion (kJ/mol), R is the gas constant (8.314 J/(mol.K)) and T is the drying temperature (K).

By plotting ln D_{eff} with respect to the reciprocal of drying temperature, the activation energy and D_0 value can then be obtained from the slope and y-intercept as shown in Equation 3.6.

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \quad (3.6)$$

3.3 Physical Characteristics

3.3.1 Colour

Sample colour was measured before drying and at specified time interval during drying by using a colorimeter (Precision, China) as shown in Figure 3.7. Aperture head of the colorimeter was pointed to the center part of the sample. The data obtained from the colorimeter were presented in L* (lightness from black - white), a* (green - red) and b* (blue - yellow). Measurements were conducted in triplicates and the mean value was calculated. In addition, hue angle and total colour change (ΔE) were calculated using the following equations (Patras *et al*., 2009). Hue angle and total colour change are typically related to degree of browning. Dried product with high total colour change and low hue angle indicates high degree of browning (Baini and Langrish, 2009).

$$\text{Hue angle} = tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (3.7)$$

$$\Delta E = [(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2]^{1/2} \quad (3.8)$$

where L_0, a_0 and b_0 are the reference values based on the fresh kedondong samples.

Figure 3.7: Colorimeter (CIE L*a*b*)

3.3.2 Texture

The texture of dried sample was evaluated by measuring the hardness using puncture test and the maximum force is related to the hardness of the dried kedondong samples. The measurements were performed using a Texture Analyser (TA. XT Plus, Stable Microsystem, England) as shown in Figure 3.8 fitted with a puncture probe (2 mm diameter). The sample was placed on a metal base and the probe punctured through the surface of the fruits to a depth of 2 mm. The measurements were conducted in triplicates for each sample and the maximum force from the force-time curve was used to evaluate the hardness.

Figure 3.8: Texture analyser

3.4 Chemical Characteristics

3.4.1 Vitamin C (VC)

Vitamin C (VC) of the kedondong samples was measured by titration method following AOAC protocol (Moo-Huchin *et al*., 2014). First, the samples were macerated using blender into powder. The powdered sample (5 g) underwent extraction process using 50 ml of 0.5 % oxalic acid and mixed for 30 seconds. The extracted sample was filtered and the volume of filtrate (V_f) was measured using a measuring cylinder. After that, 2,6-dichlorophenolindophenol (DCPIP) dye solution was prepared by dissolving 0.2 g of DCPIP in 100 ml hot distilled water. This solution was then diluted by 10 times with distilled water. Standard ascorbic acid solution was made by dissolving 0.1 mg/ml of ascorbic acid in 2 % metaphosphoric acid. About 10 ml of ascorbic acid standard solution or filtrate (V_s) from sample in 100 ml conical flask was titrated with DCPIP dye solution to a pink colour end point. The volume of DCPIP solution used to oxidize 10 ml standard solution was calculated and the dye factor was determined using Equation 3.9. The ascorbic acid content in the sample was then calculated using Equation 3.10. The measurements were conducted in triplicates.

$$\text{Dye factor} = \frac{\text{amount of ascorbic acid in 10 ml standard solution (mg)}}{\text{volume of dye to oxidize to oxidize 1 mg ascorbic acid (ml)}} \tag{3.9}$$

$$\text{Ascorbic acid content } \left(\frac{\text{mg}}{\text{100g dry solid}}\right) = \frac{\text{titre (ml)x dye factor } \left(\frac{\text{mg}}{\text{ml}}\right) \text{x } V_f \text{x } 100}{\text{aliquot for extraction (g)x } V_s} \tag{3.10}$$

3.4.2 Total polyphenols content (TPC)

Total polyphenols content (TPC) of the kedondong samples was measured by Folin-Ciocalteu assays (Hii *et al*., 2016). About five pieces of dried kedondong samples were put in the blender and ground into powder. Samples (0.1 g) were weighed and put into a test tube followed by 10 ml of 70 % acetone (Merck, Germany). The tubes were sonicated for 30 minutes in iced water and centrifuged at 5000 rpm at 4˚C for 10 minutes. About 0.5 g of gallic acid (Merck, Germany) was weighed and added into 10 ml 95 % ethanol (Fisher Scientific (M) Sdn. Bhd, Malaysia). The mixture was diluted with distilled water in 100 ml volumetric flask. Serial dilution was carried out for the mixture into 200 ppm, 400 ppm, 600 ppm, 800 ppm and 1000 ppm. Then 20 % Sodium Carbonate (Na_2CO_3) solution (R&M Chemicals, U.K.) was prepared by mixing 50 g of Na_2CO_3 with 200 ml of water and bring to boil. About 100 µl of sample or standard were introduced into a test tube followed by 7.9 ml of distilled water, 500 µl of Folin (R&M Chemicals, U.K.) and 1.5 ml of 20 % Na_2CO_3. The test tubes were left undisturbed for 2 hours. Absorption at 765 nm was measured using UV/Vis-spectrophotometer (Perkin Elmer, USA). TPC was calculated based on Equation 3.11 and expressed in gallic acid equivalents. The measurements were conducted in triplicates.

$$\text{TPC} = \frac{\left(\frac{10}{1000}\right)\text{x Concentration}}{\text{sample wt (g)}} \tag{3.11}$$

where the unit for TPC is mg GAE/g dry sample.

3.4.3 DPPH free radical scavenging assay

Extract preparation for antioxidant analysis and DPPH (1,1-diphenyl-2-picrylhydrazyl) assay were conducted according to Lim *et al.* (2007) with some modifications. Dried kedondong samples were ground into powder by using blender and 0.3 g of kedondong powder was extracted with 1 mL of 50 % ethanol. The mixture was shaken for 10 min and then centrifuged to obtain a clear supernatant. About 0.1 mM of DPPH solution in methanol was prepared and 1 mg/mL ascorbic acid was prepared as a standard solution and serial dilution was performed. About 50 µL of extract/ standard solution was added into 100 µL of DPPH solution and left for 30 min. Absorbance value at 517 nm was determined using UV/Vis spectrophotometer (Perkin Elmer, USA) and IC_{50} for the standard and extract was determined. IC_{50} is the concentration of the extract or standard solution that decrease the absorbance value of DPPH solution by 50 %. The results are expressed as ascorbic acid (AA) equivalent antioxidant capacity (AEAC) using Equation 3.12.

$$\text{AEAC} = \frac{\text{IC}_{50\,(\text{AA})}}{\text{IC}_{50\,(\text{sample})}} \text{ x } 10^5 \qquad (3.12)$$

where the unit for DPPH is mg AA/100 g dry solid.

3.4.4 ABTS radical scavenging activity

Extract preparation for antioxidant analysis and ABTS (2,2'-Azinobis-3-ethylbenzotiazoline-6-sulfonic acid) assay were conducted according to Moo-Huchin *et al.* (2014) with some modifications. Dried kedondong samples were ground into powder by using blender and 0.5 g of kedondong powder was extracted with 10 mL of acetone/water/acetic acid (70:29.5:0.5, v/v/v), sonicated for 30 min in an ultrasonic water bath (Memmert, Germany) and then centrifuged for 15 min at 15,000 g. The supernatant was collected for antioxidant capacity analysis. $ABTS^{\bullet+}$ cation was generated by reacting 19.2 mg of ABTS in 5 mL distilled water with 88 μL of 0.0378 g/mL sodium persulfate ($Na_2S_2O_8$) and incubated in dark at room temperature for 16 hours. The solution was diluted with ethanol to obtain absorbance of 0.70 ± 0.02 at 734 nm. Standard solution was prepared using Trolox solution to obtain a calibration curve. About 30 μL of sample (supernatant) or standard solution was added to 2970 μL of ABTS solution and the absorbances were recorded after 6min of mixing. The results are expressed as μM Trolox equivalent/g dry solid.

3.5 Sensory Evaluation

Sensory evaluation was conducted in the sensory laboratory of UCSI University (Kuala Lumpur, Malaysia). Fifty sensory panel from the staff members and students of UCSI took part in the sensory. Each panel was assigned to an individual cubical with good lighting, noise free and odour free. Five samples packed in a transparent, odourless plastic bag and coded with three-digit random numbers were given to the sensory panel. The panel gave ratings to the dried kedondong samples in terms of texture, sourness, sweetness, kedondong notes, kedondong aroma, browning and overall likeability on a 9-point hedonic scale (where 1 = dislike extremely, 5 = neither like nor dislike and 9 = like extremely) and also on a 5-point Just About Right (JAR) scale (where 1 = much too little, 3 = just about right and 5 = much too much). Drinking water was served as palate cleanser in between sample tasting. The sensory data collected were analysed for mean drop and penalty analyses using XLSTAT 2020 software (Addinsoft, USA).

3.6 Statistical Analysis

All experiments were conducted in triplicate. The data were expressed as mean ± standard deviations and were statistically analysed using SPSS statistical software version 22 (brand/country). One way analysis of variance (ANOVA) and Tukey HSD was used to compare the means at 95% confidence level. Pearson correlation test was used to study the relationship between antioxidant compounds (TPC and vitamin C) and antioxidant capacities (DPPH and ABTS) and the significant difference was set at $p < 0.01$.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Drying Kinetics and Product Quality of Kedondong Slices Dried by Hot Air and Infrared Drying

4.1.1 Moisture ratio

Kedondong slices were dried using hot air (HA) at temperature of 50˚C, 60˚C, 70˚C and 80˚C and infrared (IR) at temperature of 60˚C, 70˚C and 80˚C, respectively. The heated air circulating inside the oven creates temperature difference between the surrounding air and fruit samples which leads to evaporation of surface moisture and internal diffusion during HA drying. In IR drying, radiation produced from the IR emitters is directed to the fruit samples and this causes vibration of water molecules which provides the energy for heat and mass transfer to occur (Sakai and Hanzawa, 1994; Hebbar *et al*., 2004). Figure 4.1 shows the schematic diagram of moisture migration in HA and IR drying where it can be observed that HA conducts heat through the fruit surface while IR heats up the entire fruit body.

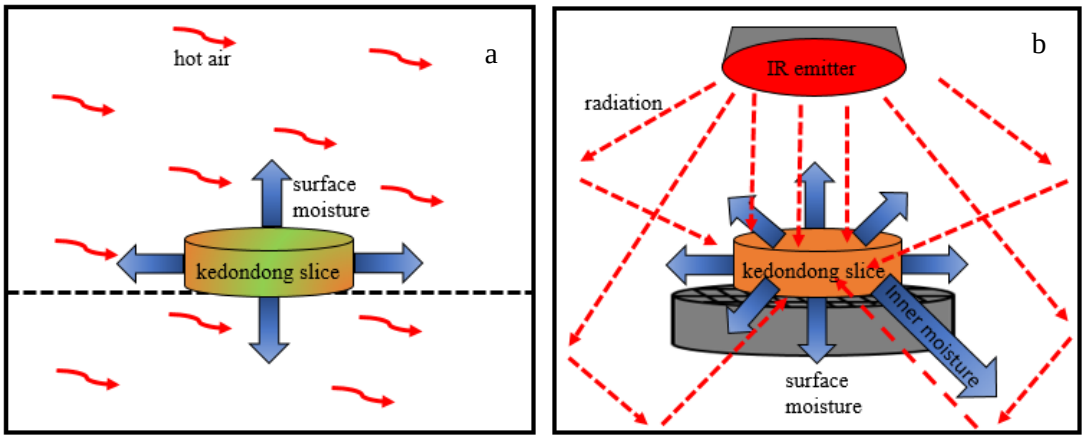


Figure 4.1: Moisture migration in (a) HA drying and (b) IR drying

The initial moisture contents of the fruit samples ranged within 12.29 – 13.37 g H_2O/g dry solid and dried to 0.24 – 0.47 g H_2O/g dry solid in all drying experiments. Figure 4.2 shows the plot of moisture ratios versus drying time.

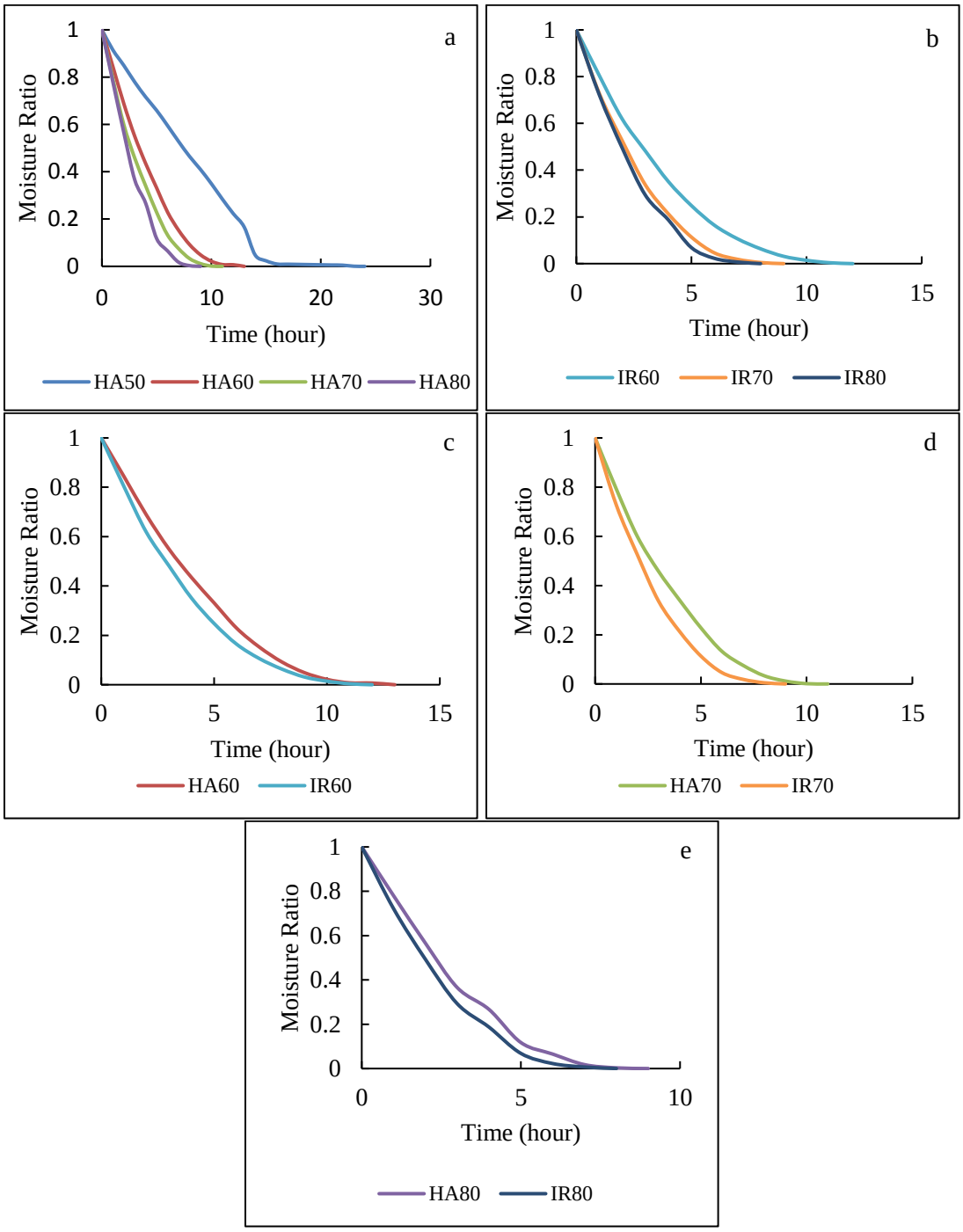


Figure 4.2: Plots of moisture ratios versus drying times for (a) HA and (b) IR drying and at different drying temperatures (c) 60˚C, (d) 70˚C and (e) 80˚C

It can be observed that higher amount of moisture at the initial drying stage within the samples caused a rapid moisture removal rate and then slowly decreased due to reducing drying force for mass transfer (lesser amount of residual moisture within the samples). Drying times for HA drying were recorded at 24 hours, 13 hours, 11 hours and 9 hours for drying temperatures at 50˚C, 60˚C, 70˚C and 80˚C, respectively. In IR drying, drying times were recorded at 12 hours, 9 hours and 8 hours for drying temperatures at 60˚C, 70˚C and 80˚C, respectively.

Figure 4.2 (a and b) shows that as drying temperatures increase, the drying curves become steeper indicating faster drying rate thus resulting in shorter drying time. In average, the gradient of HA80 is about 3.3 times faster than HA50, 1.7 times faster than HA60 and 1.4 times faster than HA70. In IR drying, the gradient of IR80 is 1.4 times faster than IR60 and 1.1 times faster than IR70. High drying temperature usually provides greater driving force for mass transfer due to the greater temperature difference between the drying air and product. These are in agreement with results from published literatures for hot air drying of chempedak (Chong *et al*., 2008), red bell pepper (Vega-Galvez *et al*., 2008), sorbus fruit (Lule and Koyuncu, 2015), apple (Sacilik and Elicin., 2006), mushroom (Giri and Prasad, 2007), tomatoes (Doymaz, 2007) and infrared drying of apple (Togrul, 2005) and carrot (Togrul, 2006). Besides, Pan *et al*. (2008) also reported that more heat was absorbed by the banana samples as IR intensities increased which subsequently reduced the drying time.

HA50 shows the longest drying time and it was 1.9 times longer than HA60. In order to prevent excessive browning and nutrient degradation, prolonged drying duration at

temperature below 60˚C is therefore not recommended. This is also applicable in IR drying and temperature setting of 50˚C was not used.

Figure 4.2 (c - e) shows comparison of drying curves for HA drying and IR drying at various temperatures. It can be seen that IR drying progresses faster than HA drying in all drying experiments. In average, gradient of IR60 and IR70 is about 1.4 time faster than HA60 and HA70 whereas IR80 is about 1.1 times faster than HA80. IR radiation is able to penetrate to greater depth and this assists in heating up the samples whereas hot air only heats up through the surface of the product. Similar observation was reported by Pan *et al*. (2008) on banana drying. Therefore, it is anticipated that utilization of IR can improve moisture removal rates of the products during drying.

4.1.2 Drying rates

A typical drying process consists of three periods namely the initial, constant rate and falling rate periods. During initial period, the heat is mainly used to warm up the samples to reach the temperature set in the dryer. At this stage, the free moisture on the sample surface is evaporated and drying rates start to increase gradually. Then, it is taken over by the constant rate period where the sample reaches the maximum drying rates and the rate of moisture diffusion from the inner part progresses at the same rate as the surface moisture evaporation on the kedondong slices. As drying progresses, the surface moisture evaporate off substantially and eventually the rate of moisture diffusion starts to reduce, this marks the end of constant rate and the onset of falling rate period. At this stage, moisture diffusion rate within the samples are insufficient to replenish the moisture being evaporated at the

surface. Therefore, the drying rate reduces continuously until the end of drying (Lule and Koyuncu, 2015).

The variations of drying rate with moisture content at different drying temperatures for HA drying and IR drying are as shown in Figure 4.3. Two falling rate periods were detected in HA drying (Figure 4.3a) at high drying temperatures (60˚C, 70˚C and 80˚C) whereas both constant rate period and falling rate periods were observed at lower drying temperature (50˚C). The surface of kedondong slices were heated through combined convection and conduction from the surrounding hot air. The inner part of the sample was heated by conduction and coupled with the low thermal conductivity of the fruit resulted in low moisture diffusion rate that was not able to replenish the moisture evaporated at the surface. Thereafter, the first falling rate occurred and eventually the surface moisture dried up and created a harden layer on the surface. This further impeded the diffusion of moisture from the inner part of the fruits and resulted in the second falling rate period.

Adak *et al*. (2017) and Togrul (2005) reported that low thermal conductivity of fruit and case hardening are main factors slowing down the drying rates. Furthermore, low drying temperature and slow diffusion rate would result in occurrence of the constant rate period before the onset of falling rate period. This can be observed from HA50 where constant rate period was observed due to the lower drying temperature as compared to HA70 and HA80 at the much higher drying temperature. However, in IR drying (Figure 4.3b), only falling rate periods were observed in all the experiments (IR60, IR70 and IR80) which could be due to the intense heating from the radiators that created a greater driving force for mass transfer and rapid removal of surface moisture. Similar findings were reported by Togrul (2006) where only falling rate period was observed in IR drying of

carrot at temperature range of 50˚C to 80˚C and internal moisture diffusion was the dominant mode of moisture transfer mechanism.

In general, the drying rates of HA drying were in the range of 0.016 – 1.136 g H_2O/g dry solid.h, 0.085 – 1.963 g H_2O/g dry solid.h, 0.042 – 2.666 g H_2O/g dry solid.h and 0.059 – 2.843 g H_2O/g dry solid.h at 50˚C, 60˚C, 70˚C and 80˚C, respectively. On the other hand, the drying rates of IR drying were in the range of 0.074 – 2.530 g H_2O/g dry solid.h, 0.055 – 3.280 g H_2O/g dry solid.h and 0.027 – 3.596 g H_2O/g dry solid.h at 60˚C, 70˚C and 80˚C, respectively. The drying rate of HA80 was 2.5 times higher than HA50 whereas IR80 was 1.4 times higher than IR60. Comparing between HA drying and IR drying, it shows that IR drying able to increase the drying rate to about 1.2 - 1.3 times at the three drying temperatures tested (60˚C - 80˚C).

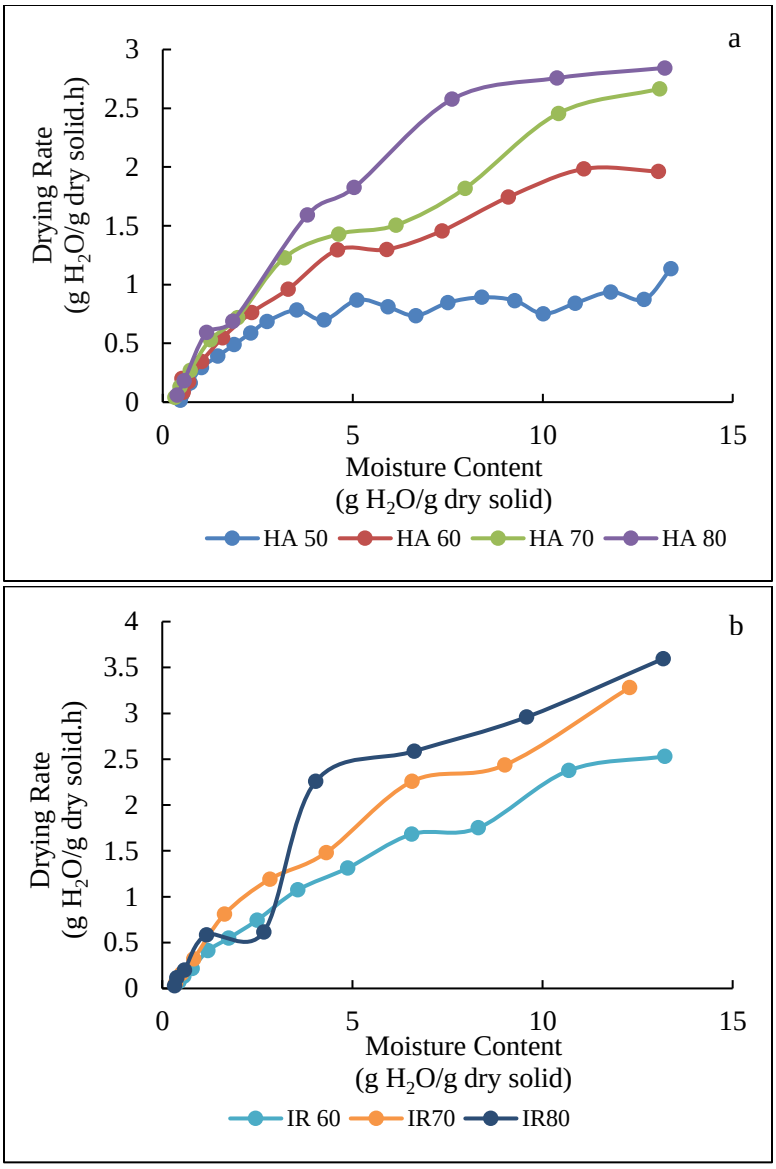


Figure 4.3: Drying rates versus moisture contents for (a) HA drying and (b) IR drying

4.1.3 Effective diffusivity and activation energy

Effective diffusivities (D_{eff}) of HA and IR drying at different drying temperatures are as shown in Table 4.1. The D_{eff} values obtained from HA drying at 50˚C, 60˚C, 70˚C and 80˚C were 8.56 x 10^{-10} m^2/s, 1.22 x 10^{-9} m^2/s, 1.64 x 10^{-9} m^2/s and 1.88 x 10^{-9} m^2/s, respectively. On the other hand, the D_{eff} values obtained from IR drying at 60˚C, 70˚C and 80˚C were 1.30 x 10^{-9} m^2/s, 1.80 x 10^{-9} m^2/s and 1.96 x 10^{-9} m^2/s, respectively. These D_{eff} values fall within the range generally reported for food materials (10^{-12} m^2/s – 10^{-8} m^2/s) according to Zogzas *et al*. (1996). The D_{eff} values of kedondong slices dried using HA and IR are comparable to HA drying of untreated whole cherry (5.68 x 10^{-10} m^2/s - 1.20 x 10^{-9} m^2/s) at 60°C - 75˚C (Doymaz and Ismail, 2011) and IR drying of jujube (4.75 x 10^{-10} m^2/s - 4.17 x 10^{-9} m^2/s) at 62 W - 125 W (Doymaz *et al*., 2016), respectively.

Apparently, D_{eff} values increase with HA drying temperatures due to increase in water vapour pressure which in turn lead to faster rate of moisture diffusion from the inner part of the sample to the surface. This is in agreement with findings reported for chempedak (Chong *et al*., 2008), salak (Ong and Law, 2009), tomatoes (Doymaz, 2007) and carrot (Togrul, 2006).

The basis of temperature selection for subsequent hybrid drying was mainly by quality attributes and not by diffusivity. However, information on diffusivity is still important as the selected drying temperature will have different diffusivity as affected by the drying rates. Comparison of diffusivities between kedondong and other fruits e.g. carrot (Table 4.2) also provide information on relative drying rates between the fruits.

Table 4.1: Effective diffusivities of kedondong slices from HA and IR drying

Drying method	Temperature (°C)	D_{eff} (m^2/s)
Hot air (HA)	50	8.56×10^{-10}
	60	1.22×10^{-9}
	70	1.64×10^{-9}
	80	1.88×10^{-9}
Infrared (IR)	60	1.30×10^{-9}
	70	1.80×10^{-9}
	80	1.96×10^{-9}

Figure 4.4 shows plot of $\ln D_{eff}$ versus 1/T using the Arrhenius equation. The equation relates D_{eff} to the range of drying temperatures used. Equation 4.1 and 4.2 show the Arrhenius equations for HA drying and IR drying, respectively.

$$D_{eff}(HA) = 1.084 \exp^{\left(-\frac{25.28}{RT}\right)} \quad (4.1)$$

$$D_{eff}\ (IR) = 1.936 \exp^{\left(-\frac{20.13}{RT}\right)} \quad (4.2)$$

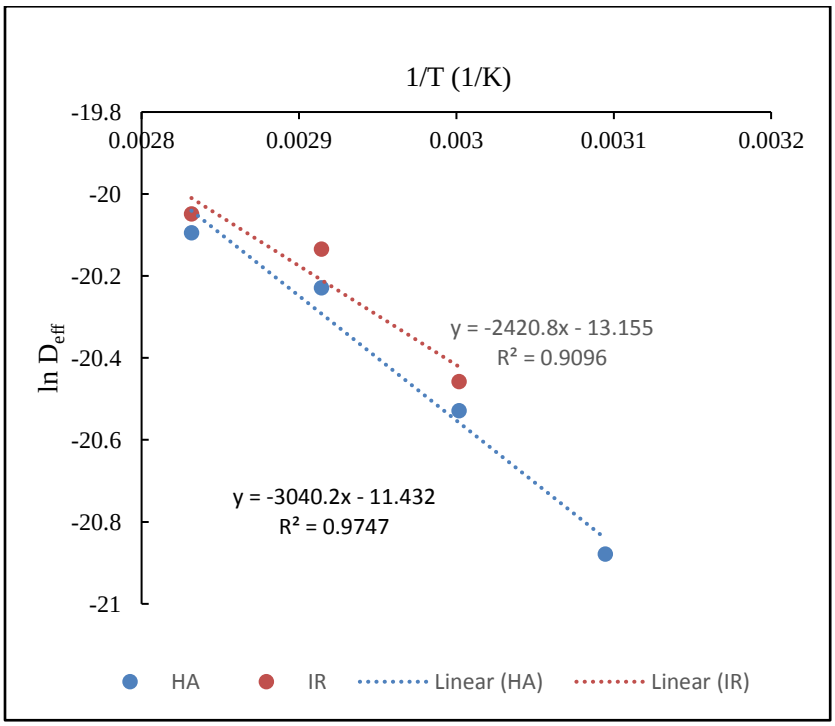


Figure 4.4: Plot of ln D_{eff} versus (1/T) for HA and IR drying

The activation energies (E_a) of HA drying and IR drying were determined at 25.28 kJ/mol and 20.13 kJ/mol, respectively. The lower activation energy in IR drying implies lower energy barrier to activate the moisture diffusion process as compared to HA drying. Therefore, duration of IR drying was shorter as compared to HA drying under the same drying temperatures. Comparison of D_{eff} and E_a values from present study with published results from other product are as shown in Table 4.2. It can be observed that carrot with almost similar structure to kedondong fruit showed similar trend where HA dried sample had the highest E_a value as compared to pretreated carrot (blanching) and IR dried carrot. The higher activation energy in HA dried products could be due to the non-isothermal temperature development where the inner core temperature is much lower than the surface temperature. Typically, the E_a values are affected by various parameters such as sample size, fruit structure/properties, drying method and pretreatment procedure.

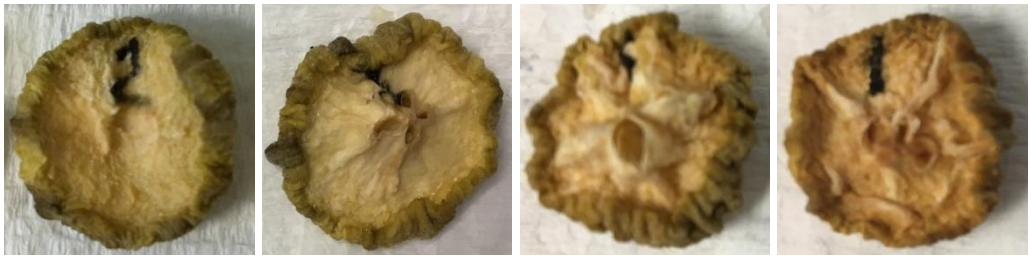
Table 4.2: Comparison of D_e and E_a values with literature findings

Product	Drying methods	Settings	D_{eff}	E_a	References
Carrot	IR	50˚C - 80˚C	$7.295 \times 10^{-11} - 1.501 \times 10^{-10}$ m^2/s	22.43 kJ/mol	Togrul (2006)
Carrot	Blanching + HA	50˚C - 70˚C	$0.776 - 9.335 \times 10^{-9}$ m^2/s	28.36 kJ/mol	Doymaz (2004)
Carrot	HA	50˚C - 70˚C	3.46×10^{-10} and 1.02×10^{-9} m2 /s	37.75 kJ/mol	Doymaz (2017)
Kedondong slices	HA	50˚C - 80˚C	$8.56 \times 10^{-10} - 1.88 \times 10^{-9}$ m^2/s	25.28 kJ/mol	Present Study
	IR	60˚C - 80˚C	$1.30 \times 10^{-9} - 1.96 \times 10^{-9}$ m^2/s	20.13 kJ/mol	

4.1.4 Colour

Figure 4.5 shows the appearances of the dried kedondong samples and Table 4.3 shows the results of colour analyses in terms of L^*, a^*, b^*, ΔE (total colour change) and h (hue angle) values of fresh and dried slices from HA and IR drying at various drying temperatures.

Fresh IR60 IR70 IR80



HA50 HA60 HA70 HA80

Figure 4.5: Appearances of kedondong samples as affected by hot air drying (HA) and infrared drying (IR) at different drying temperatures

It can be observed that browning increased gradually with drying temperatures in both HA and IR drying as indicated from the L^* values that reduced from 76.61 (fresh samples) to 48.44 – 59.24 and 51.81– 63.49 for HA dried and IR dried samples, respectively (Table 4.3). In all cases, statistical analyses showed that there was significant difference ($p < 0.05$) between the fresh and all the dried kedondong samples. It can be observed that there was an increase in a* values from 2.52 (fresh samples) to 7.32 - 13.79 and 7.82 – 13.31 in HA and IR dried samples, respectively. Significance difference ($p < 0.05$) was also observed

between the fresh and dried samples in terms of a* values. However, there was no obvious trend in b^* values and no significant difference ($p > 0.05$) was observed among the fresh and dried samples. This is in agreement with results reported by Chong *et al.* (2008) which stated that drying temperatures played an important role in governing the final colour of the dried product especially due to the browning reactions.

Table 4.3: Colour parameters of kedondong samples dried by hot air drying (HA) and infrared drying (IR) at different drying temperatures

	L^*	a^*	b^*	ΔE	h (°)
Fresh	76.61 ± 0.50^{a}	2.52 ± 0.33^{a}	17.60 ± 1.23^{a}	-	81.84 ± 1.67^{a}
HA50	48.44 ± 2.39^{e}	7.32 ± 1.21^{b}	21.12 ± 4.22^{a}	28.79 ± 1.79^{d}	70.89 ± 2.59^{b}
HA60	59.24 ± 1.38^{bc}	9.81 ± 0.64^{bc}	26.00 ± 2.09^{a}	20.63 ± 0.98^{b}	69.33 ± 0.38^{b}
HA70	56.63 ± 0.14^{cd}	10.56 ± 2.28^{bcd}	23.61 ± 2.36^{a}	22.36 ± 1.36^{bc}	65.91 ± 3.14^{bc}
HA80	55.27 ± 3.13^{cd}	13.79 ± 0.93^{d}	27.04 ± 1.67^{a}	25.92 ± 1.76^{cd}	62.98 ± 1.43^{c}
IR60	63.49 ± 0.56^{b}	7.82 ± 0.49^{b}	23.58 ± 2.18^{a}	15.36 ± 1.27^{a}	71.66 ± 1.75^{b}
IR70	58.42 ± 1.06^{c}	9.60 ± 2.07^{b}	23.94 ± 6.72^{a}	20.52 ± 3.05^{b}	68.15 ± 1.62^{bc}
IR80	51.81 ± 2.19^{de}	13.31 ± 0.83^{cd}	26.34 ± 3.59^{a}	28.43 ± 0.80^{d}	63.19 ± 2.98^{c}

Means having a common letter within the same column are not significantly different at 5% level.

In terms of total colour change (ΔE), it ranged from 20.63 to 28.79 and 15.36 to 28.43 for HA drying and IR drying, respectively, as drying temperatures increased (Table 4.3). The colour changes were mainly due to the significant reduction in L^* values and increased in a^* values in both HA drying and IR drying. This showed that dried kedondong samples became darker and redder after drying which could be due to the high temperature that promoted oxidation of ascorbic acid and digestion of protein to form carbonyl group and amino acids, respectively, which are potent browning agent for Maillard reaction (Chong *et al*., 2008; Borompichaichartkul *et al*., 2009). The ascorbic acid and protein content of kedondong fruits were in the range of 4.65 mg – 42 mg and 0.20 g/100 g FW – 2.33 g/100 g FW, respectively (Janick and Paull, 2008; Ishak *et al*., 2005; Morton, 1987; Luximon-

Ramma *et al*., 2003; Lim *et al*., 2007; Bhuiyan, 2012). Besides, kedondong contains 8.05 g/100 g FW – 10.05 g/100 g FW of sucrose (Morton, 1987). Hence, an increase in temperature could accelerate the hydrolysis of sucrose to form glucose and fructose, resulting in more browning namely caramelization (Borompichaichartkul *et al*., 2009). Another possible reason that could cause discolouration of dried kedondong samples is pigment degradation because the fruits contain of large amount of carotenoid (309 μg/100g FW of cryptoxanthin, 364 μg/100 g FW of lycopene and 201 μg/100 g FW of β-carotene) (Setiawan *et al*., 2000) and it is also thermally instable (Saxena *et al*., 2012).

It can be observed that ΔE for HA50 was significantly higher ($p < 0.05$) than HA60, HA70, IR60 and IR70 which could be due to the longer drying time that allowed longer exposure of the high sugar content and moist samples to the highly aerated environment and subsequently promoted non-enzymatic browning. Similar observations were also reported by Borompichaichartkul *et al.* (2009) in hybrid drying (hot air and heat pump drying) of macadamia nut. Furthermore, lower drying temperature could promote enzymatic browning due to the presence of polyphenols oxidase (PPO) which is responsible for the browning reaction and this enzyme is thermally instable (Chong *et al*., 2008). Kedondong fruits contain 33 mg – 686 mg of total polyphenols content (Lim *et al*., 2007; Luximon-Ramma *et al*., 2003; Ishak *et al*., 2005), 0.05 mg thiamine (Janick and Paul, 2008), 183 μg/g of flavonoids and 167 μg/g of proanthocyanidins (Luximon-Ramma *et al*., 2003) which are the phenolic compounds that reacts in the browning reaction.

On the other hand, ΔE values of HA drying were higher than IR drying at the same drying temperature namely 1.34 times and 1.09 times more than IR drying at 60˚C and 70˚C, respectively. This is mainly attributed to the mechanism of HA drying which

transfers heat from the hot air to the sample and requires longer drying time as compared to IR drying that directs the heat to the samples (both internal and external) and able to dry within a shorter drying time. Borompichaichartkul *et al.* (2009) reported that prolonged non-enzymatic browning could occur as the drying product remains high in moisture content under long drying period. This higher moisture content could dissolve more sugars and resulted in more browning as observed in samples from HA drying.

Hue angle can be presented in colour wheel graph where 0˚ or 360˚ indicates red purple colour, 90˚ indicates yellow colour, 180˚ indicates bluish green colour and 270˚ indicates blue colour (McGuire, 1992). It can be seen that the h values decreased from 81.84˚ (fresh samples) to 62.98˚ - 70.89˚ and 63.19˚ - 71.66˚ for the HA and IR dried samples, respectively (Table 4.3). This showed that the kedondong samples changed from yellowish to red purple colour as drying temperatures increased and significant difference was observed between the fresh and dried kedondong samples ($p < 0.05$).

Therefore, drying temperature in the second stage hybrid drying (HA and IR) was chosen at 60˚C in order to prevent too much colour changes from using excessively high temperature (e.g. pigment degradation, non-enzymatic browning and ascorbic acid oxidation) and excessively low temperature (e.g. dissolved sugar and enzymatic browning).

4.1.5 Texture

Texture provides important information which relates the acceptance level of consumers in terms of product hardness especially when taking the first bite. Table 4.4. shows measurements taken for dried kedondong samples after HA drying and IR drying.

Table 4.4: Hardness of dried kedondong samples dried by hot air drying (HA) and infrared drying (IR) at different drying temperatures

Drying Methods	Hardness (N)
HA50	4.62 ± 0.39^{a}
HA60	8.09 ± 0.24^{b}
HA70	10.50 ± 0.35^{b}
HA80	16.30 ± 1.92^{c}
IR60	14.35 ± 0.25^{c}
IR70	15.72 ± 1.05^{c}
IR80	36.10 ± 1.87^{d}

Means having a common letter within the same column are not significantly different at 5% level.

In general, higher drying temperatures (HA80 and IR80) resulted in significantly harder ($p < 0.05$) dried kedondong samples as compared to those from lower drying temperatures in both HA drying and IR drying. The highest hardness registered were 16.30 N and 36.10 N for HA80 and IR80, respectively. The higher readings could be attributed to the rapid reduction in moisture content coupled with formation of a harden crust layer on the surface of the dried samples as drying progressed. This further induced higher moisture gradient within the samples and subsequently caused pressure unbalance between internal and external section of the samples. This would lead to increase in contracting stress which then resulted in greater compression force due to structural collapse (shrinkage). Presents study showed that moisture content of final dried samples decreased from 0.46 g H_2O/g dry solid to 0.37 g H_2O/g dry solid in HA drying (HA50 – HA80) and from 0.42 g H_2O/g dry solid to 0.24 g H_2O/g dry solid in IR drying (IR60 – IR80) which resulted in increased

hardness of the dried kedondong samples. Chong *et al.* (2008), Ee *et al.* (2019) and Kotwaliwale *et al*. (2007) also reported hardness of chempedak, kedondong and oyster mushroom increased as drying temperature increased. Kotwaliwale *et al.* (2007) explained that rapid moisture removal at higher temperature resulted in collapsed of capillary voids inside the product thus higher hardness was recorded. On the other hand, Abbasi *et al.* (2011) observed that shrinkage percentage at higher drying temperature was much more higher than that at lower drying temperature. In addition, Maskan (2001) and Ee *et al.* (2019) found that higher rate of moisture removal facilitated the migration of solute to the surface of the samples and caused case hardening on the surface layer as drying progressed.

It can be observed that samples dried in IR drying showed significantly higher hardness ($p < 0.05$) as compared to HA drying namely about 1.50 times - 2.30 times more than HA drying at temperature range of 60˚C - 80˚C. This is because moisture was removed in a much faster rate in IR drying (about 1.07 – 1.50 times more in 60˚C - 80˚C) and subsequently resulted in greater hardness in samples. Abbasi *et al* (2011) found that initial percentage of shrinkage for hot air drying of onion was greater than final percentage of shrinkage due to case hardening which impeded the diffusion of moisture. However, Shi *et al.* (2008) reported that moisture diffusion from inner region to the outer surface was more dominant in IR drying of blueberries thus the final IR dried sample was harder as more moisture could be removed as compared to HA dried sample. This again shows that moisture removal in IR drying (via internal and surface heating) is more than HA drying which mainly gains heat through surface heating. Nevertheless, present finding is different from the results obtained from Nathakaranakule *et al.* (2010) that reported far infrared assisted heat pump drying and hot air drying reduced the hardness of final dried longan as

infrared power increased due to the puffing effect. In the case of kedondong samples, puffing was not observed during drying.

Hence, in order to reduce the hardness of final dried products thus it is suggested that the drying temperature in the second stage hybrid drying (HA and IR) be chosen at 60˚C .

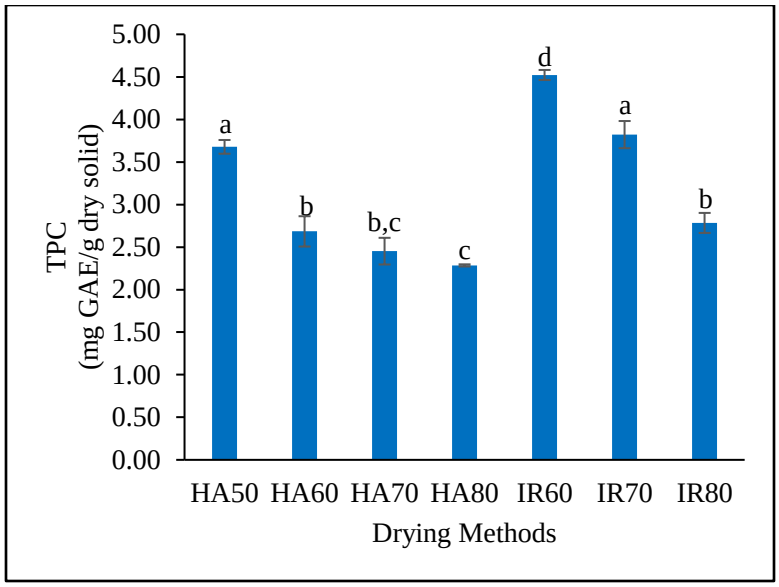
4.1.6 Total polyphenols content (TPC)

Figure 4.6 shows total polyphenols content of HA and IR dried kedondong samples obtained from various drying temperatures. It can be observed that by increasing the drying temperatures resulted in great reduction in TPC from 3.68 mg GAE/g sample to 2.28 mg GAE/g sample and 4.52 mg GAE/g sample to 2.78 mg GAE/g sample for HA and IR dried samples, respectively. This is mainly attributed to thermal degradation and sensitivity of the phenolic compounds to thermal heating as reported by Naim *et al*. (1988) and Maillard and Berset (1995). The observed results are in agreement with those reported for hot air dried sour cherries (Horuz *et al*., 2017b), strawberry (Adak *et al*., 2017), murta berry (Puente-Diaz *et al*., 2012) and quinoa (Miranda *et al*., 2010). Minatel *et al*. (2017) reported that heat treatment caused rupture of the phenol-sugar glycosidic bonds and protein. This subsequently release monosaccharides (sugar) and amino acid which then generate Maillard reaction. Miranda *et al*. (2010) and Martin-Cabrejas *et al*. (2009) also explain that reduction in TPC during drying can also be due to binding of phenolic compounds with other compounds such as protein or the alteration of polyphenols structure during drying process.

Besides, it can also be observed that TPC of IR dried samples was significantly higher ($p < 0.05$) than HA dried samples at respective drying temperature which could be to the

shorter drying time of IR drying (8 hours – 12 hours) as compared to HA drying (9 hours – 13 hours) at drying temperatures of 60˚C, 70˚C and 80˚C. Shorter drying time resulted in reduced exposure time of the samples to oxygen thus preventing oxidation of the phenolic compounds. However, the observed result is different from Adak *et al.* (2017) and Puente-Diaz *et al.* (2012) findings which showed that increasing infrared power would increase TPC of the dried products. Puente-Diaz *et al.* (2012) explained that higher infrared power could disrupt the cell wall of the samples thus released more phenolic compounds from the vacuole and high drying temperature could inactivate the polyphenols oxidase thus reducing the extent of oxidation reaction. However, this could be due to the type of samples used as whole fruit (Murta berries) were used by Puente-Diaz *et al*. (2012) which had a protective skin layer but in current research kedondong slices were used. The kedondong slices exposed the cut surfaces to direct infrared radiations and intense heating could thermally degrade the phenolic compounds.

Therefore, in order to reduce losses of TPC thus it is suggested that the drying temperature in the second stage hybrid drying (HA and IR) be maintained at 60˚C.



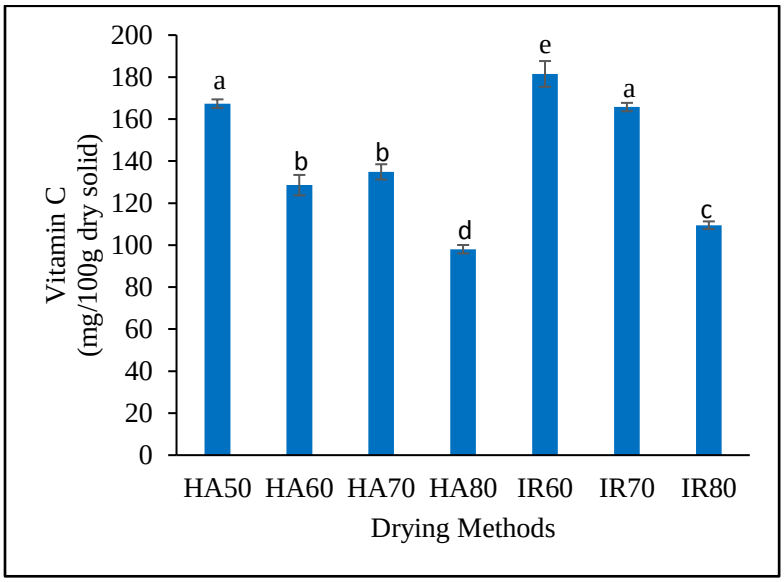
Means having a common letter are not significantly different at 5% level.

Figure 4.6: TPC of dried kedondong samples by hot air drying (HA) and infrared drying (IR) at different drying temperatures

4.1.7 Vitamin C (VC)

The preservation of vitamin C in dried kedondong produced from HA and IR drying at various temperatures are as shown in Figure 4.7. This graph showed a similar trend as TPC retention (Figure 4.6) where an increasing trend in drying temperatures resulted in significant reduction of VC. IR dried samples showed significantly higher ($p < 0.05$) retention in VC as compared to HA dried samples at each respective drying temperature. Degradation of VC depends on several factors such as pH, moisture content, metallic ion catalysis, oxygen, light and temperature (Veras *et al.*, 2012; Erenturk *et al.*, 2005). An increase in drying temperatures resulted in reduction of VC from 167.36 mg AA/100g dry solid to 98.06 mg AA/100g dry solid and 181.53 mg AA/100g dry solid to 109.49 mg AA/100g dry solid for HA drying and IR drying, respectively. Samples dried at higher temperature were also significantly lower ($p < 0.05$) in VC than that at lower temperatures

in both HA and IR drying. This is mainly due to thermal degradation of VC under elevated drying temperature condition (Mrad *et al*., 2012).



Means having a common letter are not significantly different at 5% level.

Figure 4.7: Vitamin C of dried kedondong samples by hot air drying (HA) and infrared drying (IR) at different drying temperatures

It can be observed that retentions of VC in IR dried samples were also significantly higher ($p < 0.05$) than HA dried samples at each corresponding drying temperature. Drying time or exposure time of the samples to heat and oxygen play a critical part in preserving the VC. Total drying times were 9 hours – 13 hours and 8 hours – 12 hours for HA and IR drying, respectively, at drying temperatures of 60˚C - 80 ˚C. Longer drying time exposed the samples to heat and oxygen longer and hence greater degradation of VC (e.g. oxidation) was observed in HA drying as compared to IR drying. Horuz *et al.* (2017b), Xiao *et al.* (2010), Chen *et al.* (2015), Veras *et al.* (2012), Erenturk *et al.* (2005) and Ramallo and

Mascheroni (2012) also reported that increasing drying temperature reduced VC of sour cherries, monukka grape, jujube, pepper, rosehip and pineapple.

In addition, drying temperature could play a more dominant role as compared to drying time as HA50 samples (low temperature and longer drying time) showed higher retention in VC as compared to HA80 samples (high temperature and shorter drying time). Ramallo and Mascheroni (2012) reported similar results in convective drying of pineapple. Therefore, in order to reduce the degradation of VC thus it is suggested that the drying temperature in the second stage hybrid drying (HA and IR) be maintained at 60˚C.

4.1.8 Antioxidant capacity

Antioxidant capacity was evaluated using DPPH and ABTS assay as shown in Table 4.5. The highest ABTS radical scavenging activity was observed in HA50 samples (8.29 μM Trolox equivalent/100g dry solid) and IR60 (8.45 μM Trolox equivalent/100g dry solid) from lower drying temperatures. These values were significantly higher ($p < 0.05$) as compared to HA80 and IR80 samples from the higher drying temperatures at 3.47 μM Trolox equivalent/100g dry solid and 4.94 μM Trolox equivalent/100g dry solid, respectively. DPPH free scavenging radical activity also showed similar results in hot air drying where HA50 samples showed significantly higher antioxidant capacity ($p < 0.05$) (144.86 mg AA/100g dry solid) as compared to HA80 samples (61.39 mg AA/100g dry solid) as drying temperature increased. This is in agreement with the trend observed for TPC and VC (Table 4.5) and it shows that these compounds largely contributes to antioxidant capacity. Samples with the highest TPC and VC had the highest antioxidant capacities in ABTS and DPPH. As shown in Table 4.6, ABTS radical scavenging activity

showed higher correlation with VC (R^2 = 0.859) followed by TPC (R^2 = 0.790) whereas DPPH scavenging activity showed lower correlation to VC (R^2 = 0.593) and TPC (R^2 = 0.543). An *et al.* (2016) and Yi *et al.* (2016) also reported that ABTS tends to show higher correlation with TPC. However, Udomku *et al*. 2015 reported lesser correlation of phenolic compounds with ABTS (R^2 = 0.3328) and FRAP (R^2 = 0.1177) assay which could be due to the antioxidant activity that is not affected by phenolic compounds alone but also with other constituents such as carotenoid, reducing carbohydrates, tocopherols and so on. Therefore, lower correlation of DPPH with VC and TPC could be due to the same reason. It can be observed that DPPH free scavenging radical activity showed no significant different ($p > 0.05$) among IR dried samples but the values were higher than HA dried samples. This could be due to better preservation of other constituents such as carotenoid, reducing carbohydrates, tocopherols and so on in IR drying that could act as an antioxidant substance (Udomku *et al*., 2015).

Therefore, it is suggested that the drying temperature in the second stage hybrid drying (HA and IR) be maintained at lower temperature (60˚C) in order to obtain higher antioxidant capacity.

Therefore, it is suggested that the drying temperature in the second stage hybrid drying (HA and IR) be maintained at lower temperature (60˚C) in order to obtain higher antioxidant capacity.

Table 4.5: TPC, VC and antioxidant capacity of dried kedondong samples by hot air drying (HA) and infrared drying (IR) at different drying temperatures

Drying methods	TPC (mg GAE/g dry solid)	VC (mg AA/100g dry solid)	DPPH (mg AA/100g dry solid)	ABTS (μM Trolox equivalent/100g dry solid)
HA50	3.68 ± 0.18^{a}	167.36 ± 4.85^{a}	144.86 ± 2.50^{a}	8.29 ± 0.38^{a}
HA60	2.68 ± 0.16^{b}	128.57 ± 3.61^{b}	109.80 ± 10.84^{b}	7.63 ± 0.37^{b}
HA70	2.45 ± 0.01^{bc}	134.89 ± 2.01^{b}	87.18 ± 1.93^{c}	5.07 ± 0.14^{d}
HA80	2.28 ± 0.06^{c}	98.06 ± 6.12^{d}	61.39 ± 4.65^{d}	3.47 ± 0.05^{e}
IR60	4.52 ± 0.16^{d}	181.53 ± 2.01^{e}	102.89 ± 5.11^{b}	8.45 ± 0.04^{a}
IR70	3.82 ± 0.12^{a}	165.74 ± 1.81^{a}	111.82 ± 2.59^{b}	7.03 ± 0.01^{c}
IR80	2.78 ± 0.21^{b}	109.49 ± 1.22^{c}	110.79 ± 4.92^{b}	4.94 ± 0.04^{d}

Means having a common letter are not significantly different at 5% level.

Table 4.6: Pearson correlation between TPC, VC and antioxidant capacity

	TPC	VC	DPPH	ABTS
TPC	1	0.910**	0.543**	0.790**
VC	0.910**	1	0.593**	0.859**
DPPH	0.543**	0.593**	1	0.757**
ABTS	0.790**	0.859**	0.757**	1

**. Correlation is significant at the 0.01 level (2-tailed).

4.2 Effects of Hybrid Drying on Drying Kinetics

4.2.1 Moisture ratio

Figure 4.8 shows plot of moisture ratios versus drying time for hybrid drying of kedondong slices. The samples were subjected to first stage freeze drying (FD) at either 6 or 12 hours followed by second stage HA or IR drying at 60˚C until equilibrium moisture content.

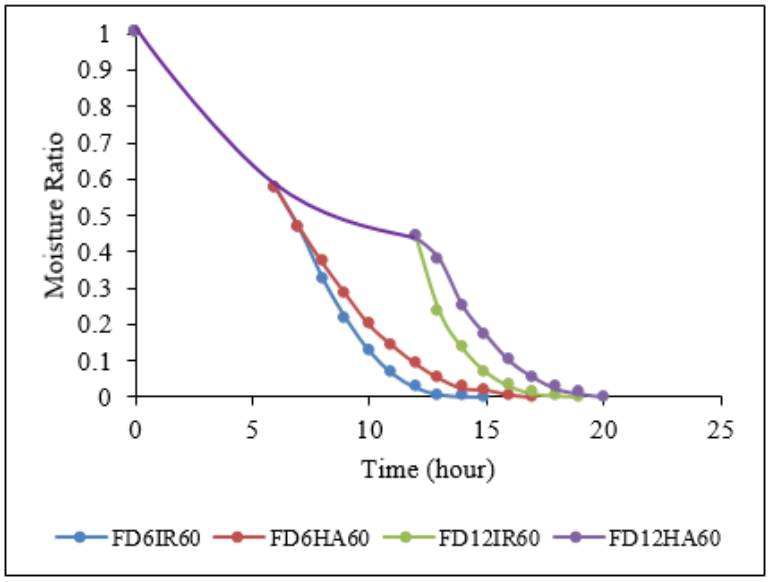


Figure 4.8: Moisture ratio against drying time for hybrid drying

It can be seen that moisture content reduced gradually in the first stage (FD) due to the slow sublimation process of FD that resulted in slower rate of moisture removal. This is necessary in order to retain the nutritional and quality attributes of freeze dried products (Ratti, 2001). Drying progressed faster in the second stage (IR or HA) due to the higher drying temperature which enhanced the moisture diffusion process. This also resulted in shorter total drying time for hybrid drying of FD6 as compared to FD12 combinations. Borompichaichartkul *et al*. (2009) reported similar finding on hybrid drying of macadamia

nut where higher temperature gradient in second stage hot air drying than the first stage heat pump drying sped up the whole drying process due to enhanced drying rates.

Results also showed that kedondong slices dried in hybrid FDIR drying (FD6IR60 and FD12IR60) were faster than hybrid FDHA drying (FD6HA60 and FD12HA60). Fruit materials usually have poor thermal conductivity (high thermal resistance) and not conducive in transferring heat from the heat source to the product. Furthermore, heat transfer by convection in HA drying increases product temperature relatively slower as compared to IR drying. In IR drying, the samples absorb radiation directly and heat can penetrate to a greater depth. Hence, this increases the rate of moisture removal from the samples and therefore hybrid FDIR drying is relatively faster than hybrid FDHA drying.

Drying times required for kedondong slices to reach final moisture contents of about 0.16 – 0.38 g H_2O/g dry solid were 15 hours, 17 hours, 19 hours and 20 hours for FD6IR60, FD6HA60, FD12IR60 and FD12HA60, respectively. This also showed that hybrid drying could save drying time by 37.5 % (FD6IR60), 29.2 % (FD6HA60), 20.8 % (FD12IR60) and 16.7 % (FD12HA60) as compared to conventional freeze drying (FD = 24 hours). By comparing between hybrid drying using HA and IR combinations, FD12IR60 was about 0.95 times faster than FD12HA60 whereas FD6IR60 was 0.88 times faster than FD6HA60. However, by comparing between hybrid drying using FD6 and FD12 combination, FD6IR60 was about 0.79 times faster than FD12IR60 whereas FD6HA60 was 0.85 times faster than FD12HA60.

4.2.2 Drying rates

Figure 4.9 shows plot of drying rates versus moisture content of kedondong slices dried using IR60, HA60 and hybrid drying (FD6IR60, FD12IR60, FD6HA60 and FD12HA60). At the onset of drying, IR and HA drying outperformed other hybrid drying due to the lower drying rates in freeze drying as expected from the slow sublimation process. Only one falling rate was observed in IR60 along the whole drying process due to the intense heating by IR radiation that was directly emitted to the samples. The heat absorbed by the samples creates molecular vibration and generated heat to remove the moisture and resulted in a faster drying rate. However, two falling rates periods were observed in HA60 (changeover at 4.6 gH_2O/g dry solid) which implied that internal diffusion is the more dominant mode of transfer as compared to surface evaporation. However, due to poor thermal conductivity, the inner part of the sample experienced poorer heat transfer and resulted in slower moisture diffusion to the surface. Therefore, moisture from the inner vicinity was not able to replenish the moisture evaporated and resulted in the first falling rate period. The occurrence of second falling rate could be due to precipitation of solute during moisture diffusion which led to case hardening that subsequently reduced further the diffusion rates (Ee *et al*., 2019). Ramos *et al*. (2004) also reported that non-volatile compounds migrated onto the surface caused formation of a thick crust as moisture evaporated. Besides, Pan *et al*. (2008) also found that crust formation could further reduced the subsequent drying rates. On the other hand, Horuz *et al*. (2017b) also reported that reduction in drying rates of sour cherry could be due to cooling effect from the moisture evaporated from the surface during initial phase of drying.

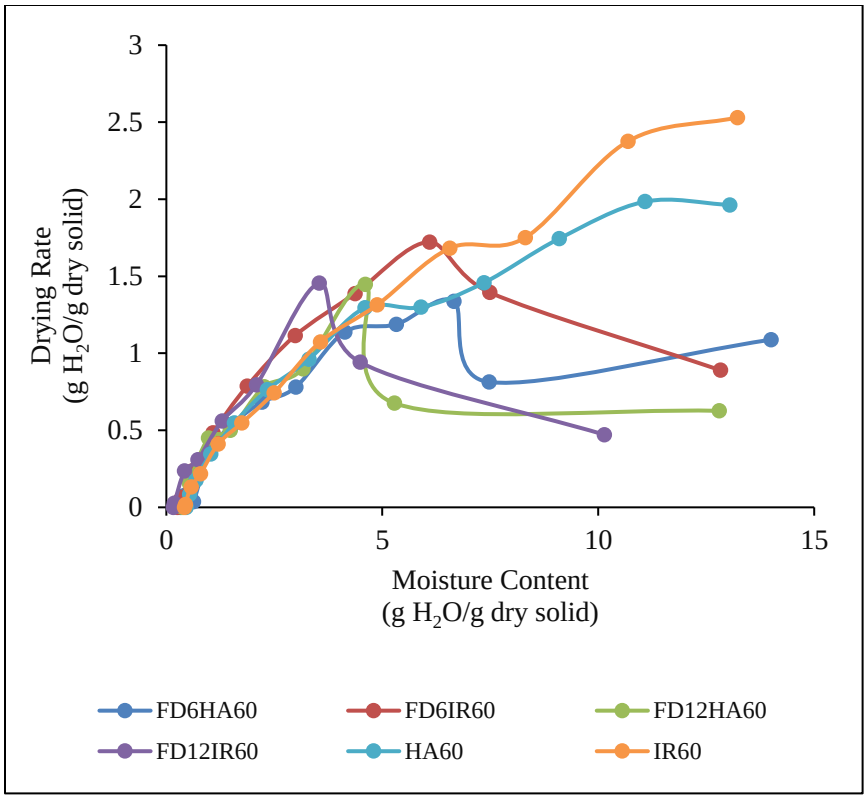


Figure 4.9: Plot of drying rate versus moisture content (HA60, IR60 and hybrid drying)

In hybrid drying, the drying rate curves of FD6IR60, FD6HA60, FD12IR60 and FD12HA60 showed a bell shape pattern which can be classified into three drying periods as shown in Figure 4.10.

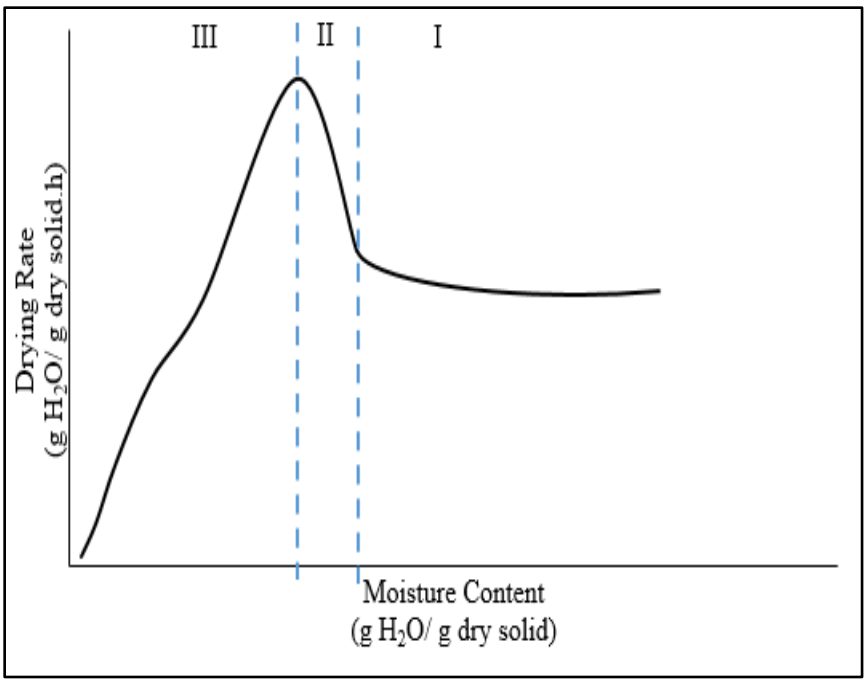


Figure 4.10: Sketch of typical drying rate curve of hybrid drying

Period I refers to drying rates during the first stage freeze drying (FD) before the second stage drying commences (HA or IR) in hybrid drying. At the changeover point, an increase in drying rates can be observed which also corresponds to a short warming up period (period II) since the sample needs to be heated up from a much lower temperature after the first stage freeze drying (FD). Thereafter, only falling rate is observed (period III) as the remaining moisture from the inner vicinity need to be removed and internal diffusion is the dominant mode of transfer.

Table 4.7: Drying rates of various periods during hybrid drying

	Range of drying rates (g H_2O/g dry solid.h)		
Drying methods	Period I	Period II	Period III
FD6IR60	0.89-1.39	1.39-1.72	0.04-1.72
FD6HA60	0.81-1.09	0.81-1.34	0.08-1.34
FD12IR60	0.47-0.94	0.94-1.46	0.03-1.46
FD12HA60	0.63-0.68	0.68-1.45	0.07-1.45

Table 4.7 shows the drying rates at every period (I, II and III) during hybrid drying. It can be seen that drying rates followed well with the trend as depicted in Figure 4.10. Drying rates in Period I were generally lower in freeze drying (0.47 g H_2O/g dry solid.h – 1.39 g H_2O/g dry solid.h) than that in HA and IR drying at the initial phase mainly due to the slower sublimation process as compared to the more intense hot air and infrared heating. The higher hot air and infrared temperatures supplied substantial amount of heat for moisture diffusion and evaporation to occur as compared to freeze drying. Higher drying rates were then observed in Period II when changeover occurred at 1.46 g H_2O/g dry solid.h - 1.72 g H_2O/g dry solid.h (FD6IR60 and FD12IR60) and at 1.34 g H_2O/g dry solid.h - 1.45 g H_2O/g dry solid.h (FD6HA60 and FD12HA60) for second stage IR and HA drying, respectively.

On the other hand, it can also be observed that FD6IR60 showed higher drying rates as compared to FD12IR60 in Period II due to the higher moisture content at the changeover point where the higher moisture content gradient generated greater vapor pressure and promoted the mass transfer process. However, this observation was not that significant in second stage HA drying due to the poor thermal conductivity of the samples and resulted in slower temperature development inside the samples.

In period III, there was no distinct trend and the drying rates in all methods generally registered drying rates within the range of 1.34 g H_2O/g dry solid.h – 1.72 g H_2O/g dry solid.h. However, higher drying rates were typically observed in IR drying (FD6IR60 and FD12IR60) than that in HA drying (FD6HA60 and FD12HA60). Towards the end of the drying process, drying rates in Period III were much lower for IR drying (0.03 - 0.04 g H_2O/g dry solid.h) (FD6IR60 and FD12IR60) as compared to HA drying (0.07 – 0.08 g H_2O/g dry solid.h) (FD6HA60 and FD12HA60) due to the reducing driving force for mass transfer in both methods. Horuz *et al*. (2017a) reported that drying rates of apricot during convective and microwave drying reduced with reducing moisture content before drying was terminated.

Nevertheless, the intense heating from IR heating created higher vapor pressure inside the sample and resulted in higher driving force for mass transfer as compared to HA drying which is in agreement with the findings reported by Pan *et al*. (2008) on IR and HA drying of banana.

4.2.3 Effective diffusivity of hybrid drying

Effective diffusivity (D_{eff}) of kedondong slices dried in hybrid drying were determined using the method of gradient and compared with single drying methods (IR60 and HA60). In hybrid drying, D_{eff} values were determined in each drying method and therefore two D_{eff} values were used to represent hybrid drying as shown in Table 4.8.

Table 4.8: Effective diffusivities of kedondong slices dried in single and hybrid drying.

Drying Method	D_{eff} (m^2/s)	
HA60	9.33×10^{-10}	
IR60	1.02×10^{-9}	
	1st stage drying	2nd stage drying
FD6IR60	1.84×10^{-10}	2.06×10^{-9}
FD6HA60	1.84×10^{-10}	1.23×10^{-9}
FD12IR60	1.98×10^{-10}	2.20×10^{-9}
FD12HA60	1.98×10^{-10}	1.59×10^{-9}

Effective diffusivity during drying depends on several factors such as moisture content, temperature, product shrinkage, drying environment and physical structure of products (Pei *et al*., 2014a, Kahyaoglu *et al*., 2012). It can be observed that the D_{eff} values of partially dried kedondong samples by freeze drying (first stage) at 6 and 12 hours were determined at 1.84×10^{-10} m^2/s and 1.98×10^{-10} m^2/s, respectively. These values were lower than that for single drying methods at 9.33×10^{-10} m^2/s and 1.02×10^{-9} m^2/s for HA60 and IR60 drying, respectively, due to difference in drying temperature and drying mechanism. Higher drying temperature of single drying method (60˚C) as compared to freeze drying promoted mass transfer and moisture evaporation leading to increase in drying rate. In addition, IR drying is more efficient in heating up the samples and able to penetrate to a greater depth in the sample. This is in agreement with observations made by Aydogdu *et*

al. (2015) where higher infrared power caused higher inner temperature development in eggplant drying. Therefore, present study intends to increase the drying rate of freeze drying by subjecting the partially dried FD samples with hot air (HA60) or infrared drying (IR60) at 60˚C. In the second stage drying, HA60 and IR60 showed higher D_{eff} values at 2.06 x 10^{-9} m^2/s, 1.23 x 10^{-9} m^2/s, 2.20 x 10^{-9} m^2/s and 1.59 x 10^{-9} m^2/s for FD6IR60, FD6HA60, FD12IR60 and FD12HA60, respectively.

It can be observed that D_{eff} values of hybrid FDIR drying is higher than FDHA drying in the second stage because of the application of infrared heating that able to increase the diffusion rate. The D_{eff} values in second stage drying were observed higher than in first stage freeze drying due to the slow drying rate attributed to the sublimation process in freeze drying.

In overall, the D_{eff} values of second stage drying were higher as compared to single drying methods (HA and IR). This could be also contributed by the formation of pores after freeze drying (first stage) which resulted in a more porous structure that was more conducive for moisture diffusion to occur from the inner vicinity to the surface of the products in HA and IR drying (second stage). Kahyaoglu *et al*. (2012) and Hussein *et al*. (2016) also reported that porosity formation and lesser shrinkage were able to enhance D_{eff} values of wheat and tomatoes. Besides, it can be observed that partial dried samples from first stage freeze drying after 12 hours showed higher D_{eff} values as compared to that after 6 hours first stage drying when subject to second stage HA and IR drying. This proved that pore formation in partial freeze dried products could play an important role in enhancing mass transfer and effective diffusivity.

These findings agreed well with those reported by researchers where improved D_{eff} values were observed from the first stage heat pump fluidized bed atmospheric freeze drying (6.94×10^{-11} m^2/s – 8.78×10^{-11} m^2/s) of green peas to the second stage microwave drying (3.39×10^{-9} m^2/s – 3.66×10^{-9} m^2/s) (Zielinska *et al*., 2013) and also in first stage freeze drying (1.291×10^{-6} m^2/s – 3.389×10^{-6} m^2/s) of button mushroom to the second stage microwave drying (2.318×10^{-5} m^2/s – 5.565×10^{-5} m^2/s) (Pei *et al*., 2014a). Besides, Puente-Diaz *et al*. (2012) also found that IR assisted convective drying of murta berry increased the D_{eff} values from 7.59×10^{-10} m^2/s – 44.18×10^{-10} m^2/s in first stage convective drying to 11.34×10^{-10} m^2/s – 80.43×10^{-10} m^2/s (400 W) and 15.38×10^{-10} m^2/s – 85.41×10^{-10} m^2/s (800W) in second stage IR drying.

4.3 Physical Characteristic of Hybrid Dried Products

4.3.1 Colour

The images and results of colour parameters of dried kedondong samples obtained from the first stage drying (FD6 and FD12), hybrid drying (FD6IR60, FD6HA60, FD12IR60 and FD12HA60), freeze drying (FD24), hot air drying (HA60) and infrared drying (IR60) are as shown in Figure 4.11 and Table 4.9, respectively. It can be observed that single stage freeze dried samples (FD6 and FD12) and fully freeze dried samples (FD24) were greenish in colour which were quite close to the fresh samples. On the other hand, hot air drying (HA60) and infrared drying (IR60) produced samples ranging from yellowish to brownish colour while hybrid drying produced samples that were pinkish as FD time increased.

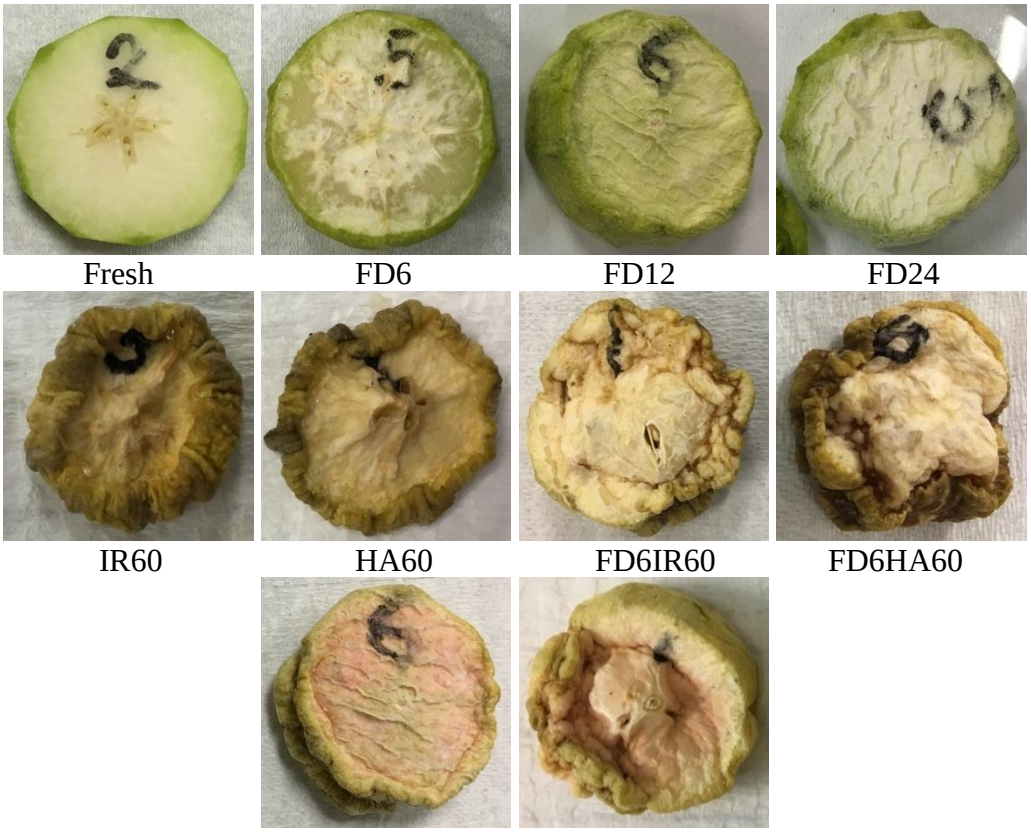


Figure 4.11: Images of dried kedondong samples subject to freeze drying, hot air drying, infrared drying and hybrid drying

Table 4.9: Colour parameter of dried kedondong samples subject to freeze drying, hot air drying, infrared drying and hybrid drying

	L^*	a^*	b^*	ΔE	h (˚)
Fresh	76.61 ± 0.50^{ab}	2.52 ± 0.33^{a}	17.60 ± 1.23^{abc}	-	81.84 ± 1.67^{a}
FD6	75.70 ± 0.22^{a}	5.05 ± 0.38^{ab}	14.93 ± 0.53^{a}	3.78 ± 0.63^{a}	71.32 ± 1.83^{bc}
FD12	79.07 ± 0.13^{a}	3.91 ± 0.85^{a}	14.65 ± 0.77^{a}	4.08 ± 0.81^{a}	75.07 ± 3.81^{ab}
FD24	80.95 ± 0.69^{a}	2.85 ± 1.53^{a}	15.34 ± 2.07^{a}	4.90 ± 1.24^{a}	79.49 ± 6.50^{ab}
IR60	63.49 ± 0.56^{cd}	7.82 ± 0.49^{bc}	23.58 ± 2.18^{cd}	15.36 ± 1.27^{bc}	71.66 ± 1.75^{abc}
HA60	59.24 ± 1.38^{d}	9.81 ± 0.64^{cd}	26.00 ± 2.09^{d}	20.63 ± 0.98^{c}	69.33 ± 0.38^{bc}
FD6IR60	61.57 ± 7.43^{d}	9.10 ± 2.00^{cd}	17.19 ± 2.40^{ab}	16.42 ± 4.34^{bc}	62.09 ± 2.70^{cd}
FD6HA60	66.61 ± 7.74^{cd}	8.90 ± 0.95^{cd}	18.01 ± 1.28^{abc}	11.87 ± 6.21^{b}	63.70 ± 1.45^{cd}
FD12IR60	70.86 ± 1.19^{bc}	11.31 ± 1.21^{d}	16.87 ± 1.21^{ab}	10.53 ± 1.60^{ab}	56.15 ± 3.23^{d}
FD12HA60	69.80 ± 0.60^{bc}	10.77 ± 2.21^{cd}	22.69 ± 4.72^{bcd}	11.85 ± 2.43^{b}	64.61 ± 6.48^{cd}

Means having a common letter within the same column are not significantly different at 5% level.

Colour measurements showed that no significant difference was observed ($p > 0.05$) in all the colour parameters (L^*, a^*, b^*) for FD6, FD12 and FD24 samples when comparing to the fresh samples. There was a tendency for L* values to increase (from $L^* = 76.61$ to 80.95), a* values to increase slightly (from a* = 2.52 to 5.05) and b* values to decrease (b* = 17.60 to 14.65), respectively, as drying time increased in the first stage and complete freeze drying. However, in second stage drying, there was tendency for L^* values to decrease in the range of 61.57 – 66.61 (FD6HA60 and FD6IR60) and 69.80 - 70.86 (FD12HA60 and FD12IR60) as compared to the partially dried samples (75.7 – 79.07) from first stage drying. Increased in a^* values were observed in the range of 8.9 – 9.1 (FD6HA60 and FD6IR60) and 10.77 - 11.31 (FD12HA60 and FD12IR60) and similarly, b^* values increased in the range of 17.19 - 18.01 (FD6HA60 and FD6IR60) and 16.87 - 22.69 (FD12HA60 and FD12IR60). Greater change in a^* values was observed (about 1.8 – 3.0 times) as compared to the partially dried samples from first stage drying and this showed a transition in colour from the brighter/greenish appearance to the final dried products from second stage drying with brownish/reddish colour.

Freeze drying has the advantages in minimizing the changes in colour due to the mild drying temperature and oxygenless condition in this drying method (Khampakool *et al*., 2019). PPO activity is inactivated due to the vacuum condition that prevents oxidation of the phenolic compounds. Second stage drying with sufficient supply of oxygen from air promotes PPO activity and coupled with the high drying temperature could further promote browning reactions.

It can be observed that total colour changes (ΔE) in hybrid drying using hot air (FD6HA60 and FD12HA60) were significantly lower ($p < 0.05$) as compared to HA60 but

no significant difference was observed ($p > 0.05$) among FD6IR60, FD12IR60 and IR60. The trends were mainly due to the increased L^* values which indicated that hybrid FDHA dried samples had brighter appearance as compared to HA dried samples. First stage freeze drying process prevented excessive exposure of the samples conducive to browning and at the same time moisture was being removed to about half of the initial amount after first stage freeze drying. In the subsequent hot air drying, the samples were exposed to a shorter duration as compared to the single HA drying process. Therefore, HA dried samples tend to have darker appearance due to greater amount of moisture available especially in the early stage of drying where sugars dissolved and led to Maillard reaction (Borompichaichartkul *et al*., 2009).

Besides, HA drying alone experienced longer exposure time to oxygen during drying and promoted PPO activity and resulted in higher degree of browning. No significant difference was observed ($p > 0.05$) for L^*, a^*, b^*, ΔE and h values between FD6HA60 and FD12HA60 samples but FD12HA60 was found to be brighter (higher L^* values), redder (higher a^* values) and yellower (higher b^* value) as compared to FD6HA60. This is in agreement to the colour appearance as shown in Figure 4.11 where FD12HA60 samples were brighter and pinkish in appearance and FD6HA60 samples were darker and yellower. The longer freeze drying period in FD12HA60 contributed to these observations as better colour and appearance could be retained during the sublimation process.

There was a tendency for FD12IR60 to have lower total colour change as compared to FD6IR60 and IR60 samples. The longer period of the first stage freeze drying (12 hours) contributed to this observation while the shorter first stage freeze drying coupled with the more intense heating in the second stage infrared drying led to greater browning. Such

observation also applied to IR60 samples where exposure of the samples with high content of dissolved sugar under intense heating also contributed to more browning. Particularly, this can be observed from the highest total colour change in HA60 samples.

Therefore, it can be concluded that sufficient freeze drying should be applied in hybrid drying in order to obtain acceptable colour and appearance of the dried kedondong samples. Present study shows that first stage freeze drying for 12 hours able to produce the best results.

In overall, the freeze dried samples (FD6, FD12 and FD24) recorded the higher range of hue angle as compared to other drying methods. Both hot air (HA60) and infrared (IR60) dried samples showed no significant difference ($p > 0.05$) with some of the hybrid dried samples (FD12HA60, FD6HA60 and FD6IR60) except for FD12IR60. All the hybrid dried samples also showed no significant difference ($p > 0.05$) among each other. Hue angle depends on yellowness (b* values) and redness (a* values) where increment in a* values could cause reduction in hue angle. It can be seen that FD6HA60 and FD12HA60 samples tend to have higher hue angle than FD6IR60 and FD12IR60 samples which indicates that the samples tend to approach red purple colour. In overall, these samples showed colour transformation from greenish to redness.

There is also a linear trend between the hue angle and total colour change as affected by drying temperatures in hot air ($R^2 = 0.9427$) and infrared ($R^2 = 0.9995$) dried kedondong samples (Figure 4.12 and 4.13). Total colour change and hue angle are commonly used as indicators to describe the degree of browning. A high value of total colour change indicates high degree of browning and it is usually associated with a low hue angle value (Baini and Langrish, 2009; Fujita *et al.*, 2006). Therefore, high drying temperature might not be

conducive to minimize browning in single drying method as compared to hybrid drying that incorporated first stage freeze drying.

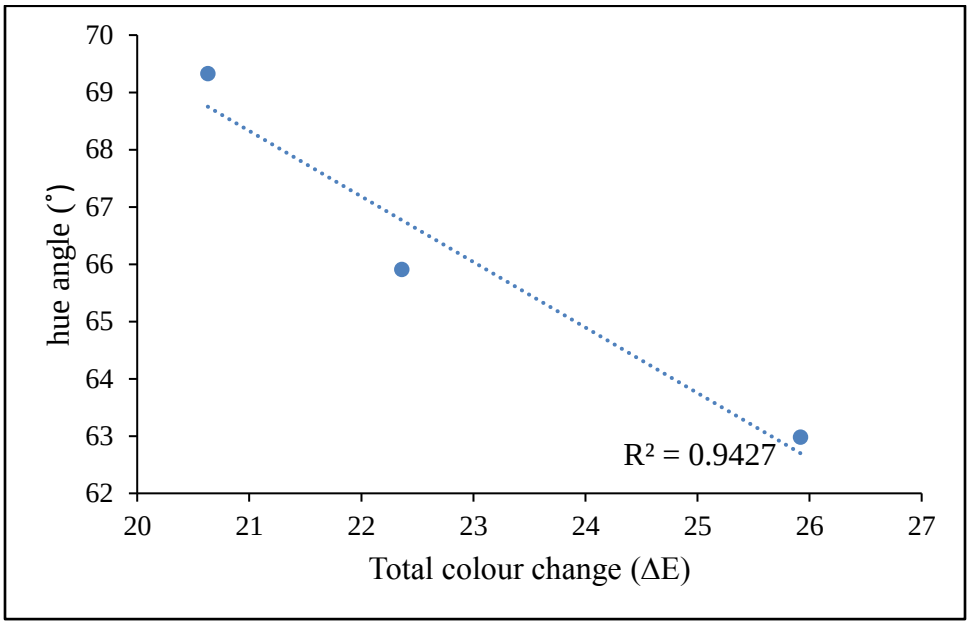


Figure 4.12: Hue angle versus total colour change of HA drying

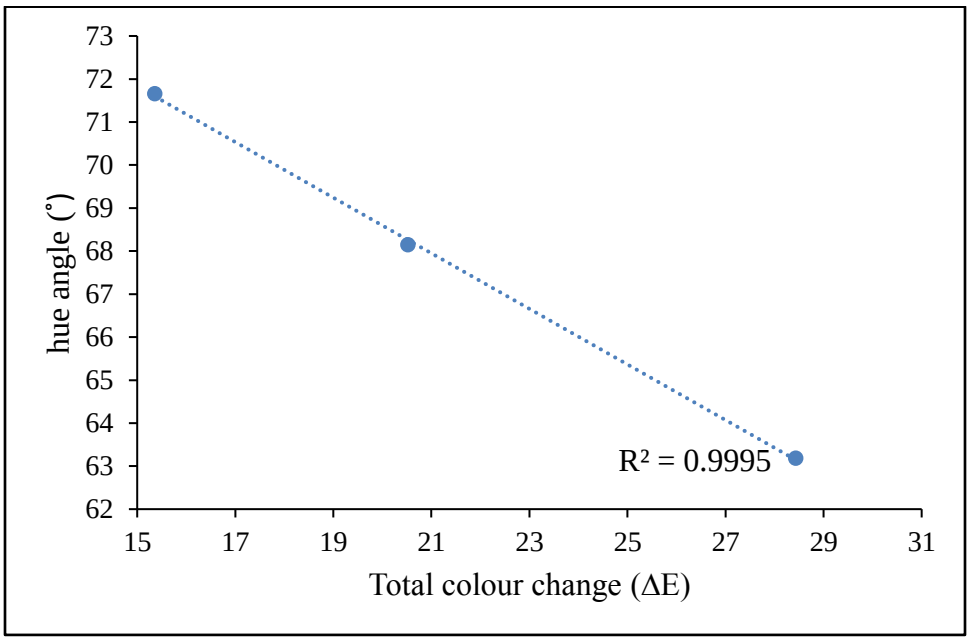


Figure 4.13: Hue angle versus total colour change of IR drying

4.3.2 Texture

Table 4.10 shows the hardness of kedondong slices dried using freeze drying, hot air, infrared and hybrid drying. It can be observed that all FD samples showed significantly lower hardness ($p < 0.05$) as compared to other dried samples and there was tendency for the hardness to decrease as freeze drying time increased from 6 hours to 24 hours. Cui *et al*. (2003) reported that porous structure of freeze dried garlic slices was the main reason for the soft texture as compared to the hot air dried samples with high degree of shrinkage and structural collapse. The partially dried FD6 and FD12 samples had higher moisture contents (7.5 g H_2O/g dry solid and 5 g H_2O/g dry solid) than FD24 samples (0.16 g H_2O/g dry solid). The higher amount of moisture removed from FD24 samples resulted in a more porous structure thus lower puncture force was required to penetrate the dried product. On the other hand, the higher amount of moisture in FD6 and FD12 samples acted as a structural support for the fruit samples and hence higher force was required.

Table 4.10: Hardness of dried kedondong samples from different drying methods

Drying Methods	Hardness (N)
FD6	4.80 ± 0.07^{a}
FD12	3.69 ± 0.65^{a}
FD24	3.47 ± 0.11^{a}
HA60	8.09 ± 0.24^{c}
IR60	14.35 ± 0.25^{e}
FD6IR60	6.77 ± 1.11^{bc}
FD6HA60	6.42 ± 0.05^{b}
FD12IR60	24.99 ± 0.69^{f}
FD12HA60	11.18 ± 0.34^{d}

Means having a common letter within the same column are not significantly different at 5% level.

FD6IR60 and FD6HA60 samples were found significantly lower ($p < 0.05$) in hardness but FD12IR60 and FD12HA60 samples were found significantly higher ($p < 0.05$) in hardness as compared to HA60 and IR60 samples. This could be due to the enhanced moisture movement after 12 hours of first stage freeze drying that brought together some solutes to the surface and formed a crusty outer layer after second stage drying. There was also tendency for FDIR dried samples to have higher hardness than FDHA dried samples as the final moisture contents of the FDIR samples (0.26 g H_2O/g dry solid and 0.16 g H_2O/g dry solid for FD6IR60 and FD12IR60, respectively) were much lower than the FDHA samples (0.33 g H_2O/g dry solid and 0.38 g H_2O/g dry solid for FD6HA60 and FD12HA60, respectively) upon completion of drying and resulted in higher hardness observed.

Visual appearances of hybrid dried samples (Figure 4.11) were found to have lesser shrinkage as compared to HA60 and IR60 samples, mainly due to the first stage freeze drying process. FD12IR60 and FD12HA60 samples also showed lesser shrinkage than FD6IR60 and FD6HA60 samples due to the extended freeze drying period. The longer period of second stage HA and IR drying removed moisture extensively and resulted in greater structural collapse after drying. Similar observation was reported by Wang *et al.* (2015) on combine freeze drying with mid-infrared drying (FD-MIRD) of mushroom where sample dried using freeze dryer (2 hours) experienced melting in subsequent mid infrared drying and led to structural collapse of the product while sufficient freeze drying time resulted in better structure of the product and no further changes when subjected to second stage drying.

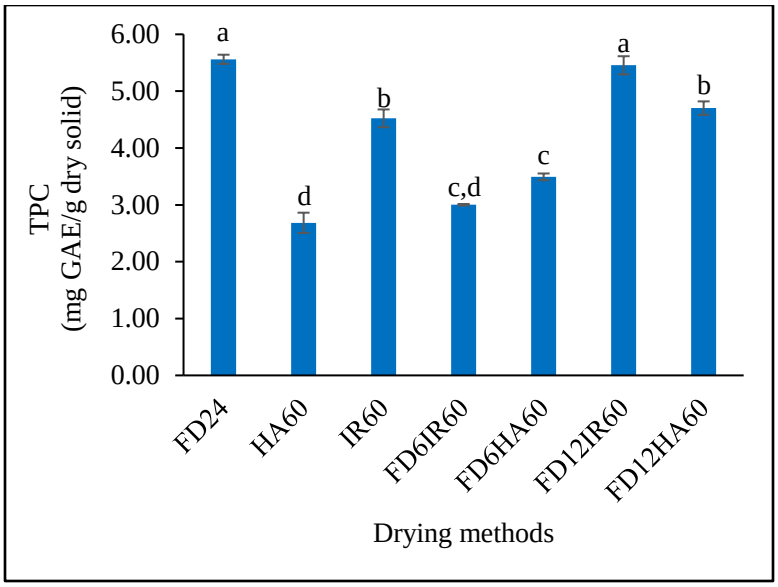
The porous structure after first stage freeze drying also promotes moisture movement in the second stage HA and IR drying. Thus, moisture content of final dried FD6HA60 (0.33 g H_2O/g dry solid) and FD6IR60 (0.26 g H_2O/g dry solid) samples were much lesser than HA60 (0.42 g H_2O/g dry solid) and IR60 (0.45 g H_2O/g dry solid) samples.

4.4 Chemical Characteristics of Hybrid Dried Products

4.4.1 Total polyphenols content (TPC)

Total polyphenols content of all the dried kedondong samples from different drying methods are as shown in Figure 4.14. Dried kedondong samples from FD24 was observed to have the highest TPC (5.56 mg GAE/g sample) as expected due to the low drying temperature and oxygenless condition in freeze drying. On the other hand, HA60 samples showed the lowest TPC mainly attributed to the high temperature and oxygen rich environment during drying.

In general, hybrid drying was found able to improve significantly ($p < 0.05$) retention of TPC especially in samples obtained from FD12IR60 (5.45 mg GAE/g sample) and FD12HA60 (4.52 mg GAE/g sample) as compared to HA60 (2.68 mg GAE/g sample) and IR60 (4.52 mg GAE/g sample). The longer first stage freeze drying period (12 hours) and shorter exposure time (7 hours – 8 hours) to high temperature in second stage drying (HA and IR drying) able to preserve better the phenolics compounds as compared to samples obtained from HA60 and IR60 which exposed the samples to heat and oxygen for a longer period of time (12 hours – 13 hours).



Means having a common letter within the same column are not significantly different at 5% level.

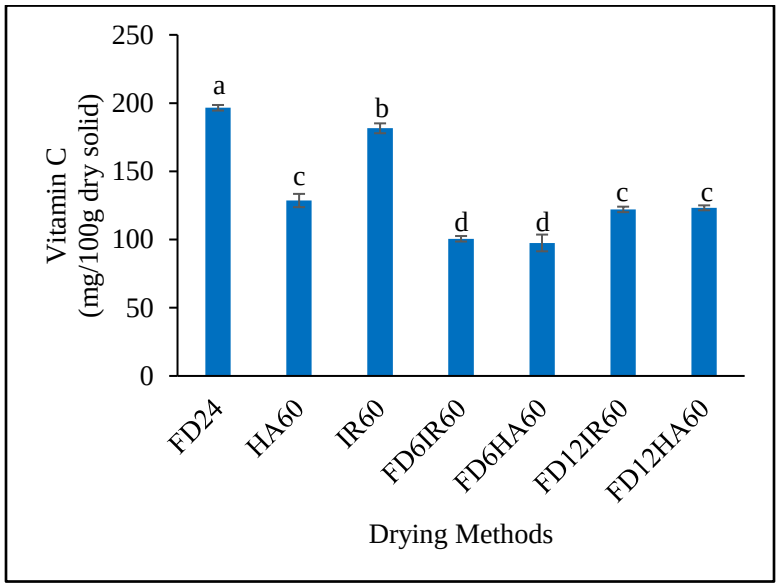
Figure 4.14: TPC of dried kedondong samples by hot air drying (HA), infrared drying (IR) and hybrid drying (FDHA and FDIR)

In addition, no significant difference ($p > 0.05$) between dried kedondong samples from FD24 (5.56 mg GAE/g sample) and FD12IR60 (5.46 mg GAE/g sample) was observed. This proves that IR drying is able to contribute in reducing the total drying time of complete freeze drying by operating in hybrid mode and at the same time able to retain similar amount of TPC as in freeze drying. Horuz *et al.* (2017b) found that hybrid infrared drying and hot air drying of sour cherries led to reduction in drying time that subsequently reduced the exposure time to oxygen and prevent oxidation of phenolics compound and yielded higher TPC retention. An *et al.* (2016) reported that freeze drying of ginger obtained the highest TPC as compared to hot air drying, infrared drying and microwave drying and Yi *et al.* (2016) also found that freeze drying of jackfruit recorded the highest retention of TPC as compared to instant control pressure drop assisted freeze drying (FDDIC) and instant control pressure drop assisted hot air drying (ADDIC). Present study

shows improvement of hybrid drying in the retention of TPC and is a potential method that can be used to reduce the operating cost and drying time as compared to complete freeze drying method.

4.4.2 Vitamin C (VC)

Figure 4.15 shows the retention of vitamin C of the dried kedondong samples from the various drying methods. As expected, freeze dried samples (FD24) showed the highest VC retention at 196.56 mg AA/100 g dry solid which is significant different ($p < 0.05$) as compared to other drying methods due to the low temperature and oxygenless condition of the drying process. The second and third highest VC retention were from IR60 (181.53 mg AA/100 g dry solid) and HA60 (128.57 mg AA/100 g dry solid) samples, respectively.



Means having a common letter within the same column are not significantly different at 5% level.

Figure 4.15: VC of dried kedondong samples by hot air drying (HA), infrared drying (IR) and hybrid drying (FDHA and FDIR)

However, dried kedondong samples from hybrid drying did not improve much VC retention and reduced VC to 100.54 mg AA/100 g dry solid, 97.48 mg AA/100 g dry solid, 122.97 mg AA/100 g dry solid, and 123.22 mg AA/100 g dry solid for FD6IR60, FD6HA60, FD12IR60 and FD12HA60 samples, respectively.

A possible explanation to this observation could be due to the porous structure of the partially dried kedondong samples after the first stage freeze drying that facilitated the moisture movement in the second stage HA and IR drying. Furthermore, VC is water soluble and will maintain dissolve until the food product reaches very low moisture content (Guine, 2018). Therefore, losses in VC were found higher in hybrid dried samples (FDHA and FDIR) as more moisture were being removed and the final moisture contents were much lower (0.16 g H_2O/g dry solid - 0.38 g H_2O/g dry solid) than single drying (HA and IR) method (0.42 g H_2O/g dry solid - 0.45 g H_2O/g dry solid). On the other hand, the higher VC retention in HA and IR dried samples was due to lesser removal of moisture and this restricted moisture movement due to the higher degree of shrinkage and formation of a crusty layer on the surface of the samples.

4.4.3 Antioxidant capacity

Table 4.11 shows the TPC, VC, and antioxidant activity (DPPH and ABTS) of the various dried kedondong samples from various drying methods. In terms of ABTS, the highest antioxidant activity was found in FD24 (9.67 μM Trolox equivalent/100g dry solid) followed by FD12IR60 (9.55 μM Trolox equivalent/100g dry solid), FD12HA60 (8.75 μM Trolox equivalent/100g dry solid), IR60 (8.45 μM Trolox equivalent/100g dry solid), HA60 (7.63 μM Trolox equivalent/100g dry solid), FD6HA60 (6.86 μM Trolox

equivalent/100g dry solid) and FD6IR60 (6.31 μM Trolox equivalent/100g dry solid). The general trend of DPPH antioxidant activity is similar to ABTS where FD24 was the highest (216.41 mg AA/g dry solid), followed by FD12HA60 (121.42 mg AA/g dry solid), FD12IR60 (119.62 mg AA/g dry solid), HA60 (109.80 mg AA/g dry solid), IR60 (102.89 mg AA/g dry solid), FD6HA60 (84.49 mg AA/g dry solid) and FD6 IR60 (63.31 mg AA/g dry solid).

Results also showed that FD6IR60 and FD6HA60 samples showed significantly lower ($p < 0.05$) DPPH and ABTS as compared to FD12IR60 and FD12HA60 samples. The results are consistent with the TPC and VC measurements which also showed a similar trend statistically. In Table 4.12, ABTS radical scavenging activity was found to have higher correlation to TPC ($R^2 = 0.895$) and moderate correlation to VC ($R^2 = 0.662$) whereas DPPH was observed to have higher correlation to VC ($R^2 = 0.757$) than TPC ($R^2 = 0.698$).

Table 4.11: TPC, VC, DPPH and ABTS of dried kedondong samples by hot air drying (HA), infrared drying (IR) and hybrid drying (FDHA and FDIR)

Drying methods	TPC (mg GAE/g dry solid)	VC (mg AA/100g dry solid)	DPPH (mg AA/100g dry solid)	ABTS (μM Trolox equivalent/100g dry solid)
FD24	5.56 ± 0.08^{a}	196.56 ± 2.04^{a}	216.41 ± 4.02^{a}	9.67 ± 0.57^{a}
HA60	2.68 ± 0.16^{d}	128.57 ± 3.61^{c}	109.80 ± 10.84^{bc}	7.63 ± 0.37^{de}
IR60	4.52 ± 0.16^{b}	181.53 ± 2.01^{b}	102.89 ± 5.11^{c}	8.45 ± 0.04^{cd}
FD6IR60	3.00 ± 0.26^{cd}	100.54 ± 1.69^{d}	63.31 ± 3.11^{e}	6.31 ± 0.26^{f}
FD6HA60	3.49 ± 0.21^{c}	97.48 ± 0.14^{d}	84.49 ± 3.12^{d}	6.86 ± 0.12^{ef}
FD12IR60	5.46 ± 0.14^{a}	122.07 ± 7.33^{c}	119.62 ± 2.50^{b}	9.55 ± 0.45^{ab}
FD12HA60	4.70 ± 0.23^{b}	123.22 ± 2.49^{c}	121.42 ± 6.97^{b}	8.75 ± 0.11^{bc}

Means having a common letter within the same column are not significantly different at 5% level.

Table 4.12: Pearson correlation of TPC, VC and antioxidant capacity

	TPC	VC	DPPH	ABTS
TPC	1	0.577**	0.698**	0.895**
VC	0.577**	1	0.757**	0.662**
DPPH	0.698**	0.757**	1	0.782**
ABTS	0.895**	0.662**	0.782**	1

** Correlation is significant at the 0.01 level (2-tailed).

4.5 Sensory Evaluation

Figure 4.16 shows panel's ratings on six sensory attributes (texture, browning, sweetness, sourness, kedondong note and kedondong aroma) for HA60, IR60, FD6HA60, FD12IR60 and FD24 samples. The JAR scale for "much too little" and "somewhat not too" were compiled as "too little" and "somewhat too" and "much too" were compiled as "too much" to ease explanation (Estiaga, 2015). It can be seen that FD24 and FD6HA60 samples showed the highest JAR score for texture at 32% to 34%, respectively, and 90% of the panel rated IR60 samples as too much hardness. This is in agreement with the hardness determined (Section 4.3.2) where IR60 samples were the second highest in hardness among all other dried samples. However, FD12IR60 samples recorded the highest hardness but sensory evaluation showed that only 66% of panel rated as too much hardness and there was a slight increase in JAR score from 8% to 24%. Similar result was obtained in FD6HA60 samples where 40% of the panel rated as too much hardness as compared to 64% for HA60 samples. Many panel (64%) rated FD24 samples as having too little hardness which is expected as freeze dried samples are usually more porous, spongy and have a softer mouthfeel. This is in agreement with the lowest hardness determined in texture analysis (section 4.3.2) as compared to other dried kedondong samples.

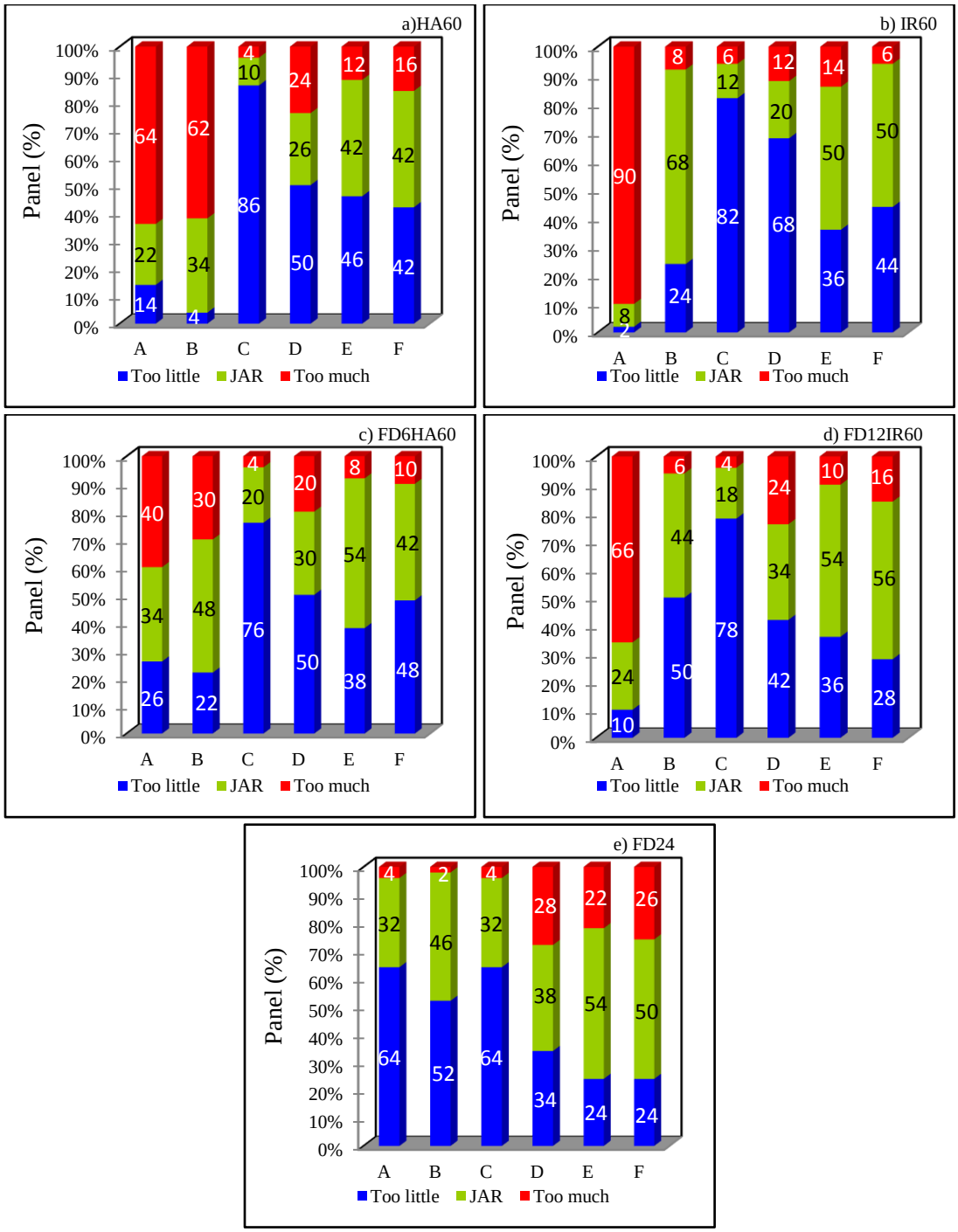


Figure 4.16: Percentage of panel that rated for "too little", just about right "JAR" and "too much" for attributes A: texture, B: browning, C: sweetness, D: sourness, E: kedondong notes and F: kedondong aroma

In terms of browning attribute, HA60 samples showed the highest percentage among panel (62%) rating the samples was too much browning and IR60 samples showed the highest percentage (68%) of JAR score followed by FD6HA60 (48%), FD24 (46%) and FD12IR60 (44%). Higher percentage of panel (52%) rated that FD24 samples showed very little browning and panel also tend to perceive fruit snacks having light brown colour like those sold in the market. Therefore, HA60 samples with the highest rating on too much browning also showed the highest total colour chance ($\Delta E = 20.63$) as compared to IR60, FD6HA60, FD12IR60 and FD24 samples at a lower range of ΔE values ($\Delta E = 4.9 – 15.36$) based on Table 4.9.

Most of the panel rated all the dried kedondong samples had too little sweetness (percentage range 64% - 86%) due to the identity of the fruit itself which is naturally sour. However, panel also rated the dried kedondong samples had too little sourness (percentage range 42% - 68%) except for FD24 samples (34%) which also showed the highest JAR (38%). Dried kedondong samples having higher percentage range of too little sourness (HA60, IR60, FD6HA60 and FD12IR60 samples) could be attributed to the higher temperature (60°C) in the second stage drying (HA or IR) that evaporated some of the organic acid such as ascorbic acid that contributed to the sourness (Kim *et al*., 1993; Rakhmawati and Yunianta, 2015) . Kim *et al*. (1993) also reported that reducing in acidity of heat treated apple as compare to non-heated apple slices.

In terms of kedondong notes, about 24% - 46% of panel rated too little kedondong notes but 42% - 54% of panel rated as JAR. FD24, FD6HA60 and FD12IR60 samples showed the highest JAR score (54%). On the other hand, in terms of kedondong aroma, 24% - 48% of panel rated too little kedondong aroma but 42% - 56% of panel rated as JAR

and FD12IR60 samples showed the highest JAR score (56%). HA60 samples showed the lowest JAR score (42%) among all samples which could due to the continuous hot air drying condition that degraded the natural identity of kedondong notes and aroma.

Penalty or mean drop analysis is a method to identify potential directions for improvement of the product. It assists in identifying attributes that can lead to an increase in overall liking by showing how many points lost (mean drop) as compare to JAR score. Figure 4.17 shows scatterplot of mean drop against percentage panel on six attributes for HA60, IR60, FD6HA60, FD12IR60 and FD24 samples where (-) indicates too little and (+) indicates too much. Typical skew cut off used by food industry is about 20% (Zhi *et al*., 2016), therefore the mean drop for percentage panel below 20% is not considered. Attributes that located at lower left quadrant in the graph is known as high acceptability attributes where low mean drop and low percentage of panel are obtained. Whereas attributes located at upper right quadrant is known as most penalized attributes and should be improved first (higher mean drop). For the attributes that are located at lower right quadrant means that higher percentages of the panel claim the attributes is not right however panel tend to prefer the not-JAR taste.

In this case, the attributes that require improvement in FD24 dried kedondong sample are texture(-), browning (-), sweetness (-), sourness (-), kedondong notes (-), sourness (+), kedondong aroma (-), kedondong notes (+) and kedondong aroma (+) where sourness, kedondong notes and kedondong aroma are the bipolar preference attributes due to the difference between percentage of panel of too much and too little in these attributes which is less than 12 %. Thus, this is also known as candidate for penalty. For HA60 samples, attributes that require improvement are kedondong notes (-), kedondong aroma (-),

sourness (-), sweetness (-), texture (+), and browning (+) whereas for IR60 samples are texture (+), sweetness (-), sourness (-), kedondong aroma (-), kedondong notes (-) and browning (-).

Attributes that need to be improved in FD6HA60 samples are sweetness (-), sourness (-), kedondong notes (-), texture (-) and browning (-). However, percentage of panels on the penalty attributes showed reducing trend as compared to HA60 samples. Furthermore, more than 20% of the panel claimed preference for texture (+), kedondong aroma (-) and browning (+) for FD6HA60 samples and this was favoured although it is not-JAR attributes.

For FD12IR60 samples, attributes that need to be improved are texture (+), sweetness (-), kedondong notes (-), sourness (-) and kedondong aroma (-). Comparison with IR60 samples also showed that the percentage of panel on penalty attributes of FD12IR60 showed reducing trend and more than 20% of the panel claimed that FD12IR60 samples had too little browning but it was favoured although is not-JAR browning.

Overall, hybrid drying (FD6HA60 and FD12IR60) are the preferred samples as compared to samples from FD24, HA60 and IR60 due to reduction in the percentage of panel that rated the not-JAR attributes (FD6HA60: sweetness (-) and kedondong notes (-) whereas for FD12IR60: texture (+), sweetness (-), sourness (-) and kedondong aroma (-)) but nevertheless some of the not-JAR attributes (FD6HA60: texture (+), kedondong aroma (-) and browning (+) whereas for FD12IR60: browning (-)) are favoured by sensory panel.

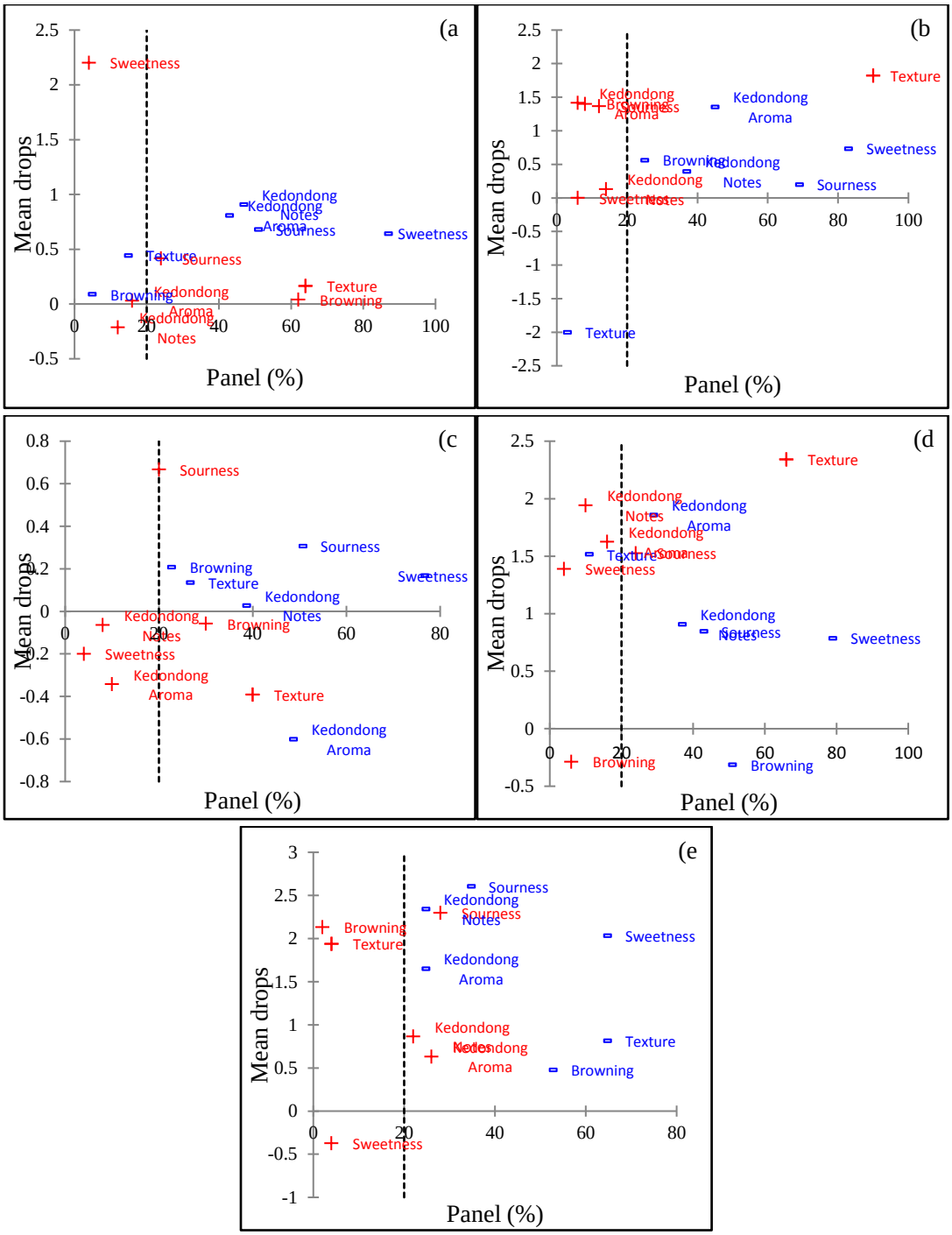


Figure 4.17: Penalty analysis plot for sample a: HA60, b: IR60, c: FD6HA60, e: FD12IR60 and f: FD24

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

The drying kinetics results showed that HA drying required longer drying time as compared to IR dying. Two falling rate periods were detected in HA drying at high drying temperatures (60˚C, 70˚C and 80˚C) whereas both constant rate and falling rate periods were observed at lower drying temperature (50˚C). In IR drying, only falling rate periods were observed in all the experiments. The D_{eff} values obtained from HA drying at 50˚C, 60˚C, 70˚C and 80˚C were 8.56 x 10^{-10} m^2/s, 1.22 x 10^{-9} m^2/s, 1.64 x 10^{-9} m^2/s and 1.88 x 10^{-9} m^2/s, respectively. On the other hand, the D_{eff} values obtained from IR drying at 60˚C, 70˚C and 80˚C were 1.30 x 10^{-9} m^2/s, 1.80 x 10^{-9} m^2/s and 1.96 x 10^{-9} m^2/s, respectively. The activation energies (E_a) of HA drying and IR drying were determined at 25.28 kJ/mol and 20.13 kJ/mol, respectively. Hybrid drying technique used in this study (FDHA and FDIR) have some advantages over freeze drying, hot air drying and infrared drying such as reduction in drying time and increase in D_{eff} values. Hybrid drying could save drying time by 37.5 % (FD6IR60), 29.2 % (FD6HA60), 20.8 % (FD12IR60) and 16.7 % (FD12HA60) as compared to conventional freeze drying (FD = 24 hours). D_{eff} values of partially dried kedondong samples by freeze drying (first stage) at 6 hours and 12 hours were determined at 1.84 x 10^{-10} m^2/s and 1.98 x 10^{-10} m^2/s whereas for second stage drying were determined at 2.06 x 10^{-9} m^2/s, 1.23 x 10^{-9} m^2/s, 2.20 x 10^{-9} m^2/s and 1.59 x 10^{-9} m^2/s

for FD6IR60, FD6HA60, FD12IR60 and FD12HA60, respectively, which is higher as compared to single drying methods (HA and IR).

In terms of preservation of bioactive compounds in HA and IR drying, it is found that increasing the drying temperatures resulted in great reduction in TPC from 3.68 mg GAE/g sample to 2.28 mg GAE/g sample and 4.52 mg GAE/g sample to 2.78 mg GAE/g sample for HA and IR dried samples, respectively. Also, an increase in drying temperatures resulted in reduction of VC from 167.36 mg AA/100g dry solid to 98.06 mg AA/100g dry solid and 181.53 mg AA/100g dry solid to 109.49 mg AA/100g dry solid for HA drying and IR drying, respectively. Lower temperature shows higher antioxidant capacity in term of ABTS for both HA and IR drying. Samples with the highest TPC and VC had the highest antioxidant capacity in ABTS. ABTS radical scavenging activity showed higher correlation with VC ($R^2 = 0.859$) followed by TPC ($R^2 = 0.790$) whereas DPPH scavenging activity showed lower correlation to VC ($R^2 = 0.593$) and TPC ($R^2 = 0.543$). Hybrid drying was found able to improve significantly ($p < 0.05$) retention of TPC especially in samples obtained from FD12IR60 (5.45 mg GAE/g sample) and FD12HA60 (4.52 mg GAE/g sample) as compared to HA60 (2.68 mg GAE/g sample) and IR60 (4.52 mg GAE/g sample). Pearson correlation showed that ABTS radical scavenging activity was found to have higher correlation to TPC ($R^2 = 0.895$) and moderate correlation to VC ($R^2 = 0.662$) whereas DPPH was observed to have higher correlation to VC ($R^2 = 0.757$) than TPC ($R^2 = 0.698$).

In terms of physical characteristics, an increase in sample's browning was observed with drying temperatures in both HA and IR drying as indicated from the L^* values that reduced from 76.61 (fresh samples) to 48.44 – 59.24 and 51.81– 63.49 and increase in a*

values from 2.52 (fresh samples) to 7.32 - 13.79 and 7.82 – 13.31 for HA dried and IR dried samples, respectively. In terms of total colour change (ΔE), it ranged from 20.63 to 28.79 and 15.36 to 28.43 for HA drying and IR drying, respectively, as drying temperatures increased. Higher drying temperatures (HA80 and IR80) resulted in significantly harder ($p < 0.05$) dried kedondong samples as compared to those from lower drying temperatures in both HA drying and IR drying. Hybrid drying was found to have tendency in reducing total colour changes (ΔE) as compared to HA and IR drying.

Sensory evaluation analyzed by penalty analysis found that hybrid dried kedondong samples of FD6HA60 and FD12IR60 reduced the percentage of panel on penalty attributes as compared to HA60 and IR60 dried kedondong samples (FD6HA60: sweetness (-) and kedondong notes (-) whereas for FD12IR60: texture (+), sweetness (-), sourness (-) and kedondong aroma (-)) and some of the not-JAR attributes are preferable such as texture (+), kedondong aroma (-) and browning (+) for FD6HA60 dried samples whereas browning (-) for FD12IR60 dried sample. Therefore, the hybrid drying techniques investigated in this research can be recommended as an alternative drying option that can be applied in the food industry especially in producing premium quality dried kedondong snacks.

5.2 Future Works

The research works carried out have successfully proved the potential of hybrid drying as an alternative option that can be used by the food industry. Such technique is therefore worth further investigation to contribute on knowledge advancement of hybrid drying. Therefore, the following future works are recommended:

- Optimization studies incorporating pretreatment methods: Kedondong samples will undergo some pre-treatment processes such as blanching or steaming to inactivate the enzymes (e.g oxidases) to prevent loss of vitamin C and reduce browning.
- Structural changes of dried kedondong samples: Upon first and second stage drying during hybrid drying, the dried kedondong samples will be examined in more details on the structural changes using scanning electron microscopy (SEM) and relate to wider range of texture parameters and sensory attributes.
- Energy efficiency and analyses: A more detailed studies will be carried out to determine the total energy requirements and determine the energy efficiency of the hybrid drying methods using various operating parameters.
- Hybrid drying strategies using combination of other drying methods: This can be carried out by incorporating other advanced drying methods such as microwave drying, ultrasound, pulse electric field and etc for fruits, vegetables and food drying.

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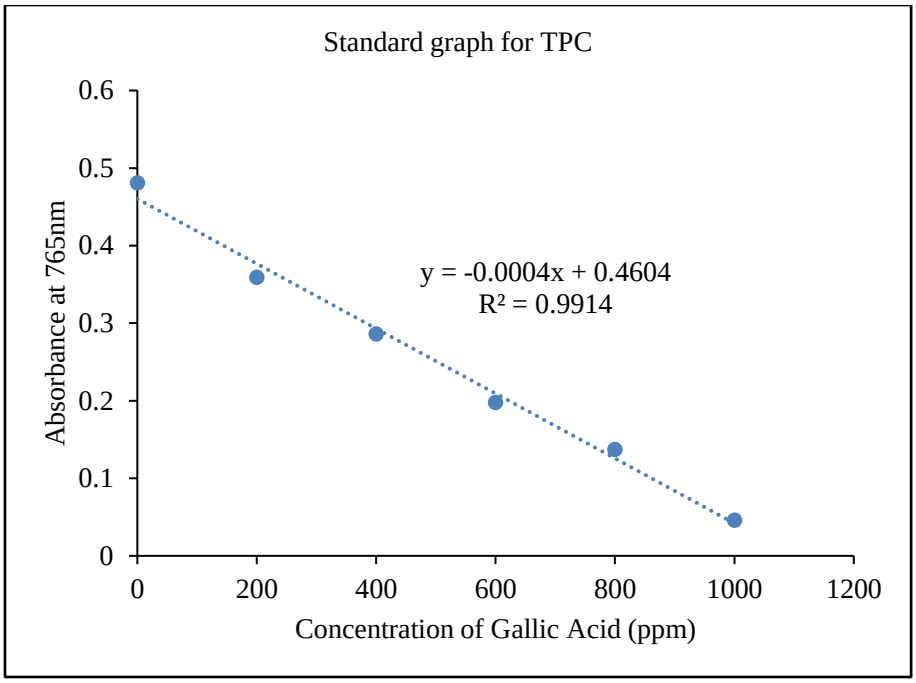
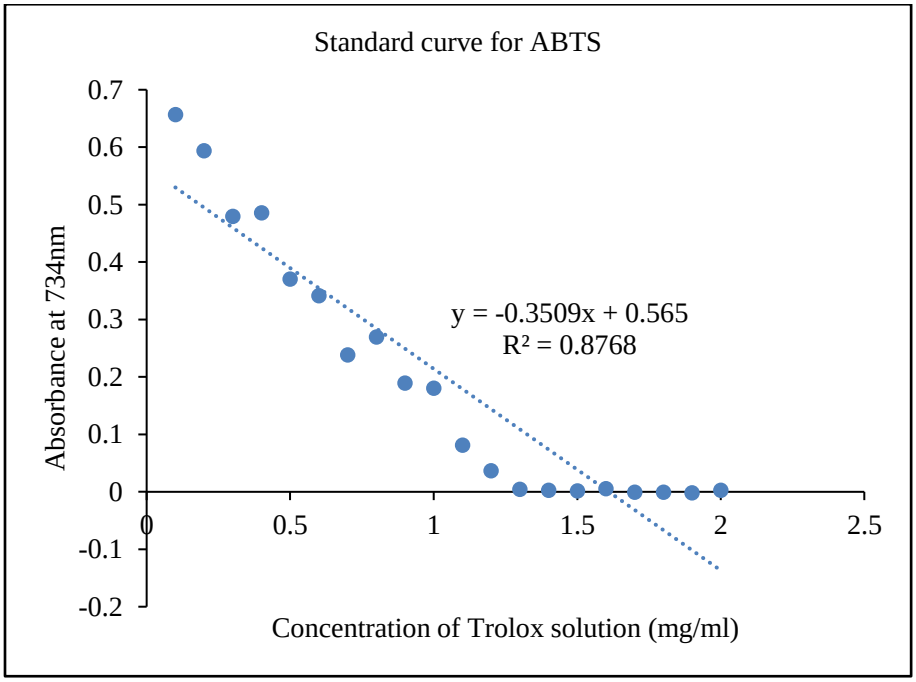
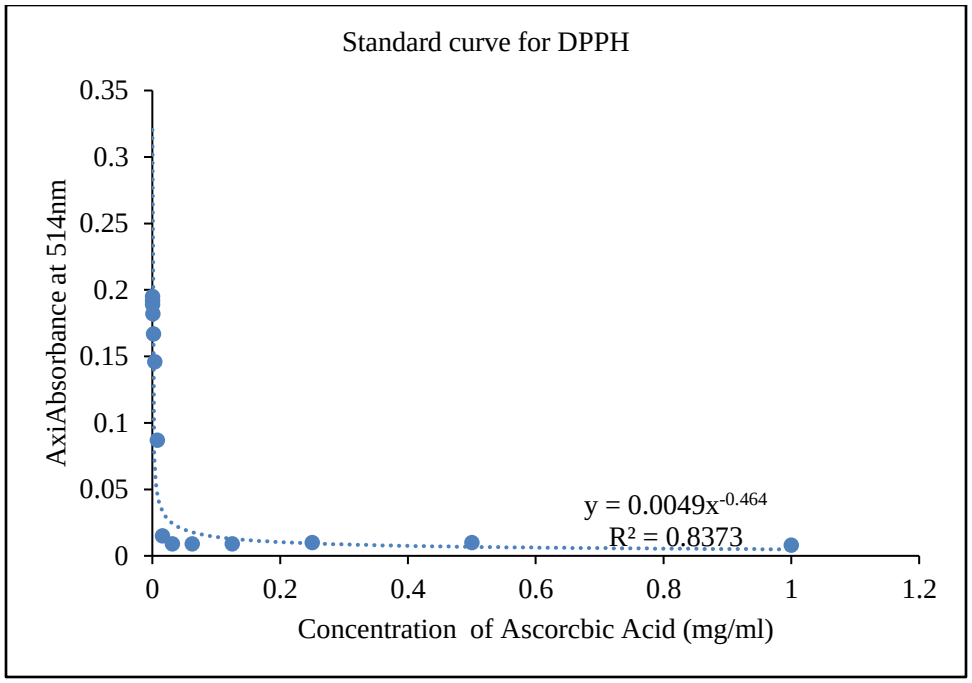
APPENDIX I: Standard Curve


Standard graph for TPC
Absorbance at 765nm
0.6
0.5
0.4
0.3
0.2
0.1
0
y = -0.0004x + 0.4604
R² = 0.9914
0
200
400
600
800
1000
1200
Concentration of Gallic Acid (ppm)


Standard curve for ABTS
Absorbance at 734nm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
y = -0.3509x + 0.565
R² = 0.8768
0
0.5
1
1.5
2
2.5
Concentration of Trolox solution (mg/ml)



IC_{50} AA = 0.0024 mg/ml for triplicate experiments

APPENDIX II: Sensory Evaluation Form

Sensory Evaluation Form

Sensory Evaluation of Dried Kedondong

I am a PG student and currently I am doing a drying research on kedondong fruits for my PhD project. The objective of this sensory form is to obtain information regarding the sensory attributes of the Dried Kedondong and overall preferences which are required for my project and all information obtained is confidential. Please kindly spend some time to complete this form. Your kindness and feedback is much appreciated. Thank you for your cooperation.

Name/Program : _____

Gender : M / F

Age : _____

Please read the following instructions carefully before you proceed. Thank you.

Instructions:

- You are given samples of Dried Kedondong. Please answer the following questions based on the coded samples
- Please rinse your mouth with water each time before starting and between tasting of sample
- Evaluate the samples by first feeling and observing its texture and browning. Next, tasting it and judging its sourness, sweetness, kedondong notes, and kedondong aroma.
- Consider ALL characteristics (texture, sourness, sweetness, kedondong notes, kedondong aroma and browning) and indicate your overall preference by marking a tick (√) on the appropriate scale provided. For example:

Much too weak	Somewhat too weak	Just About Right	Somewhat too strong	Much too strong	1	2	3	4	5	6	7	8	9
○	○	✓	○	○	○	○	○	○	○	○	✓	○	○

- Please request for a retest product when necessary

Definition of sensory attributes:

TEXTURE: Sensory expression of the structure or inner makeup of products including hardness, moistness, smoothness etc. (perceived by tongue)

SOURNESS: Sourness is an acid taste, resembling that of vinegar, lemon juice, etc.

SWEETNESS: Sweetness is a taste or flavor characteristic of sugar, honey, etc.

KEDONDONG NOTES: Kedondong notes is a special fruity taste/flavour that can only be found in kedondong fruit.

KEDONDONG AROMA: kedondong aroma is a special fruity odor/smell that can only be found in kedondong fruit.

BROWNING: Browning is a dark colour with a yellowish or reddish hue by visual inspection.

OVERALL LIKEABILITY: By considering ALL characteristics (texture, sourness, sweetness, kedondong notes, kedondong aroma and browning).

Sample Code: _____

Please indicate the intensity of the following attributes of the dried kedondong and grade the degree of liking from 1 (dislike extremely) to 9 (like extremely):

TEXTURE

Much too little hard	Somewhat not too hard	Just About Right	Somewhat too hard	Much too hard	1	2	3	4	5	6	7	8	9
○	○	○	○	○	○	○	○	○	○	○	○	○	○

SOURNESS

Much too little hard	Somewhat not too hard	Just About Right	Somewhat too hard	Much too hard	1	2	3	4	5	6	7	8	9
○	○	○	○	○	○	○	○	○	○	○	○	○	○

SWEETNESS

Much too little hard	Somewhat not too hard	Just About Right	Somewhat too hard	Much too hard	1	2	3	4	5	6	7	8	9
○	○	○	○	○	○	○	○	○	○	○	○	○	○

KEDONDONG NOTES

Much too little hard	Somewhat not too hard	Just About Right	Somewhat too hard	Much too hard	1	2	3	4	5	6	7	8	9
○	○	○	○	○	○	○	○	○	○	○	○	○	○

KEDONDONG AROMA

Much too little hard	Somewhat not too hard	Just About Right	Somewhat too hard	Much too hard	1	2	3	4	5	6	7	8	9
○	○	○	○	○	○	○	○	○	○	○	○	○	○

BROWNING

Much too little hard	Somewhat not too hard	Just About Right	Somewhat too hard	Much too hard	1	2	3	4	5	6	7	8	9
○	○	○	○	○	○	○	○	○	○	○	○	○	○

OVERALL LIKEABILITY

Much too little hard	Somewhat not too hard	Just About Right	Somewhat too hard	Much too hard	1	2	3	4	5	6	7	8	9
○	○	○	○	○	○	○	○	○	○	○	○	○	○

Comments (if any):

_____

Thank you *for your cooperation. Your feedback in the evaluation test is much appreciated.*

Disclaimer*: While all reasonable efforts have been taken to ensure that the dried samples that you are provided in hygienic condition, we shall not be held responsible for any possible adverse effects caused by the sensory evaluation.*