INFLUENCE OF DRYING CONDITIONS ON DEGRADATION OF CURCUMINOIDS AND BIOACTIVE COMPOUNDS IN TURMERIC (*Curcuma longa* L.)

By
MISS Nilobon KOMONSING

A Thesis Submitted in Partial Fulfillment of the Requirements
for Doctor of Philosophy (FOOD TECHNOLOGY)
Department of FOOD TECHNOLOGY
Graduate School, Silpakorn University
Academic Year 2021

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MISS NILOBON KOMONSING : INFLUENCE OF DRYING CONDITIONS ON DEGRADATION OF CURCUMINOIDS AND BIOACTIVE COMPOUNDS IN TURMERIC(*CURCUMA LONGA* L.) THESIS ADVISOR : ASSISTANT PROFESSOR BUSARAKORN MAHAYOTHEE, Ph.D.

Turmeric is being used as spice, traditional medicine, food coloring, and food supplement. Solar drying is a simple and cost effective method for producing dried herbs and spices in many parts of the world. However, the effect of temperature and light during solar drying on several properties of turmeric is still ambiguous. This study investigated the influences of drying temperature and light exposure on the drying behavior, color, curcuminoids contents (curcumin, demethoxycurcumin, and bisdemethoxycurcumin), total phenolic contents, and antioxidant capacity of turmeric. Fresh turmeric rhizomes at the maturity of 9 - 10 months were used in all experiments. The turmeric slices dried in a parabola-type greenhouse solar dryer were bright orange-yellow while the sun dried products were dark brown-orange. To investigate the influence of light on total curcuminoids and color of turmeric powder, the powder was directly exposed to mimic natural sunlight for 0, 10, 20, 30, and 40 h. The results showed that the light significantly affected b^*, C^*, and $h°$ and reduced total curcuminoids content. On the drying study, Page and Midilli Kucuk models could well describe the drying characteristics of turmeric slices in the temperature range 40 – 80 °C. However, Page model was more suitable because of its simplicity. Effective moisture diffusivities and the drying rate constants increased with the drying temperature and the light exposure. The results showed that drying at high temperature led to shorter drying time and resulted in preservation of color quality in the dried product. This might be due to the retardation of enzymatic browning reaction at high temperature. The percentage changes of these curcuminoids after drying under the without-light condition were higher at every temperature compared to the with-light condition. The combination of light exposure and drying temperature was further investigated under polycarbonate (UV impermeable) and poly(methyl metacrylate) (UV permeable) covers at 40 – 70 °C. It was found that light exposure was a major factor for deterioration of color and curcuminoids contents. Percentage changes of DPPH, ABTS, FRAP, and TPC after drying were not significantly influenced by temperature and light exposure. The results suggested that drying at 70 °C without UV light was the best condition to preserve curcuminoids, color, total phenolic contents, and antioxidant capacity. Drying under these conditions resulted in shorter drying time without negative impact on curcuminoids contents. This fundamental knowledge can be further applied for the optimization of the drying process for turmeric slices in a solar dryer in order to improve quality and reduce cost and energy consumption.

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CHAPTER 1

General Introduction

1.1 Research Problem and Its Significance

Turmeric (*Curcuma longa* L.) is one of the world's most important spices. It is mainly cultivated in Asian countries including India, Bangladesh, China, Thailand, Cambodia, Malaysia, Philippines, and Indonesia (Ravindran et al., 2007). More than 80% of turmeric on the international market is from India. Thailand is one of the turmeric exporters supplying turmeric products to the international market with a value of 2.8 million USD in 2020. The leading importing countries for turmeric products are the United States, Bangladesh, United Kingdom, Germany, and Iran (TradeMap, 2021). Due to its distinctive orange-yellow color, unique flavor, and pharmacological properties, turmeric is utilized as a spice, coloring agent (E100), food supplement, traditional medicine, and dye. It exhibits various bioactivities including anti-inflammatory, anticancer (Zhang et al., 2015), antioxidant (Yang et al., 2020), and antimicrobial properties (Gavara and Hern, 2017). Increasing health awareness leads to a rising demand for turmeric products (Database CBI Market Information, 2021). Adding turmeric in culinary is an integration of condiment and pharmacological usage enhancing wellness and reducing health risk factors.

The rhizomes of *C. longa* L. resemble those of ginger and are the part of the plant most commonly used for consumption. The fresh rhizome is mainly added in curry, stew, and soup. However, it has a short shelf-life due to fungal and bacterial growth. In non-treated rhizomes stored at 10 °C, visible fungal growth can be expected in 20 days (Dhanya et al., 2009). Typically, turmeric rhizomes are harvested once in a season which implies limitations in the off-season supply of fresh turmeric. It is more widely available in dried form on the world market. It is primarily used as a spice and a raw material to produce ground turmeric, curry powder, turmeric oleoresin, turmeric oil, curcuminoids extract, and curcumin.

Drying is the most common and essential method used to preserve medicinal plants (Ray et al., 2022). It also reduces volume, weight, and cost for handling, packaging, and transportation. Various drying methods have been applied for

processing of turmeric including sun drying, solar drying, hot-air drying, heat pump drying, and microwave drying (Komonsing et al., 2022; Sharma et al., 2021; Seanmeema et al., 2018; Lakshmi et al., 2018; Gagare et al., 2015; Jose and Joy, 2009). Traditional open-sun drying is the cheapest and most widely employed method. However, it comes with drawbacks, such as long drying time (10 – 15 days), extreme dependence on weather, and hygiene problems, e.g., rodents, insects, and various contaminations. Although hot-air, heat pump, and microwave drying overcome some of these problems and have been extensively studied (Jeevarathinam et al., 2021; Seanmeema et al., 2018; Monisha et al., 2016), these methods require costly equipment and consume fossil or electric energy. Solar drying, on the other hand, is a more cost-efficient alternative that directly utilizes solar energy which is vastly available in tropical and subtropical regions. However, it is well known that solar radiation and high temperature influence the qualities and bioactive compounds in agricultural products (Mühlbauer and Müller, 2020).

The major bioactive compounds in turmeric products are curcuminoids which are comprised of curcumin, demethoxycurcumin, and bisdemethoxycurcumin (Li et al., 2011). The general structure of curcuminoids consists of 2 polyphenol rings linked by a seven carbon chain with an α,β-unsaturated β-diketone moiety (Priyadarsini, 2014). The difference between the curcuminoids is the number of methoxyl groups. Curcumin has two groups, demethoxycurcumin has one group, and bisdemethoxycurcumin lacks a methoxyl group. The degradation of curcuminoids, which depended on pH, light, temperature, and oxygen, has been studied for decades (Kumavat et al., 2013; Lee et al., 2013; Pricez and Buescher, 1996; Souza et al., 1997; Wang et al., 1997) However, the stability of curcuminoids still generates debates (Appendino et al., 2022). Particularly, the information on the degradation of curcuminoids by temperature and light is still inconclusive.

From previous studies, it is known that curcuminoids, which are chromophores, absorb strongly the visible light spectrum leading to fading of their yellow color (Pricez and Buescher, 1996; Lee et al., 2013; Khurana and Ho, 1988). The photodegradation reaction of curcumin in solutions follows first-order kinetics (Tønnensen et al., 1986)

. Irradiation of curcumin under visible light for 4 h produces 7-hydroxy-1-[(2E)-3-(4-hydroxy-3-methoxyphenyl)prop-2-enoyl]-6-methoxy-naphthalen-2(1H)-one

(Heger et al., 2014). The photochemical degradation products of curcumin after exposure to sunlight for 120 h were mainly vanillin, ferulic aldehyde, ferulic acid, and vanillic acid (Jankun et al., 2016). Thermal processing also influences the stability of curcuminoids (Kharat et al., 2018). Boiled turmeric rhizomes show lower curcuminoids contents compared to unboiled rhizomes (Nithya et al., 2020). However, a study found that high temperature pretreatment increases total phenolic content in the dried product (Prathapan et al., 2009).

In order to design and optimize solar dryers for the drying of turmeric, the optimum drying parameters to preserve curcuminoids in the dried product need to be determined. While there are some studies on solar drying of turmeric (Borah et al., 2015; Jose and Joy, 2009; Karthikeyan and Murugavelh, 2018; Raza et al., 2018; Sharma et al., 2021), the optimum combination of drying parameters such as temperature and light intensity in the dryer are still unclear. Therefore, the main objective of this study was to investigate the influences of drying temperature, light, and cover material on the quality of dried turmeric. Since the conditions in existing solar dryers vary with inconstant environmental factors, a high precision hot air dryer was used in combination with simulated sunlight.

1.2 Objectives

From the main objective of this study, which was to investigate the influences of drying temperature, light, and, cover material on the quality of dried turmeric, the following, more specific objectives can be derived: First, it needed to be determined how drying temperature affected the drying characteristics of turmeric and fundamental quality properties, particularly color, curcuminoids, and bioactive compounds in the dried product. Second, the influence of light on the drying behavior and the aforementioned properties had to be investigated. Moreover, it was necessary to understand the effect both temperature and light in combination and determine the optimal conditions for the solar drying of turmeric. For the practical applicability of the research, a comparison of different cover materials for solar dryers and their influence on the product needed to be conducted.

1.3 Structure of Research

This thesis is structured as follows: In Chapter 3, the effect of drying temperature and drying method on color of dried turmeric is studied. In this preliminary study, turmeric slices are dried at 40, 50, 60, and 70 °C, respectively, in a hot-air dryer and the color of the dried slices in the CIE L^* a^* b^* color space is compared. Additionally, the color values of turmeric slices dried in direct sunlight and a greenhouse solar dryer are compared. In Chapter 4, the influence of light on the degradation of color and curcuminoids in turmeric powder is monitored after different exposure times (0, 10, 20, 30, and 40 h). Chapter 5 continues these studies with the investigation of the effect of drying temperature in combination with light on the drying characteristics and bioactive compounds in turmeric slices. Particularly, the degradation of curcumin, demethoxycurcumin, and bisdemethoxycurcumin is observed both with and without simulated solar radiation in a high-precision hot-air dryer at 40, 50, 60, 70, and 80 °C, respectively. Finally, in Chapter 6 drying characteristics, color, and degradation of curcuminoids are investigated under different cover materials. Turmeric slices are dried at 40, 50, 60, and 70 °C, respectively, under simulated solar radiation through polycarbonate (UV impermeable) and poly(methyl metacrylate) (UV permeable). An overview of the thesis is shown in Figure 1.

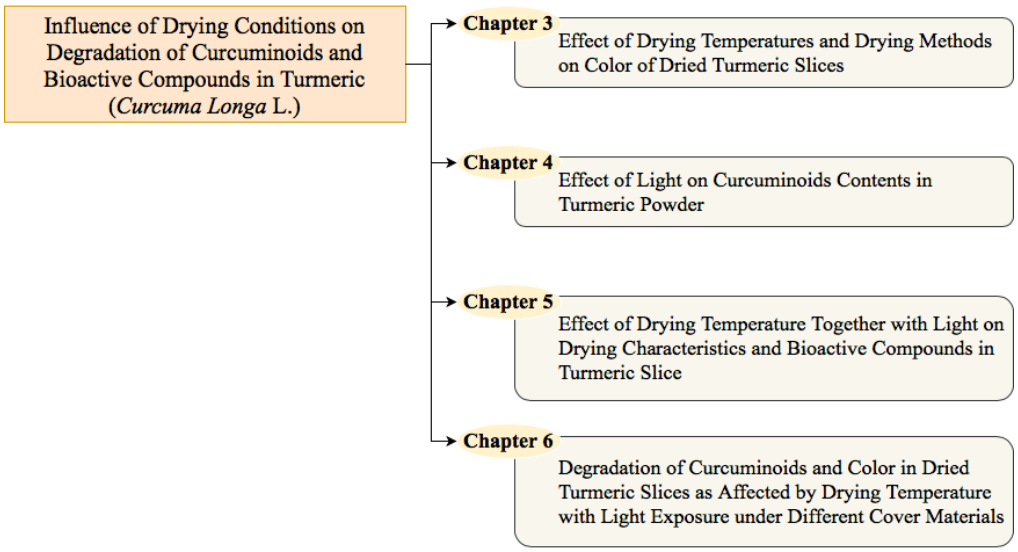


Figure 1 Overview of the thesis.

CHAPTER 2

Literature Review

2.1 Turmeric

Turmeric (*Curcuma longa* L.) is a member of the Zingiberaceae family. Its rhizome looks similar to ginger and galangal. Turmeric is native to South-East Asia (Das, 2016) and nowadays mainly cultivated in countries with warm and rainy climate, including India, Bangladesh, China, Thailand, Cambodia, Malaysia, the Philippines, and Indonesia (Ravindran et al., 2007). On a small scale, it is also grown in the most tropical regions of Africa, America, and islands of the Pacific Ocean. The world's largest turmeric producer, consumer, and exporter is India. Chemical analyses have shown that dried turmeric rhizome contains 69.4% carbohydrate, 13.1% moisture, 6.3% protein, 5.8% essential oil, 5.1% fat, and 3.5% mineral (Amalraj et al., 2017). The major bioactive compounds which provide a characteristic yellow color in the flesh of turmeric are curcuminoids comprising curcumin, demethoxycurcumin, and bisdemethoxycurcumin. The aroma of turmeric is due to essential oil constituents, which contain 28% ar-turmerone, 27% α-turmerone, 19% β-turmerone, 5% α-phellandrene, 2% γ-eudesmol, 1.4% β-curcumene, and 1.4% α-zingiberene (Ray et al., 2022).

Figure 2 Turmeric rhizomes (*C. longa* L).

Figure 2 shows fresh turmeric rhizomes which grow mature in the ground. Length and diameter are in the range of 6.0 – 12.0 and 0.7 – 1.9 cm, respectively. Drying of the leaves and stem indicates that the rhizomes are ready for harvest, the skin turns orange-brown color, rough, and shows intense segment lines. Maturity significantly

affects constituents of turmeric rhizomes. The best time to harvest turmeric is 8 – 11 months after planting to obtain a high yield of bioactive compounds (Cooray et al., 1988; Li, 2011; Choudhary and Rahi, 2018). Turmeric rhizome is consumed in fresh and dried forms. The fresh rhizome is mainly added in curry, stews, and soup. Dried products is more available in the markets. There are many products are made using turmeric which have huge commercial acceptability in domestic and international markets. Some of the examples are fresh turmeric rhizome, ground turmeric, curry powder, turmeric capsule, tea, healthy drinks, oleoresin, cosmetic, supplement, etc. (Figure 3). Ground turmeric is widely used as coloring agent for food, such as curry powder, mustard, and cheese. The E number of curcumin powder is 100 in European Union. The ground turmeric is also used to produce turmeric capsule and tea. Turmeric oleoresin obtained from extraction of ground turmeric. It is orange–red in color which can be used for flavoring and coloring. Curcumin, demethoxycurcumin, bisdemethoxycurcumin and volatile oil are contained in turmeric oleoresin. Drinks from turmeric can be produced from fresh and ground powder, such as turmeric shot, energy drink, milk, turmeric juice, etc.

Figure 3 Products manufactured using turmeric.

2.2 Chemical Composition of Turmeric

Fresh turmeric contains 84.3% moisture, 9.1% carbohydrates, 1.2% proteins, 1.1% fat, 0.7% ash, and 0.7% crude fiber (Mane et al., 2018). Nutritional composition in dried turmeric consists of 69.9% carbohydrates, 8.9% fat, 8.5% protein, 6.8% ash, 6.0% moisture, and minerals, such as calcium, phosphorus, sodium, potassium, iron, ascorbic acid, thiamine, riboflavin, and niacin (Sasikumar, 2001). The active components of turmeric are curcuminoids and volatile oils. Beside appearance, color, and moisture content, the price and health benefits of turmeric vary depending on curcuminoids contents, volatile oils, phenolic contents, and flavonoids (Chumroenphat et al., 2021). These phytochemicals are responsible for antioxidant, anti-inflammatory, anticancer, and antimicrobial activities of turmeric.

2.2.1 Curcuminoids

Curcuminoids are the major phenolic pigments responsible for the yellow color in turmeric flesh with a content varying from 2 – 8%. Curcuminoids are hydrophobic and insoluble in water at acidic and neutral pH and saline but soluble in ethanol, acetonitrile, and dimethyl sulfoxide. The solubility of curcuminoids can be changed depending on the ratio of different curcuminoid combinations (Kiuchi et al., 1993). World Health Organization (WHO) stated the acceptable daily intake of curcuminoids as a food additive is 0.3 mg kg^{-1}. The administration of curcumin in human of up to 12 g per day has not been found to exert toxic effects (Lao et al., 2006). Figure 4 presents the structures of curcuminoids. Commercial curcuminoids contain 77% curcumin, 17% demthoxycurcumin, and 3% bisdemethoxucurcumin (Sandur et al., 2007). Small amounts of cyclocurcumin were detected (Kiuchi et al., 1993).

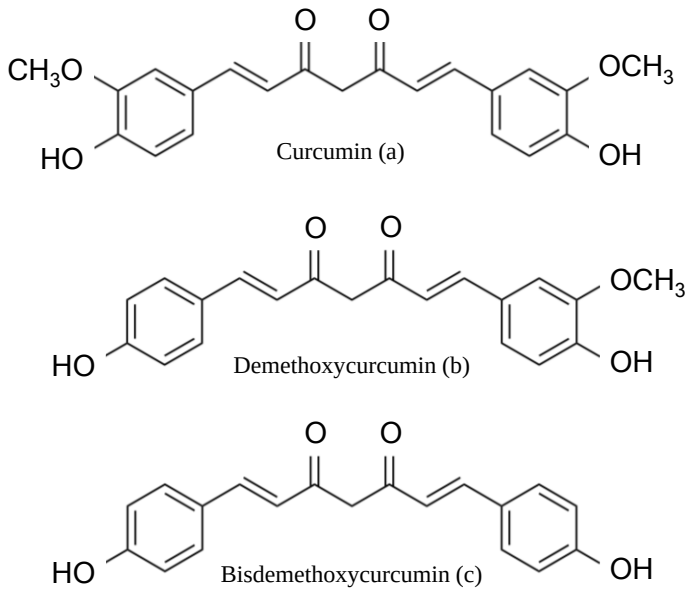


Figure 4 Chemical structures of curcumin (a), demethoxycurcumin (b), and bisdemethoxycurcumin (c).

Source: Jayaprakasha et al. (2005)

Biosynthesis of curcuminoids is a multiple-step process (Figure 5). The main curcuminoids precursors are phenylalanine and tyrosine. Figure 5 shows that phenylalanine ammonia lyase (PAL) enzyme catalyzes the deamination of phenylalanine to cinnamic acid. Subsequently the cinnamic acid is hydroxylated to p-coumaric acid by cinnamate-4-hydroxylase (C4H) enzyme, or tyrosine ammonia lyase (TAL) catalyzes tyrosine to p-coumaric acid. The p-coumaric acid is catalyzed by coumaric acid 3-hydroxylase (C3H) and methoxytransferase (COMT) to generate caffeic acid and ferulic acid. Subsequently, the CoA ester is synthesized by 4-coumaryl CoA ligase (4CL). Diketone CoA synthase (DCS) catalyzes the coumaroyl-CoA, caffeoyl-CoA, and feruloyl-CoA to coumaroyl-diketide-CoA and feruloyl-diketide-CoA. Curcumin synthase (CURS) catalyzes the conversion of diketone CoA ester to β-diketone acid and the polymerization of different β-diketone acid with different CoA esters to form curcumin, demethoxycurcumin, and bisdemethoxycurcumin (Yixuan et al., 2021).

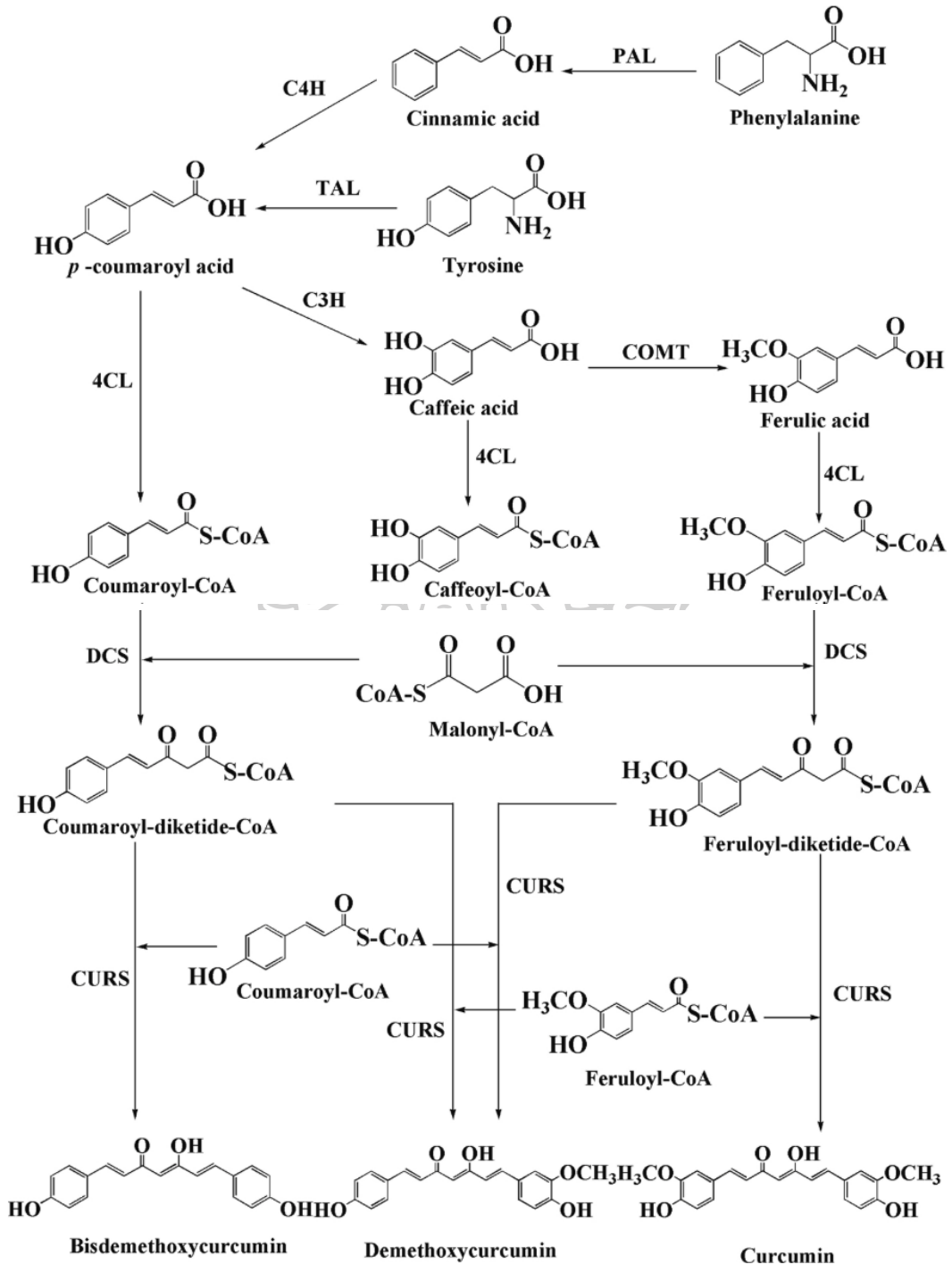


Figure 5 Curcuminoids biosynthesis pathway.

Source: Yixuan et al. (2021)

Curcumin, known as diferuloylmethane ($C_{21}H_{20}O_6$), is the major active compound in turmeric which usually is referred to by the word “curcuminoids”.

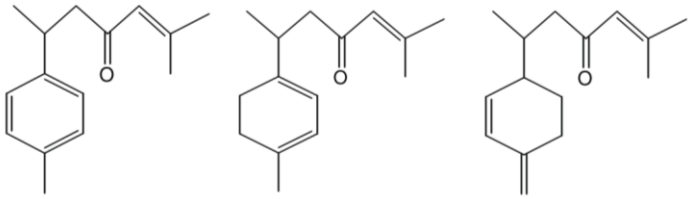
Curcumin was first isolated in 1815, obtained in crystalline in 1870, and the feruloylmethane skeleton was confirmed in 1910 (Aggarwal et al., 2006). The molecular weight and melting point of curcumin are 368.38 g mol^{-1} and 183 °C, respectively (Gantait et al., 2011). Its IUPAC name is 1,7-bis(4-hydroxy-3-methoxy phenyl)-1,6-heptadiene-3,5-dione (1E-6E). Curcumin is approved as a food ingredient by the Codex Alimentarius Commission (INS No. 100(i)). Curcumin exhibits maximum absorption at a wavelength ranging from 408 – 434 nm. The extinction coefficient of curcumin in most solvents is approximately 20,000 – 50,000 M^{-1} cm^{-1} (Priyadarsini, 2009). Curcumin has a brilliant hue at pH 2.5 - 7 and a red hue at pH > 7 (Aggarwal et al., 2006). The structure of curcumin is β-diketone moiety which links between two methoxy phenol rings containing ortho-methoxy phenolic OH^- groups (Figure 4). The presence of hydrogen atoms at the β-diketone chain causes intramolecular H^+ transfer which leads to keto and enol tautomeric conformation in equilibrium. The keto-enol tautomer of β-diketone moiety exists in *cis* or *trans* forms depending on physical conditions such as concentration, temperature, and polarity of solvent, pH, as well as substitutions of aromatic rings (Lee et al., 2013). The ratio of *cis* and *trans* forms also influences the physiochemical and antioxidation properties of curcumin. The enol form with intracellular hydrogen bond of curcumin strongly enhances its radical-scavenging activity. Analog demethoxycurcumin (4-hydroxy cinnamoyl (feruloyl) methane) has only one methoxy group. No methoxy group is found in the structure of analog bisdemethoxycurcumin (*bis*-4-hydroxy cinnamoyl). The methoxy groups play a crucial role in inhibiting the proliferation of tumor cells and increase antioxidant activities of curcumin and demethoxycurcumin. The activity of curcumin is higher than that of demethoxycurcumin, while bisdemethoxycurcumin shows less activity compared to these curcuminoids (Sandur et al., 2007). The anticancer properties of curcuminoids depend on the OH^- group of the phenolic rings. Table 1 shows curcuminoinds in different plants. *C. longa* contains curcumin, demethoxycurcumin, and bisdemethoxycurcumn, while only curcumin is found in Cassumunar ginger (*Zingiber cassumunar*). Two curcuminoids (Curcumin and demethoxycurcumin) are contained in *C. phaeocaulis*.

Table 1 Curcuminoids contents in plants.

Plants	Location	Curcumin	Demethoxycurcumin	Bisdemethoxycurcumin	Total curcuminoids	References
Zingiber cassumunar	Thailand	3.7 – 4.9 mg g^{-1} d.b.	-	-	-	Mahayothee et al. (2020)
C. domestica	Ethiopia	-	-	-	5.12 – 6.81%	Kebede et al. (2021)
C. phaeocaulis	China	0.026 – 0.072 mg g^{-1}	0.004 – 0.026 mg g^{-1}	Not detect	0.030 – 0.098 mg g^{-1}	Li et al. (2011)
C. zedoaria	Thailand	-	-	-	1.1%	Thongchai et al. (2009)
C. longa	Thailand	2.8 mg g^{-1} d.b.	0.6 mg g^{-1} d.b.	0.4 mg g^{-1} d.b.	3.80 mg g^{-1} d.b.	Chumroenphat et al. (2021)
	China	4.18 – 22. 28 mg g^{-1}	1.08 – 9.26 mg g^{-1}	0.40 – 9.50 mg g^{-}	5.66 – 40.36 mg g^{-1}	Li et al. (2011)
	Brazil	2.1 – 6.1 mg g^{-1}	5.9 – 7.0 mg g^{-1}	10.2 mg g^{-1}	18.24 – 23.3 mg g^{-1}	Osorio-tobón et al. (2016)
	Thailand	-	-	-	0.9 – 4.4%	Thongchai et al. (2009)
	China	30.65 mg g^{-1} d.b.	-	-	-	Long et al. (2022)
	India	9.5 mg g^{-1}	1.82 mg g^{-1}	1.56 mg g^{-1}	12.88 mg g^{-1}	Dhanya et al. (2011)

2.2.2 Essential Oils

Turmeric contains 3 – 5% essential oils. It possesses anti-inflammatory, antifungal, antihepatotoxic, antiarthritic, antimicrobial, and central nervous system (CNS) depressant activities and exhibits hypothermic, sedative, anxiolytic, and anticonvulsant properties (Oyemitan et al., 2017; Raina et al., 2002; Singh et al., 2010; Yadav et al., 2013). Generally, essential oils are extracted by hydrodistillation of turmeric powder and show pale yellow color (Sasikumar, 2001). The essential oils of turmeric are reported to have monoterpenoids, monoterpene hydrocarbons, oxygenated monoterpenes, sesquiterpene hydrocarbons, and oxygenated sesquiterpenes. Sesquiterpenes are the main component in turmeric essential oils. Raina et al. (2002) reported that the rhizomes of *C. longa* from Lucknow in India contain 84 oil constituents. The main components are 1, 8 cineole (11.2%), α-turmerone (11.1%), β-caryophyllene (9.8%), ar-turmerone (7.3%), β-sesquiphellandrene (7.1%), zingiberene (5.6%), and β-turmerone (5.0%). The unique aroma of turmeric is derived from turmerone constituents, p-cymene, β-sesquiphellandrene, and sesquiterpene alcohols (Nair, 2013). Singh et al. (2010) identified 38 components in the oils of both fresh and dried turmeric rhizomes accounting for 73.1 and 79.9% of the total weight of the oils, respectively. The major components in fresh rhizome oils are ar-turmerone (24.4%), α-turmerone (20.5%), and β-turmerone (11.1%) and the major components in dried rhizome oils are ar-turmerone (21.4%), α-santalene (7.2%), and ar-curcumene (6.6%). The lower percentage of α- and β-turmerone may be due to the absence of an aromatic ring and presence of two conjugated double bonds which may undergo oxidation or polymerization very easily. Figure 6 presents the turmerone constituents of essential oils of *C. longa* rhizomes.



ar-turmerone α-turmerone β-turmerone

Figure 6 Turmerone constituents in the rhizomes of *C. longa.*

Source: Singh et al. (2010)

2.2.3 Other Phenolic Compounds

Turmeric rhizomes contain phenolic acids and flavonoids. The phenolic acids were detected by Chumroenphat et al. (2021) as hydroxybenzoic acids and hydroxycinnamic acids which are distinguished by constitutive carbon structures. The hydroxybenzoic acids found in fresh rhizome are gallic acid, protocatechuic acid, *p*-hydroxybenzoic acid, vanillic acid, and syringic acid, while the hydroxycinnamic acids are caffeic acid, *p*-coumeric acid, feruric acid, and sinapic acid. The biosynthesis of benzoic and cinnamic derivatives is derived from the aromatic amino acid L-phenylalanine in the shikimate pathway (Chumroenphat et al., 2021). The predominant phenolic acids in fresh and sun dried turmeric are caffeic acid (10.95 μg g^{-1} d.b.) and vanillin (112.76 μg g^{-1} d.b.), respectively. Yang et al. (2020) reported that the phenolic components in dried turmeric rhizomes obtained from ultrasound-assisted extraction are mainly gallic acid (781.0 mg 100 g^{-1} dry extract), ferulic acid (187.0 mg 100 g^{-1} dry extract), epicatechin (45.6 mg 100 g^{-1} dry extract), protocatechuic acid (33.1 mg 100 g^{-1} dry extract), genistein (33.1 mg 100 g^{-1} dry extract), coumarin (25.0 mg 100 g^{-1} dry extract), and catechin (20.3 mg 100 g^{-1} dry extract). Quantification of phenolic compounds of fresh turmeric rhizomes revealed that important bioactive compounds like *p*-coumaric acid (162.46 mg kg^{-1}), catechin (107.67 mg kg^{-1}), sinapic acid (417.36 mg kg^{-1}), and flavonoids like quercetin (2,746.21 mg kg^{-1}) are also present in the rhizomes (Pal et al., 2020). Other flavonoids found in turmeric rhizomes include kaempferol, rutin, apigenin, and myricetin (Chumroenphat et al., 2021). The major flavonoid in fresh and dried turmeric oils is myricetin which is stable to heat and sun drying.

2.3 Degradation of Curcuminoids

Although curcuminoids have extraordinary potential as bioactive compounds, the major factor that limits their uses and bioavailability is the instability under physical conditions (Kharat et al., 2017). The stability of curcuminoids still generates debates (Appendino et al., 2022). One of the most studied factors is the degradation of curcumin by autoxidation reaction in a pH-dependent condition (Wang et al. 1997; Ansari et al., 2005; Kumavat et al., 2013; Gordon et al., 2015). Curcumin degrades rapidly in a buffer system at a neutral basic condition (Kumavat et al., 2013). More than 90% of curcumin in pH 7.2 – 10.0 phosphate buffer solution was decomposed after incubation at 37 °C for 30 min. In the basic condition, a proton removes from a phonolic hydroxyl group, leading to the destruction of the structure. The color of the solution turns brownish-yellow to red. The main degradation product was identified as *trans*-6-(4-hydroxy-3-methoxyphenyl)-2,4-dioxo-5-hexenal. Minor degradation products are vanillin, ferulic acid, and feruloyl methane. In contrast, the degradation of curcumin is extremely slow in acidic solution. Curcuminoids emit bright yellow color. This might be due to the conjugated diene structure (Wang et al., 1997).

Curcuminoids undergo much faster degradation under UV/visible radiation because they are photolabile substances (Treesinchai et al., 2020; Appendino et al., 2022). Curcuminoids absorb strongly the visible light spectrum leading to fading of their yellow color under daylight, artificial light, and sunlight in both organic solutions and solid state. It was postulated that the photodegradation of curcumin might be involved with the formation of triplet excited electronic states (Priyadarsini, 2009). Curcumin in both distilled water and phosphate buffer solution degrades by approximately 50% under UV irradiation at 254 nm for 2 – 8 h, whereas more than 64% of curcumin still remains after incubation at a dark place for 24 h (Lee et al., 2013). Irradiation of curcumin solution under UV radiation (260 – 600 nm) induces major changes in the molecular structure. However, visible light destroys curcumin more than UV radiation (Jankun et al., 2016). Curcumin under UV radiation produces three degradation products while exposing curcumin to sunlight produces more degradation products (Khurana and Ho, 1988). The degradation rate of curcumin increases with light intensity (Pricez and Buescher, 1996). The photodegradation reaction of curcumin

in solutions follows first-order kinetics. Its chemical stability under visible light (400 – 700 nm) is solvent dependent; methanol > ethyl acetate > chloroform > acetonitrile (Tønnensen et al., 1986). This is due to the ability of curcumin to form inter- and intra-molecular bonding which might stabilize or destabilize curcumin toward photochemical degradation (Tønnesen and Karlsen, 1985). Irradiation of curcumin under a wavelength of 400 – 750 nm for 4 h produces 7-hydroxy-1-[(2E)-3-(4-hydroxy-3-methoxyphenyl)prop-2-enoyl]-6-methoxy-naphthalen-2(1H)-one (Heger et al., 2014). Light exposure at a wavelength of 400 – 510 nm removes two hydrogen atoms from a curcumin molecule. The molecular weight is thereby reduced from 368 to 366 g mol^{-1}. This could happen in three possible ways; by forming a triple bond in a vinyl group (Pacáková et al., 2017), by forming a methylenedioxy-group in an aromatic ring (Leigh and Srinivasan, 1983), or by ring closure within the molecule (Cowan and Drisko, 1976). A cyclisation degraded product is generated very fast after irradiation at the wavelength of 400 – 510 nm for 15 min and it is detected only in methanol and chloroform solutions. The solution is completely decolorized within 35 min (Tønnensen et al., 1986). The postulated structure of the cyclisation degraded product is shown in Figure 7.

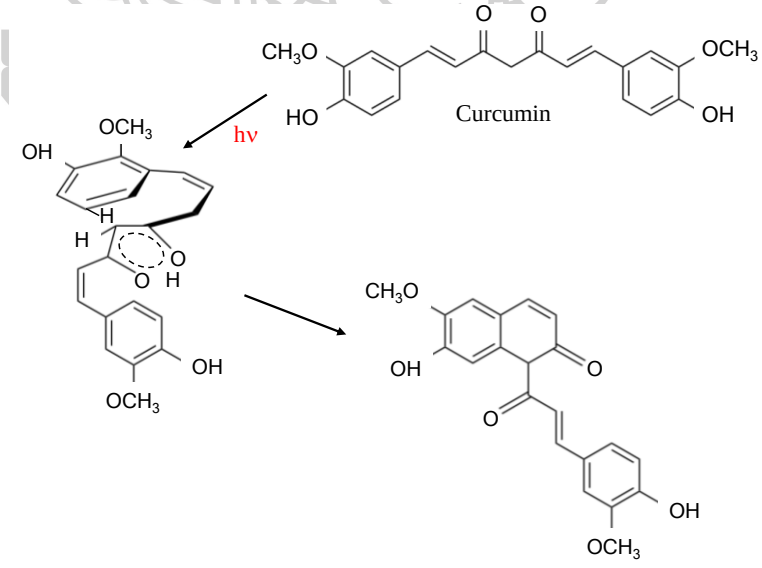


Figure 7 Ring-closure of curcumin after light exposure at 400 – 510 nm.

Source: Tønnensen et al. (1986)

In addition to the main cyclisation degraded product (Figure 7), light breaks the β-diketone link and produces some more degradation products, such as vanillin, vanillic acid, ferulic acid, ferulic aldehyde, and 4-vinulguaiaco (Figure 8). However, the presence of an -OH group in the curcuminoid structures (Figure 4) does not play a significant role in the photodegradation process. In the presence of full sunlight, stability of curcumin increases in acidic solution and decreases as the pH increases. The half-life of curcumin in solutions at pH 1.2 and pH 7.4 is 6.55 and 0.75 h, respectively (Kumavat et al., 2013). A study under fluorescent lighting at 1,450 lux found that the stability order of curcuminoids in acid-brine solution is curcumin > demethoxycurcumin > bisdemethoxycurcumin. This could be due to the antioxidant ability of the individual curcuminoids. Curcumin is the least effective antioxidant, thus its chromophoric system has a lower tendency to break down by free radicals (Pricez and Buescher, 1996). In contrast, another study reports that curcumin is the most sensitive to UV among the curcuminoids (Lee et al., 2013). The degradation of curcuminoids in turmeric extract seems to be lower than in pure curcumin. This is due to the presence of demethoxycurcumin and bisdemethoxycurcumin possibly slowing down degradation (Gordon, et al., 2015). Other curcuminoids can improve the stability of molecular curcumin in pure curcumin solution under low radiation (Appendino et al., 2022).

The photodegradation of curcuminoids also occurs in a solid state. The yellow color of tablets coated with curcumin solution in chloroform completely fades after daylight exposure for one hour. The degradation of a thin curcumin film under daylight follows second-order kinetics. The degradation products are similar to those found after irradiation in solutions. The photochemical degradation of solid state curcumin after exposure to sunlight for 120 h leaves mainly 34% vanillin, 0.5% ferulic aldehyde, 0.5% ferulic acid, and 0.5% vanillic acid (Jankun et al., 2016). These compounds still exhibit antioxidant activity due to a hydroxyl methoxyphenyl group in their structure. Turmeric powder is much more resistant to UV radiation than in aqueous solvents. There is no significant change in yellowness, DPPH, and ABTS activities of turmeric powder after irradiation at 254 nm (Lee et al., 2013). The degradation products form photodegradation are shown in Figure 8.

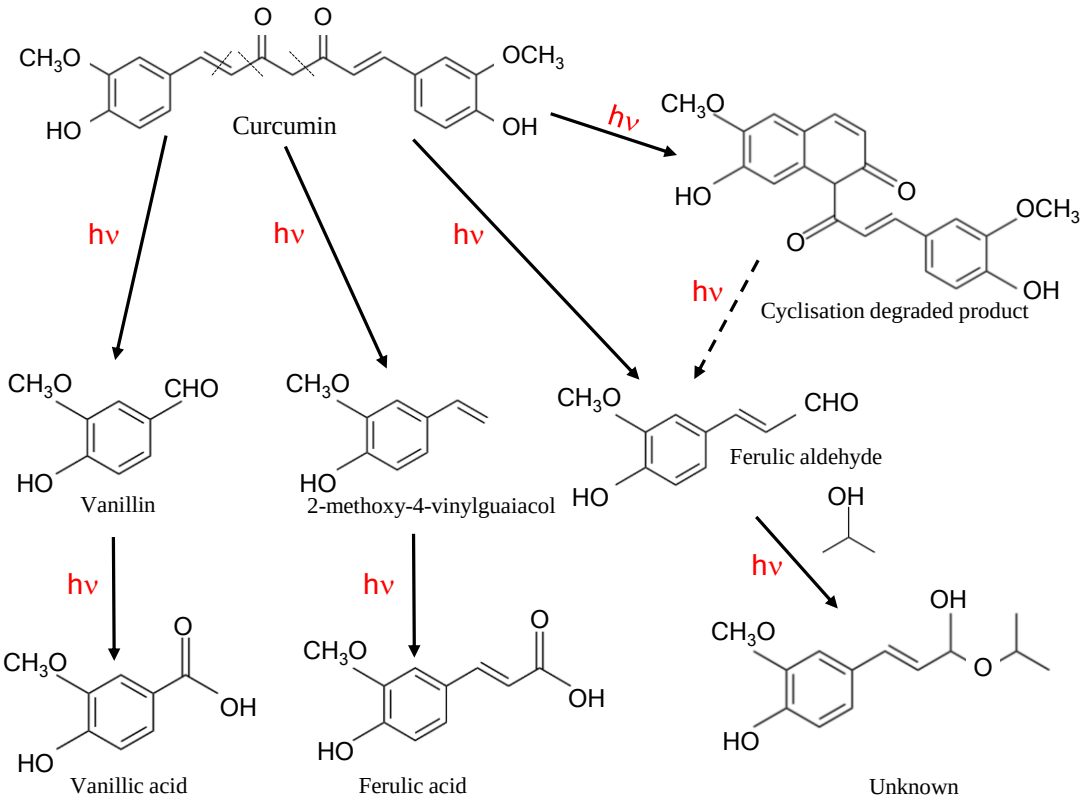


Figure 8 Photodegradation of curcumin in isopropanol at a wavelength of 400 – 510 nm.

Source: Tønnensen et al. (1986)

Thermal processing causes a problem due to its influence on the stability of curcuminoids. The degradation of curcumin emulsion and fading of yellow color during storage is faster at 55 °C than at 37 °C (Kharat et al., 2018). Boiled turmeric rhizome shows the lowest curcuminoids contents. A better recovery of curcumin is found in unboiled rhizomes (Nithya et al., 2020). Increased cooking time results in curcumin reduction. Curcumin loss from pressure cooking of turmeric for 10 min is 53% (Suresh et al., 2007). Pretreatment of turmeric rhizomes in hot water at 50 – 100 °C for 30 min before drying reduces the total phenolic content in dried product (Prathapan et al., 2009). In this study, there was no significant change in the concentration of curcuminoids among the heat-treated samples, except in the sun-drying condition. Total phenolic content value of boiled rhizomes increases with temperatures and time of heat treatment. The maximum total phenolic content values are found at 90 – 100 °C. This

is because heat treatment above 60 °C inactivates the polyphenol oxidase enzyme (Chisari et al., 2007). The photodegradation of curcumin also involves with oxygen and other mechanisms independent of oxygen (Tønnensen et al., 1986). There is small increase in rate of degradation of curcuminoids in oxygen-acid brine system (Pricez and Buescher, 1996). On the contrary, a study reported that the combined effects of light and air are the most deleterious for curcumin and turmeric oleoresin-microcrystalline cellulose model systems (Souza et al., 1997). This is due to the fact that curcumin acts as a photosensitizer of singlet oxygen, which actively induces the oxidation of free radicals. The major degradation product from autoxidation is bicyclopentadione (Gordon, et al., 2015).

2.4 Drying

2.4.1 Principle of Drying

Drying is the most common and essential method to preserve fruits, vegetables, herbs, grains, fish, meat, and other agricultural products. It also reduces volume, weight and cost for handling, packaging, and transportation. Dried product can be used as an intermediate for further processing. Drying involves the mechanism of heat and mass transfer (Mujumda and Devahastin, 2000). A conceptual representation of the thermal drying process for a solid food material is shown in Figure 9. Heat is applied to wet material by convection, conduction, or radiation which results in vaporization of water from the material to the atmosphere (Onwude et al., 2016). The moisture of the feedstock is reduced to a safe limit leading to a minimization of the activity of enzymes, bacteria, yeast, and mold (Prakash and Kumar, 2014). However, drying may cause quality changes of the dried product such as shrinkage, puffing, odor, and color change (Mujumda and Devahastin, 2000) as well as the degradation of bioactive compounds (Mahayothee et al., 2018). The major factors affecting the drying process include initial moisture content of raw material, size or thickness, drying air temperature, air humidity, and air velocity (Müller and Mühlbauer, 2012).

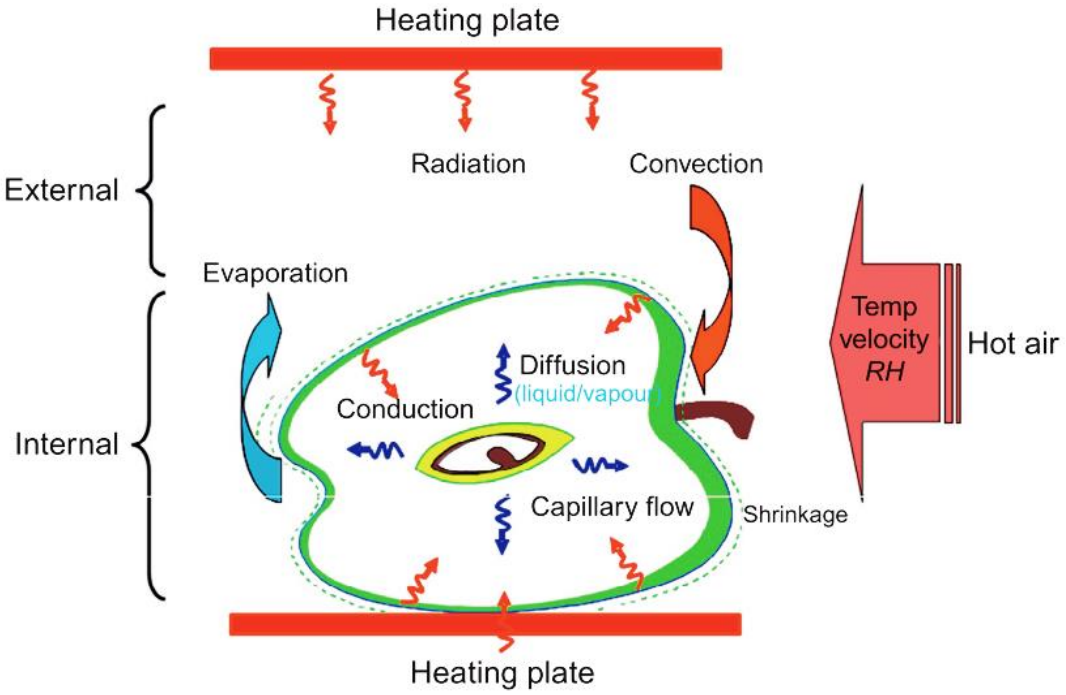


Figure 9 A conceptual representation of the thermal drying process for a solid food material.

Source: Sabarez (2015)

Moisture transportation within the material during the drying process follows the mass transfer including liquid diffusion, vapor diffusion, Knudsen diffusion, surface diffusion, or hydrostatic pressure differences (Mujumda and Devahastin, 2000). Free moisture entrapped in void space of material is removed easily. Bound water tightly binds at active sites of hydrophilic macromolecules in the food matrix. The amount of water which is lost to the surrounding per unit of surface area per time is called drying rate.

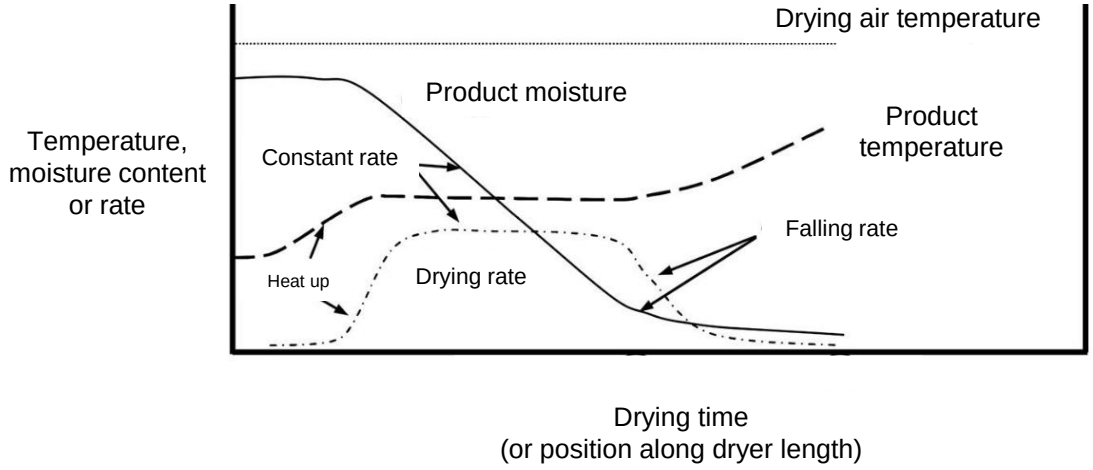


Figure 10 Typical drying curve.

Source: Wood et al. (2018)

Figure 10 presents a typical drying rate curve for food and agricultural products. In the initial warm-up period, heat from hot air transfers to the material surface. The surface temperature and drying rate increase gradually. There is a slight change in moisture content. The constant-rate period starts when free water is evaporated continuously. Water is continuously transported to the surface by mass transfer and the surface remains saturated with free water. Drying of fruits and agricultural products shows very short or no constant-rate period (Jeevarathinam et al., 2021; Qiu et al., 2019; Hossain and Bala, 2007). The constant-rate period ends when the rate of internal water migration to the surface is less than the rate of evaporation. This is the critical point of entering to the falling-rate period. At this point, the remaining water is bound more strongly. There is no continuous water supply to the surface of the material and the surface becomes dry. Product temperature rises rapidly and reaches drying air temperature. The falling-rate period takes longest time and is dominated by a diffusion mechanism. Drying process stops when the moisture content of the product reaches its equilibrium moisture content (Onwude et al., 2016).

2.4.2 Modeling of Thin-Layer Drying

Various drying methods, such as sun drying, solar drying (Udomkun et al., 2020), cabinet or tray drying, freeze drying (Chumroenphat et al., 2021b), spray drying

(Yazmin et al., 2016), vacuum drying, microwave drying (Hirun et al., 2014; Argyropoulos et al., 2011), fluidized bed, and mixed-mode drying (Veerakumar et al., 2014), are applied depending on different purposes and product requirements. Drying kinetics are considered for design and construction of new drying systems. They are also helpful for the optimization of the drying process, minimization of energy requirements, as well as the improvement of product qualities. Appropriate models are therefore explored to describe the kinetics of the drying processes. One of them is thin-layer equation which involves heat and mass transfer operations (Onwude et al., 2016). The concepts of thin-layer models are 1) material has to be dried in a single layer because the temperature distributes easily and is assumed to be uniform (Kucuk et al., 2014) or 2) they can be applied with multilayer of different slice thicknesses in the same thermodynamic condition of drying temperature and relative humidity at any time of the drying process (Onwude et al., 2016).

There are three categories of thin-layer drying models: Theoretical, semi-theoretical, and empirical models. Theoretical models make exaggerate assumptions, resulting in a large number of errors. They consider both the internal and external resistance of mass transfer. Fick's second law of diffusion is widely used as a theoretical model for thin-layer drying. The common models used to describe the drying of fruits and agricultural products are semi-theoretical and empirical models (Henderson, 1974). Semi-theoretical models are simplified from the Newton's law of cooling (Lewis, Page, Modified Page, etc.) and derived from the Fick's second law of diffusion (exponential model, Two-term exponential model, three-term exponential model, and simplified forms). The thin-layer models applied for fruits and agricultural products are shown in Table 2.

Table 2 Thin-layer drying models for fruits and agricultural products.

Model names	Equations	References
Lewis or Newton	$MR = exp(-kt)$	Lewis (1921)
Page	$MR = exp(-kt^n)$	Page (1949)
Modified Page	$MR = exp(-kt)^n$	Overhults et al. (1973)
Henderson and Pabis	$MR = a\ exp(-kt)$	Henderson and Pabis (1961)
Logarithmic	$MR = a\ exp(-k_1 t) + b$	Yaldiz et al. (2001)
Midilli and Kucuk	$MR = a\ exp(-kt)^n + bt$	Midilli and Kucuk (2003)
Two-term model	$MR = a\ \exp(-k_0 t) + b\ \exp(-k_1 t)$	Henderson (1974)
Two-term exponential model	$MR = a\ exp(-kt) + (1-a)exp(-kat)$	Yaldiz et al. (2001)
Wang and Singh	$MR = 1 + at + bt^2$	Yaldiz et al. (2001)
Weibull model	$MR = exp(-[t/\beta])^{\infty}$	Onwude et al. (2016)
Thompson	$t = a\ ln\ MR + b(ln\ MR)^2$	Thompson et al. (1968)
Peleg model	$MR = 1 - t/(a + bt)$	Peleg (1988)
Verma	$MR = a\ exp(-kt) + (1-a)exp(-ct)$	Verma et al. (1985)

MR: moisture ratio, *k*, *n*, *a*, *b*, and *c*: empirical parameters of the models, α: shape parameter of Weibull model (dimensionless), and β: scale parameter of Weibull model, and *t*: drying time.

In order to select the best model to describe the drying behavior of the products, the reduction of moisture content of the material during drying experiments is compared to the reduction of moisture content predicted by simulation of various thin-layer drying models. The model with the lowest values of sum of square error (*SSE*), root mean square error (*RMSE*), mean relative percentage error (*MPE*), mean bias error (*MBE*), or Akaike information criterion (*AIC*) and the highest values of coefficient of determination (R^2) or modelling efficiency coefficients (*EF*) is the most likely to be selected to describe the drying behavior of the materials (Kucuk et al., 2014; Akaike,

1974). The best model should be simple and predict results similar to experimental data. According to literature, the ability of each model depends on structure and properties of material, thickness, and drying conditions. Newton is the simplest model with just one constant. It was used to describe thin-layer drying characteristics of papaya cubes (Udomkun et al., 2015). Midilli and Kucuk model is considered to be the best model describing drying behaviors for various product such as bitter leaves (Alara et al., 2018), shitake mushrooms (Supakarn and Theerakulpisut, 2018), chili peppers (Rabha et al., 2017), purple potato slices (Gan et al., 2019), rupturewort (Bahammou et al., 2020), banana (Nasri, 2020), and turmeric slices (Komonsing et al., 2022). Page and Modified Page are the second best used models for drying of some fruits and agricultural products after Midilli and Kucuk model (Kucuk et al., 2014). They are used to predict the drying behavior of chili peppers (Rabha et al., 2017), potato slices (Aghbashlo et al., 2009), raw mango slices (Goyal et al., 2006), litchis (Janjai et al., 2011), turmeric rhizomes (Borah et al., 2015), and tomato slices (Doymaz, 2007). Verma model is the best model for predicting the drying curve of whole turmeric rhizomes in a mixed-mode forced convection solar tunnel dryer. Logarithmic model can describe thin layer forced solar drying of shelled and unshelled pistachios (Midilli and Kucuk, 2003). The two-term model can satisfactorily describe the solar drying curve of Sultana grapes (Yaldiz et al., 2001) and black turmeric (Lakshmi et al., 2018). Modified Henderson and Pabis model presents the best prediction of the drying of garlic slices (Younis et al., 2018). Thin layer drying characteristics of hazelnut roasting are satisfactorily described by an empirical Thompson model (Özdemir and Onur Devres, 1999).

2.4.3 Sun and Solar Drying

Open sun drying is the most common preservation method practiced in developing countries (Mühlbauer and Müller, 2020). Agricultural products are spread on a mat, concrete, floor, or road in the sun. The process can be done in-field or on-farm, which depends on weather conditions and fluctuating parameters including temperature and relative humidity of ambient air, wind speed, solar radiation, and rainfall. Open sun drying can be accelerated by high temperature and solar radiation, low relative humidity, and turning the product periodically. However, sun dried product

is exposed to various contaminations including dirt, rodents, birds, insects, and pathogenic contaminations. The basic principle of open sun drying is illustrated in Figure 11. Short-wavelength solar radiation is directly incident to the surface of agricultural products. The product absorbs the radiation and converts it to thermal energy, while the remaining part is reflected back to the environment. Temperature of the product increases, resulting in the formation of internal water vapor which then diffuses toward to the product's surface. Evaporation of water continues until equilibrium with the ambient conditions is reached. Convective heat loss during the drying process is due to the loss of long-wavelength radiation to the ambient and blowing wind.

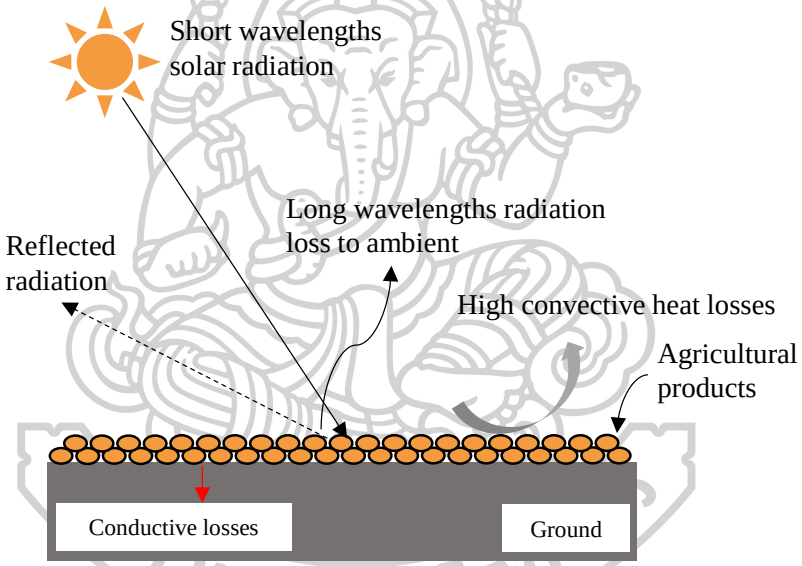


Figure 11 Principle of open sun drying method.

Source: Gorjian et al. (2021)

Solar drying is an advanced version of sun drying to reduce post-harvest losses of agricultural products and overcome those disadvantages of open sun drying. Various types of solar dryers are developed, such as cabinet solar dryers, solar tunnel dryers, and greenhouse solar dryers. The basic principle of solar drying is shown in Figure 12. Agricultural products are placed in a transparent box in a single layer and allowed to be exposed in the sun. The difference of sun drying and solar drying is that the solar drying requires a solar collector and the products are not exposed directly to the sunlight. Solar

radiation passes through a transparent sheet and retains as heat in the drying chamber or solar collector (Udomkun et al., 2020). The products absorb short-wavelength solar radiation leading to increasing of product temperature. The long-wavelength solar radiation is emitted and accumulated in the transparent box due to the presence of transparent cover. Temperature above the products in the drying chamber becomes higher. Moisture from the product is evaporated to hot air. Humid air is removed by replacing some of the circulating air with fresh make-up air with lower specific moisture content.

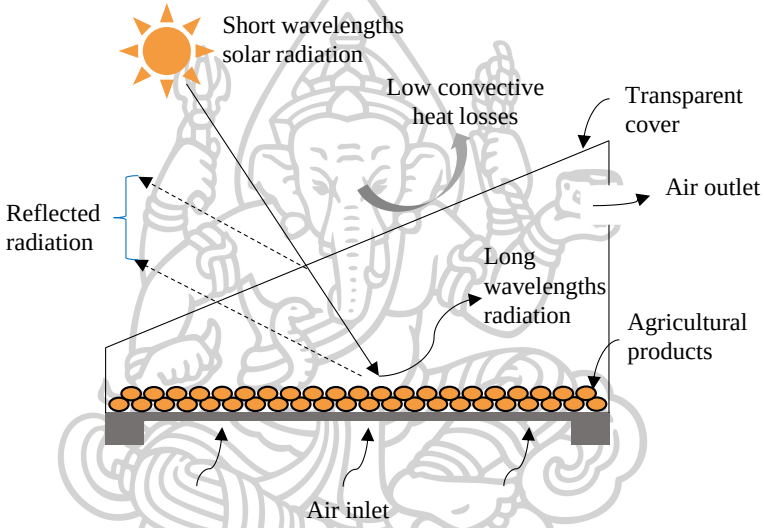


Figure 12 Principle of direct solar drying.

Source: Sharma et al. (2009)

2.4.4 Turmeric Drying

Dried turmeric is more available in the global markets than fresh rhizomes (Hirun et al., 2014). It can be used in several industrial sectors, such as cooking, food processing, medicinal, dye, and curcumin and oleoresin extraction. The production of dried turmeric is uncomplicated. There are three main types of dried products obtained from drying process including dried turmeric rhizome, dried turmeric slices, and turmeric powder (Manuraj et al., 2020; Tamuno, 2020; Thomas et al., 2015; Pothitirat and Gritsanapan, 2005; FAO, 2004).

Figure 13 shows typical drying process of turmeric. Fresh turmeric rhizomes are harvested from a plantation. To produce the dried whole turmeric (Figure 14 (a)), the rhizomes are boiled in water for 30 – 90 min or until soft. This step is called curing process which is responsible for the uniform distribution of color, it also reduces odor and drying time. The boiled rhizomes are spread on floor or a mat with the thick layer of 5 – 7 cm to minimize direct sunlight which promotes surface discoloration. The drying process normally takes 10 to 15 day until the moisture content of the dried turmeric rhizomes is lower than 12% (wet basis). The dried rhizomes are continued to the polishing and coloring process which can be done either by mechanically or by manually. The dried rhizomes with rough surface or unattractive skin will be more uniform (Manuraj et al., 2020) after this step. Turmeric powder is used in this step in order to improve the yellow color. The dried whole rhizome is mostly produced in India and Sri Lanka. The benefits of curing turmeric include reduction of drying time, improving the color distribution of the rhizomes, and sterilization of the rhizomes before drying. However, curing process results in reduction of curcumin, essential oils, and oleoresin contents (Hirko et al., 2019; Jayashree and John Zachariah, 2016). To reduce drying time, the fresh turmeric rhizomes are sliced into a thickness of 2–5 cm and might be boiled in water to inactivate enzymatic reaction or obtain uniform color before drying. This step produces the dried turmeric slices (Figure 14 (b)). Both dried rhizomes and dried slices can be grinded to fine powder (Figure 14 (c)). The moisture content of turmeric powder should be lower than 10% (FAO, 2004). Although turmeric slices are more likely to be exposed to sunlight, they take shorter drying time and are easier to achieve a lower final moisture content (Borah et al., 2015). Turmeric powder (60-80 mesh) is mostly used on the retail markets and by the food processors. Since curcuminoids deteriorate under light, heat, and oxidative conditions, ground turmeric should be packed in UV protective packaging and appropriately storage. Turmeric powder is a major ingredient in curry powder and curry paste. In the food industry, it is mostly used to obtain unique color and flavor in mustard. It is also used in bouillon, chicken soup, sauce, gravy, and dry seasoning.

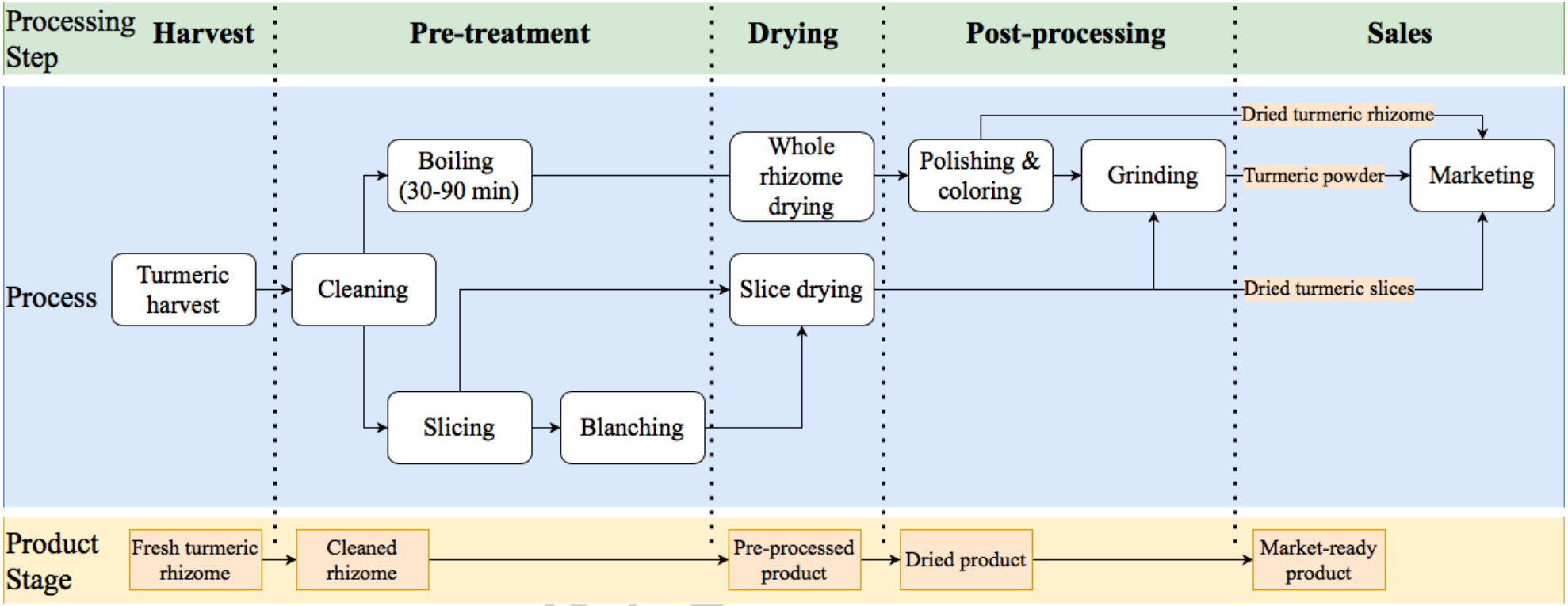


Figure 13 Traditional drying process of turmeric.

Figure 14 The products obtained from drying process of turmeric.

In Thailand, the most common drying methods for turmeric are sun drying, solar drying, and hot-air drying. The whole rhizomes are usually sliced and dried by sun drying and parabolic greenhouse dryer (Figure 15) for 15-20 days to a moisture content of 10% w.b. before grinding into powder.

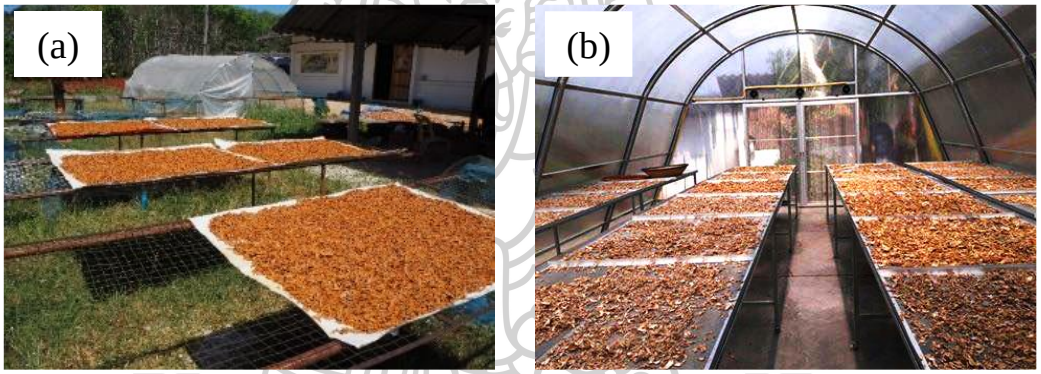


Figure 15 Sun drying and solar drying of turmeric in Thailand.

Pictures of turmeric drying in Asian and African countries using sun drying, solar drying, hot air drying are shown in Figure 16.

India
Source: https://timesofindia.indiatimes.com

India
Source: https://madteaparty.wordpress.com

India
Source: https://www.villagesquare.in

India
Source: https://www.indiamart.com/

India
Source: https://www.indiamart.com

India
Source: https://www.newindianexpress.com

Figure 16 Turmeric drying in Asian and African countries.

Indonesia
Source: http://tripper.com/

Indonesia
Source: https://jabar.tribunnews.com

Indonesia
Source: https://repjogja.republika.co.id

Vietnam
Source: Pinterest of Dong Duong Dragon Imex Co., Ltd

Pakistan
Source: https://yesangfood.com/turmeric-supplement/

Myanmar
Source: Myanmardelinews

Cambodia
Source: Facebook: Chhung Boleak

Figure 16 Turmeric drying in Asian and African countries (continue).

Ethiopia
Source: http://www.voicesofsita.com/

Ethiopia
Source: https://www.kaieteurnewsonline.com

Nepal
Source: https://thespicejournal.com/about-us/

Srilanka
Source: Department of Export Agriculture

Figure 16 Turmeric drying in Asian and African countries (continue).

2.4.5 Effects of Drying on Quality and Curcuminoids Content

Proper drying of turmeric is very important for the quality of final products. Sun dried turmeric samples were found contaminated with aflatoxin B1 (120 µg kg^{-1}) (Khan et al., 2016). Sun drying also causes a significant reduction in the color, curcumin, mineral contents (sodium, calcium, magnesium, iron, and manganese) in turmeric powder (Tamuno, 2020). Different drying methods have been investigated to preserve the qualities of dried turmeric comparing to sun drying. Solar drying and hot-air drying are the most widely studied (Borah et al., 2015; Buakaew et al., 2017; Karthikeyan and Murugavelh, 2018; Prasad et al., 2006). Drying time of turmeric is reduced by half with tunnel drying. This method shows higher retention of curcumin, volatile oil, and oleoresin than sun drying (Jose and Joy, 2009). However, solar drying still causes the highest curcumin reduction due to solar radiation (Chumroenphat et al., 2021). Raza et

al. (2018) compared shade, direct sunlight, solar dryer, convection oven, and hot-air drying on the concentration of curcumin. Sun dried products have the lowest curcumin content. The optimum condition for drying of turmeric rhizomes is drying at 70 °C in a hot-air dryer. However, Sharma et al. (2021) reports that the major loss of curcuminoids is lesser for direct solar drying samples (42.60%) than hot-air drying (44.77%). Singh et al. (2010) presents that the optimum hot-air drying conditions for the best product qualities are found to be air temperature of 55 – 60°C and an air velocity of 2 m s^{-1}.

Microwave drying requires shorter drying time. Gagare et al. (2015) reports that the power level of 1.5 kW for 5 hours is the optimum for microwave drying of turmeric rhizomes. Microwave drying at up to 4000 W for 30 min inactivates enzymatic browning reactions, resulting in better color and higher contents of bioactive compounds in the final products (Hirun et al., 2014). Vacuum drying is a potential drying technique for heat sensitive products which take place at low temperature and pressure in reduced oxygen environment. Nithya et al. (2020) reports that vacuum drying yields superior quality turmeric than tray drying and microwave drying.

Freeze drying has the reputation to maintain quality, but it involves long drying times and expensive procedure. Chumroenphat et al. (2021) found that freeze drying shows the lowest curcumin degradation (55%) comparing to solar drying (72%) and hot-air drying (61%). Microstructure changes were least after freeze drying, but were still evident comparing to the fresh turmeric. The loss of curcumin from freeze drying was due to light during the process. Long et al. (2022) also reported that freeze drying shows better nutrition preservation and better antioxidant activities in the dried products. Freeze dried turmeric rhizomes contained higher volatile constituents, such as ar-turmerone, α-turmerone and β-turmerone, and similar volatile profiles when compared with fresh samples (Ray et al., 2022). An infrared assisted with hot air drying was developed to retain the qualities of turmeric during drying. It was found that a drying temperature of 60 °C could be the suitable operating condition to produce better quality turmeric in term of curcumin, oleoresin, color, and starch content (Jeevarathinam et al., 2021). Another, heat pump drying is a method for commercial turmeric drying (Seanmeema et al., 2018).

CHAPTER 3

Effects of Drying Temperatures and Drying Methods on Color of Dried Turmeric Slices*

Turmeric is nowadays one of important Thai herbs. Dried turmeric is available on both domestic and international markets. It uses as food colorant, spices, and traditional medicine. However, color of dried turmeric is influenced by drying temperature and drying method. In this study, the effects of drying temperature and drying methods (sun and solar drying) on quality of turmeric slices were investigated. Fresh turmeric rhizomes at the maturity of 9 - 10 months with a length of 50 - 100 mm were used. To study the effect of drying temperature, drying experiments were carried out at 40, 50, 60 and 70 °C using a tray dryer. Solar drying and sun drying were used to study the effect of drying method. Turmeric rhizomes were sliced lengthwise with a thickness of 2 mm. Turmeric slices were dried in a single layer until the moisture content was below 10%. It was found that drying temperatures and drying methods significantly affected ($p \leq 0.05$) the color of turmeric slices. The optimum drying temperature for turmeric slices is 70 °C due to short drying time (4 h 20 min) which gave a bright orange-yellow color dried product with L^*, a^*, b^*, C^*, $h°$ and ΔE values of 43.24 ± 4.85, 25.04 ± 1.02, 37.47 ± 3.32, 45.10 ± 3.38, 44.27 ± 17.78 and 19.13 ± 1.06, respectively. Solar drying in greenhouse-type dryer resulted in reduction of drying time compared to sun drying. In addition, the products dried in a greenhouse solar dryer were orange-yellow bright color. L^*, a^*, b^*, C^*, $h°$ and ΔE values were 42.42 ± 1.52, 23.67 ± 0.76, 35.96 ± 1.13, 43.09 ± 1.35, 56.65 ± 0.03 and 25.35 ± 0.78, respectively. For sun dried products, L^*, a^*, b^*, C^*, $h°$ and ΔE values were 44.01 ± 1.09, 22.38 ± 0.45, 33.01 ± 0.52, 39.95 ± 0.66, 55.86 ± 0.22 and 28.01 ± 0.12, respectively which gave dark brown-orange color.

* This chapter has been published in Proceedings of the 44th National Graduate Research Conference, Thailand

3.1 Introduction

Turmeric is traditionally used as both fresh and dried products as food additives, coloring agent (Surojanametakul et al., 2010), spices and medicinal herbs (Revathy et al., 2011). It contains phenolic compounds, terpenes, essential oils, steroids and fatty acids. Major bioactive compounds in turmeric are curcuminoids (curcumin, demethoxycurcumin and bisdemethoxycurcumin) which exhibit the unique orange-yellow color in the flesh. These compounds can serve important roles as antioxidants as well as anti-inflammatory, anti-bacterial, and anti-carcinogen agents, anti HIV infection (Surojanametakul et al., 2010)

Common method used to preserve turmeric in Thailand is sun drying which is simple but induces high risk of mold contamination and causes nutrient loss (Afolabi, 2014) in the agricultural products. Greenhouse solar drying is currently being promoted for drying medical plants in Thailand to replace unhygienic sun drying. However, limited research is available on the influences of drying temperatures and drying methods on color of dried turmeric. Therefore, the objectives of this study was to evaluate the influence of drying temperatures and drying methods (sun and solar drying) on color of dried turmeric slices.

3.2 Materials and Methods

3.2.1 Raw Materials

Four lots of turmeric at the maturity of 9 - 10 months after planting from Phatthalung province, Thailand were used. This maturity is commonly used for traditional medicine production. Rhizomes with the diameter of 100 - 300 mm and length of 50 - 100 mm were cleaned and packed in the carton. They were transported to the laboratory in Nakhon Pathom, then kept at 10 ± 1 °C before drying experiments.

3.2.2 Preparation of Turmeric Slices

Prior to drying, fresh rhizomes were washed under running tap water, then soaked in 10 ppm peroxyacetic acid solution for 10 min, air dried at room temperature for 20 min and cut to obtain the equal length of 50 cm Figure 17 (a). After that, they were sliced to a thickness of 2 mm Figure 17 (b).

Figure 17 Rhizomes (a) and turmeric slices (b).

3.2.3 Drying Equipment

Study on drying temperatures using tray dryer. Two lots of fresh turmeric rhizomes were used. In each experiment, 1.2 kg of turmeric slices were placed in a single layer on an aluminum tray with size of 53 × 73 × 3 cm (width × length × height). Drying experiments were conducted using electric convention tray dryer (Model 24 trays, size 160 × 89 × 198 cm (width × length × height), 12 KW/380 V, KluayNamThaiTowOp, Thailand) at four different temperatures (40, 50, 60 and 70°C). The samples were weighted in the laboratory for drying curve using analytical balance with an accuracy 0.01 g. Interval weighing time of 10 min were used during the first hour of drying, then 30 min until the weight was constant.

Study on drying methods using greenhouse solar dryer and sun drying. For greenhouse solar drying, the experiments were conducted in February 2016. Two lots of fresh turmeric rhizomes were used. 1.2 kg of turmeric slices were placed on a tray with the width, length, and height of 100, 90, and 2 cm, respectively in a single layer. The samples were dried in greenhouse solar dryer from 9.30 a.m. to 4.00 p.m. Details of the dryer was described as Janjai et al. (2009). The dryer was installed at the experiment site of Solar Energy Research Laboratory, Silpakorn University, Thailand. The parabolic roof of this dryer made from polycarbonate sheets on a gray concrete floor. The dryer has a width of 9.0 m, length of 12.4 m and height of 3.45 m. The schematic diagram of greenhouse solar dryer is shown in Figure 18.

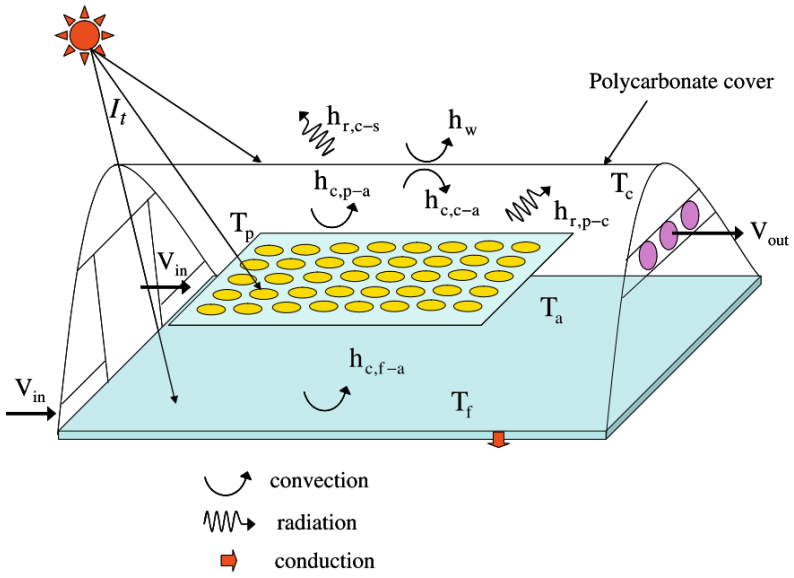


Figure 18 Schematic diagram of energy transfer inside greenhouse solar dryer.

Source: Janjai et al. (2009)

For sun drying, the drying experiment were done in parallel with greenhouse solar drying. 1.2 kg of turmeric slices from the same lots were placed on 100 × 90 × 2 cm (width × length × height) tray in a single layer. The samples were dried under the sunlight from 9.30 a.m. to 4.00 p.m. The temperature and relative humidity inside the dryer and of environment were recorded during drying experiments using the data loggers. The weight of sample was monitored every 1 h until the weight reached constant. During the night time, unfinished dried samples were kept in the cabinet to prevent resorbed moisture from humid air.

3.2.4 Quality Evaluation

Color: 25 pieces of the fresh and dried turmeric slices were measured for color at one position per piece using a colorimeter (MiniScan XE PLUS, Hunter Associates Laboratory, Reston, USA). Data were reported as CIE $L^*a^*b^*$ values with the illuminant D65 and observer angle of 10°. The positive value of a^* and b^* indicate redness and yellowness, respectively while L^* represents lightness of the sample. Values of chroma (C^*), hue angle ($h°$) and total color change (ΔE) were calculated from L^*, a^* and b^* values by the following equations:

$$C^* = (a^{*2} + b^{*2})^{1/2} \quad (3.1)$$

$$h^\circ = tan^{-1}(b^*/a^*) \quad (3.2)$$

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{½} \quad (3.3)$$

where Δ refers to difference of each parameter between fresh and dried sample i.e.

$\Delta L = (L^*_{dried} - L^*_{fresh})$, $\Delta a = (a^*_{dried} - a^*_{fresh})$ and $\Delta b = (b^*_{dried} - b^*_{fresh})$

Moisture content (MC): 3.0-5.0 g of mashed samples were used for determination of the moisture content by hot air oven method. (AOAC, 2000).

Water activity (a_w): water activity was measured in triplicate using a water activity meter (AW-DIO, Rotronic, Switzerland) after equilibrating for 15 min in a thermostatic cell at ambient temperature.

3.2.5 Statistical Analysis

Statistical analyses were performed using SPSS (version 17). ANOVA and Duncan multiple Rank test were applied to evaluate the significant difference of color quality of dried samples compared to fresh sample using sample lots as blocks

3.3 Results and Discussion

3.3.1 Effects of Drying Temperatures on Drying Behavior

The drying curves of turmeric slices obtained from tray dryer at different temperatures are shown in Figure 19. The drying curves were obtained by plotting moisture ratio versus drying time. Initial moisture ratio rapidly decreased within second hour at 50, 60 and 70 °C. However, the results show no statistical different between drying rate for these conditions, whereas obvious lower drying rate was found at the drying temperature of 40 °C. The falling-period rate were occurred after forth hour. The surfaces of turmeric slices were partly dried. Drying processes were conducted until the moisture content was constant or the moisture content was less than 10% which is safe from the microbial growth according to requirement of Thai Industrial standard for turmeric powder (Thai Industrial Standard Institute, 1989). Drying time was considerably decreased when the temperature was increased (40 °C = 24 h, 50 °C = 9 h, 60 °C = 7 h and 70 °C = 4 h 20 min).

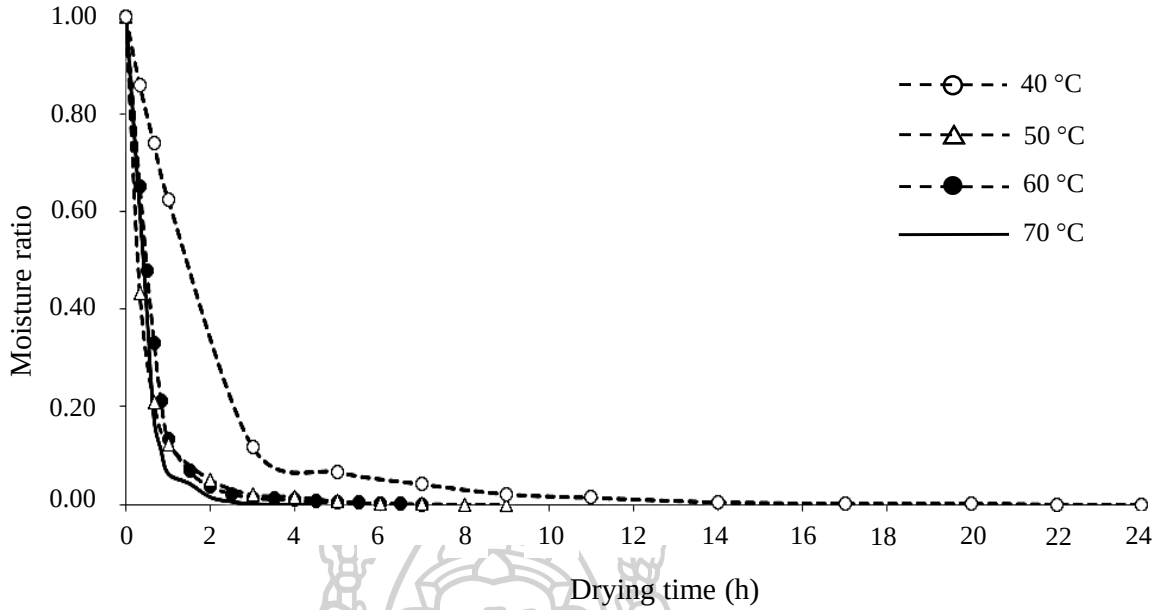


Figure 19 Drying behavior of turmeric slices using tray dryer at various temperatures.

Moisture content (*MC*) and water activity (a_w) of fresh and dried samples obtained from tray drying are shown in Table 3. It was observed that only the drying at 60 and 70 °C could reduce the moisture content to less than 10%. In contrast, drying at 40 and 50 °C could not remove the moisture content to less than 10% due to the equilibrium moisture content between hot air and the sample surfaces.

Table 3 Moisture content (*MC*) and water activity (a_w) of fresh and dried turmeric slices obtained from tray drying.

Temperature (ºC)	Drying time	*MC* (%)	a_w
Fresh sample		80.99 ± 1.21[a]	0.984 ± 0.01[a]
Dried sample			
40	24 h	10.51 ± 0.39[b]	0.496 ± 0.02[b]
50	9 h	10.58 ± 0.39[b]	0.485 ± 0.02[b]
60	7 h	9.81 ± 0.05[ab]	0.436 ± 0.02[b]
70	4 h 20 min	8.51 ± 0.22[c]	0.335 ± 0.01[d]

Data are expressed as the mean ± standard deviation.

[a, b, c, d] Different letters within each column mean significant difference ($p \leq 0.05$).

3.3.2 Effects of Solar Drying on Drying Behavior

The drying curves of turmeric slices using greenhouse solar dryer comparing with sun drying are shown in Figure 20. The moisture content during drying using both methods rapidly decreased from an initial value of 80.54% in the first day, then slowly lowered when the moisture content reached 19% and the drying process was done after the moisture content of solar dried products reached 8.26% within 2 days whereas the moisture content of sun dried products was 10.17% within 3 days (Table 4). It could be seen that sun drying was ineffective to reach the moisture content to less than 10% due to the equilibrium moisture content between surrounding air and sample surfaces.

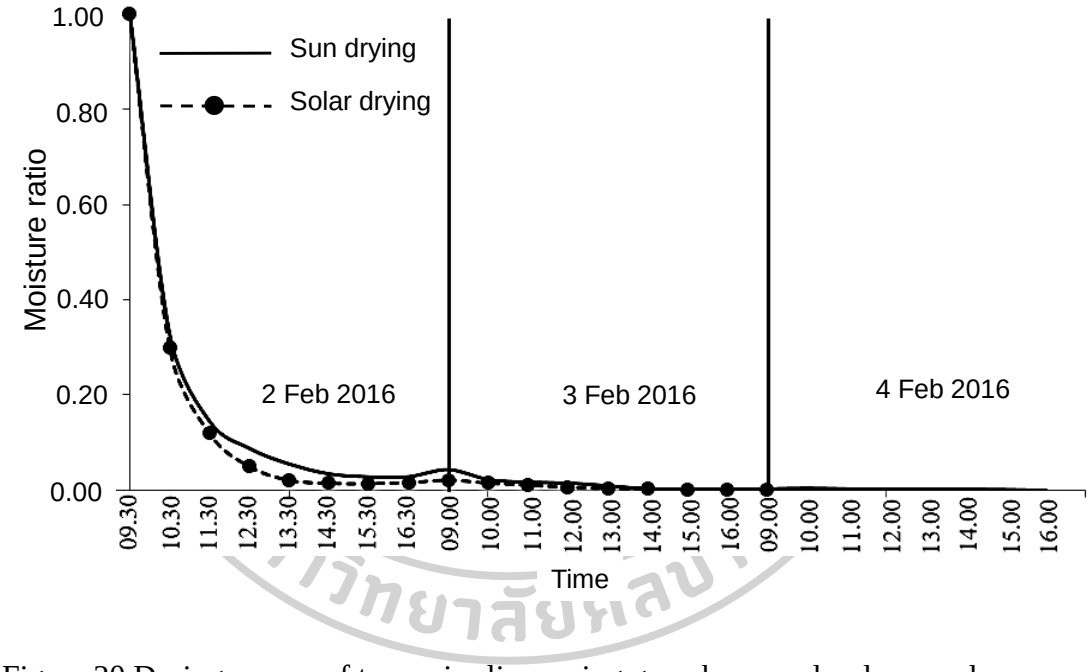


Figure 20 Drying curves of turmeric slices using greenhouse solar dryer and sun drying.

From the temperature profiles in Figure 21, it was found that the temperatures inside the greenhouse dryer were in the range 48 - 60 °C which were higher than the ambient temperature (33 - 42 °C). In contrast, the relative humidity of air in the greenhouse solar dryer (14 - 32%) was lower than sun drying (34 - 50%) as illustrated in Figure 22. The lower relative humidity of air due to higher temperature, therefore the water holding capacity of drying air was increased leading to faster drying (Janjai, 2012). Although there was a great difference between the temperature and humidity but

the results show slightly different drying rate between solar drying and sun drying. It might be effected by the difference of air velocity (0.2 - 0.5 m s^{-1} for solar drying and 0.01 - 0.02 m s^{-1} for solar drying) which influenced on moisture evaporation. However, drying in the greenhouse solar dryer resulted in shorter drying time. However, as expected, temperatures inside the greenhouse solar dryer were varied depending on sunlight intensity of the day.

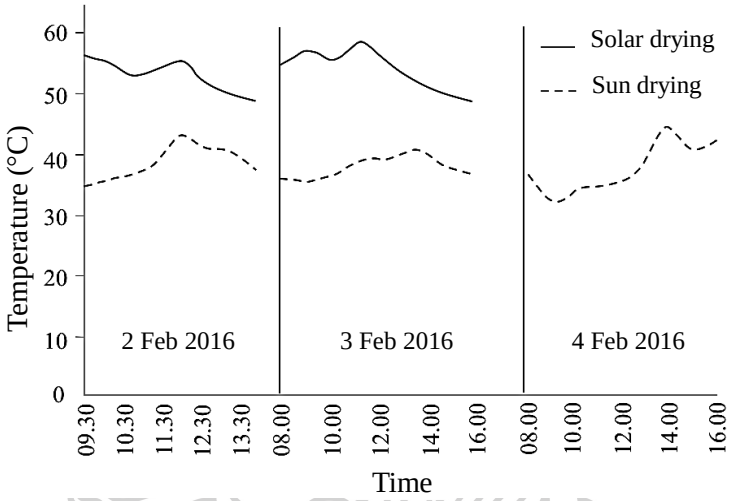


Figure 21 Temperature profiles inside and outside the greenhouse solar dryer during experiments on 2-4 February 2016.

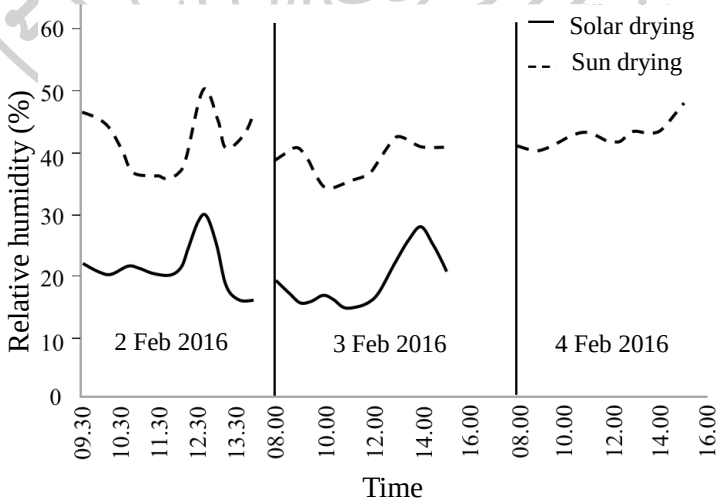


Figure 22 Relative humidity profiles inside and outside the greenhouse solar dryer during experiments on 2-4 February 2016.

MC and a_w of fresh and dried turmeric slices are shown in Table 4.

Table 4 Moisture content (*MC*) and water activity (a_w) of fresh and dried turmeric slices obtained from sun drying and greenhouse solar drying.

Samples	Drying time	*MC (%)*	a_w
Fresh sample		80.54 ± 0.43^{a}	0.979 ± 0.01^{a}
Dried sample			
Sun drying	3 days	10.17 ± 0.20^{b}	0.448 ± 0.01^{b}
solar drying	2 days	8.26 ± 0.17^{c}	0.335 ± 0.03^{c}

Data are expressed as the mean ± standard deviation.

$^{a, b, c,}$ the different letters within each column are significantly different ($p \leq 0.05$).

3.3.3 Effects of Drying Temperatures on Color Quality

The color of fresh and dried turmeric slices were measured using a colorimeter and the results are shown in Table 5. Drying temperatures produced significant change in the shade of color, as compare with the fresh turmeric especially *L**, *a**, *b**, *C** and ΔE values. The color shade of fresh turmeric slices changed from bright orange-yellow to orange-brown after drying.

*a** and *b** in the positive direction show redness and yellowness, *C** shows the intensity of dried turmeric slices. From Table 5, the results showed that the drying at 40 °C gave the highest *a**, *b** and *C** values. In contrast, non-significantly different was found at 50, 60 and 70 °C on *b** and *C** values. The total color change (ΔE) is a colorimetric parameter used to estimate the variation of color between fresh turmeric and dried slices. The ΔE values were significantly increased ($p \leq 0.05$) as the drying temperature decreased and the highest ΔE was obtained at 40 °C. The dried samples obtained from this condition were dark brown-orange color (Figure 23) which might due to an enzymatic browning reaction. This agreed with Prathapan et al. (2009) who reported that heating fresh turmeric at 60 - 100 °C caused a reduction in enzymatic browning reaction in fresh turmeric rhizomes.

Table 5 Color of fresh and dried turmeric slices obtained from tray drying.

Temperature (°C)	L^*	a^*	b^*	C^*	$h^{o\ ns}$	ΔE
Fresh sample	47.00 ± 4.16	33.42 ± 3.87	58.68 ± 8.38	66.55 ± 8.39	60.11 ± 3.50	-
Dried sample						
40	43.23 ± 2.18^{a}	26.38 ± 2.29^{a}	41.68 ± 1.67^{a}	49.37 ± 2.65^{a}	57.67 ± 0.65	27.44 ± 1.01^{a}
50	39.35 ± 1.34^{b}	24.37 ± 2.63^{ab}	36.99 ± 3.81^{b}	44.33 ± 4.61^{b}	56.49 ± 0.23	25.91 ± 4.67^{b}
60	38.25 ± 0.08^{b}	23.39 ± 1.82^{c}	35.39 ± 3.30^{b}	42.45 ± 3.75^{b}	56.57 ± 0.38	24.34 ± 3.64^{b}
70	43.24 ± 4.85^{a}	25.04 ± 1.02^{ab}	37.47 ± 3.32^{b}	45.10 ± 3.38^{b}	56.25 ± 0.78	23.11 ± 1.06^{c}

Data are expressed as the mean ± standard deviation.

$^{a, b, c}$ the different letters within each column are significantly different ($p \leq 0.05$). ^{ns} indicates nonsignificant difference.

40 °C 50 °C 60 °C 70 °C

Figure 23 Dried products obtained from tray drying at different temperatures.

3.3.4 Effects of Solar Drying on Color Quality of Dried Turmeric Slices

Drying methods significantly affected the color of dried turmeric slices. From Table 6, there were no significant differences in L^*, a^* and $h°$ values obtained from different drying methods however the drying methods significantly affected ΔE and b^* values. The results show b^* values effected on the total color change (ΔE). The products obtained from solar drying shows more intense shades of orange-yellow color than sun drying.

Table 6 Color of fresh and dried turmeric slices obtained from sun drying and greenhouse solar drying.

Samples	L^*	a^*	b^*	C^*	h^o	ΔE
Fresh sample	49.52 ± 1.42[a]	33.64 ± 2.57[a]	56.90 ± 1.20[a]	66.28 ± 0.23[a]	59.22 ± 2.37[a]	-
Dried sample						
Sun drying	44.01 ± 1.09[b]	22.38 ± 0.45[b]	33.01 ± 0.52[c]	39.95 ± 0.66[c]	55.86 ± 0.22[b]	28.01 ± 0.12[a]
Solar drying	42.42 ± 1.52[b]	23.67 ± 0.76[bc]	35.96 ± 1.13[b]	43.09 ± 1.35[b]	56.65 ± 0.03[b]	25.35 ± 0.78[b]

Data are expressed as the mean ± standard deviation.

[a, b, c] the different letters within each column are significantly different ($p \leq 0.05$).

The ΔE value of greenhouse solar dried products revealed a lower change than sun dried products. This indicated that higher temperature (48 - 60 °C) and lower

relative humidity (14 - 32%) in greenhouse solar drying could retard the activity of polyphenol oxidase in fresh turmeric slices. In addition, *C** value of dried turmeric slices were varied by *b** values which is higher in solar dried product. The products obtained from sun drying and greenhouse solar drying are shown in Figure 24.

Fresh sample Sun drying Greenhouse solar drying

Figure 24 Dried products obtained from sun drying and greenhouse solar drying.

3.4 Conclusion

Drying temperature and drying methods significantly affected the shades of orange-yellow color of dried turmeric slices. Drying at 70 °C resulted in shorter drying time and showed more intensive orange-yellow in dried products. Drying in this condition save time and fuel consumption. Solar drying in a greenhouse solar dryer resulted in considerable reduction in drying time compared to sun drying and the obtained products possessed better color qualities in term of higher redness, yellowness, and intensity. The solar dried products were intense orange-yellow color.

3.5 Suggestion

The color qualities of the dried slices should be measured in both sides. The appropriate sampling number for color measurement should be determined. For better understanding on color change of the products during drying, the effect of solar drying on degradation of bioactive compounds turmeric should be further investigated.

CHAPTER 4

Effect of Light Exposure Period on Curcuminoids Contents in Turmeric Powder*

This study investigated the influence of light on total curcuminoids and color of turmeric powder by an exposure of turmeric powder (35 - 50 mesh) to mimic natural sunlight for 0, 10, 20, 30, and 40 h. The results showed that the light significantly affected b^*, C^*, $h°$, and total curcuminoids of turmeric powder in the direct light exposure area. Losses of total curcuminoids of the direct light exposure area and scattered light area were 23.56 and 5.81%, respectively after exposed to the light for 40 h.

* This chapter has been published in Proceedings of the 7th European Drying Conference, Italy

4.1 Introduction

Turmeric (*C. longa*), a member of Zingiberaceae family, is one of the most powerful antioxidant spices and medicinal plants in the world for centuries. It is cultivated primarily in India, Bengal, China, Taiwan, Sri Lanka, Indonesia, Peru, Australia, and Thailand (Yadav et al. 2009). According to the survey of the Agricultural Extension Department (2016), the production of turmeric in Thailand was about 1,818 tons. The appearance of turmeric rhizomes are similar to ginger. But the skin of turmeric rhizome is slightly more yellowish and the internal color is more intense orange than ginger which is responsible from high amount of curcuminoid pigments (Figure 25(a)).

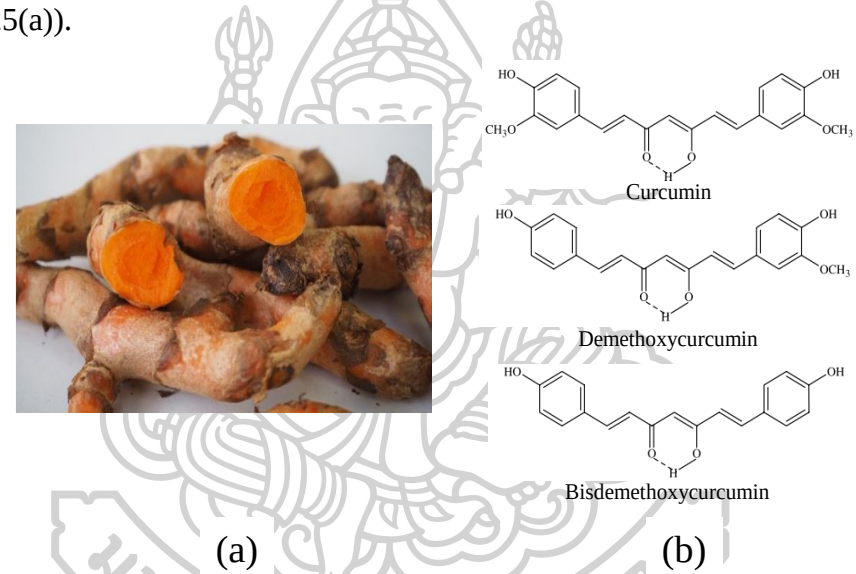


Figure 25 Fresh turmeric rhizomes (a) and structures of curcuminoids (b).

Curcuminoid contents of turmeric can vary from 0.3 to 8.6% w/w (Miłobędzka et al., 1910; Jayaprakasha et al., 2002; Joe et al., 2004; Heath et al.. 2004). There are 3 main structures of curcuminoids in turmeric, including curcumin (77%), demethoxycurcumin (17%), and bisdemethoxycurcumin (3%) as shown in Figure 25(b) (Ahsan et al., 1999). Many studies on health benefits associated with curcuminoids were reported. Curcuminoids exhibited numerous medicinal properties, such as anti-inflammatory (Zhang et al., 2015), antioxidant (Jayaprakasha et al., 2006), and antiviral activities (Mathew and Hsu, 2018). Curcuminoids contents usually correlates with the characteristic orange-yellow color of turmeric powder (Amalraj et al., 2017).

Turmeric is mostly sold as powder and curcuminoids extract and utilized as spice or additive in food and pharmaceutical industries. Traditionally, the whole rhizome is usually dried by sun drying for a month to a moisture content of 10% w.b. before grinding into powder. To reduce the drying time and improve extractability of curcuminoids, fresh turmeric rhizomes can be also sliced to increase surface area for moisture evaporation. However, solar radiation promotes degradation of curcuminoids which was observed by color change from orange-yellow to dark brown color.

A few studies reported that curcuminoids were stable in dark (Price and Buescher, 1996) but easily decomposed by UV, visible, and daylight. Tonnesen et al. (1986) studied the stability of curcumin in solution under the lamps with emission ranges of 240 - 600, 180 - 350, and 400 - 510 nm and found that curcumin could be degraded by both UV and visible light. Decomposition of curcumin extract was also found to follow the first order kinetics under daylight with a degradation rate constant of 0.1188 h^{-1} and a half-life of 5.83 h (Kumavat et al., 2013). Moreover, Syed et al., (2015) stored a curcumin emulsion in a UV cabinet (365 nm) for 24 h. They found that the degradation of curcumin was 48.69%, whereas curcumin was stable at least for 24 h at room temperature under dark condition.

However, degradation of curcuminoids in turmeric powder might be different from model system and only a few studies on degradation of curcuminoids in turmeric powder were reported. Therefore, the aim of this study was to investigate the effect of simulated sunlight on color and total curcuminoids contents in turmeric powder.

4.2 Materials and Methods

4.2.1 Preparation of Turmeric Powder

Forty kilograms of fresh turmeric rhizomes with an age about 9 - 10 months were purchased directly from a grower in Surat Thani province, Thailand. The average weight and diameter of the rhizome are 21.06 ± 5.37 g and 15.10 ± 0.98 mm, respectively. They were delivered to the laboratory in Nakhon Pathom within 2 days after harvesting. Fresh rhizomes were washed under running tap water, air dried, and sliced into a thickness of 3.5 mm. The slice samples were cut using a special made cutter into size of 8 × 40 × 3.5 mm (width × length × height) pieces. They were dried

in a single layer at 50 °C using a tray dryer. Dried turmeric slices with the moisture content of 9.5% was ground using a food blender (Phillips, Netherlands) and passed through a sieve (35 – 50 mesh) to obtain powder sample. The powder was kept at -18°C before experiments.

4.2.2 Light Exposure

Light exposure experiment instrument consisted of 1) a xenon cold light source (XD302-350W, China) which provide white light that closely mimics natural sunlight in the wavelength of 200 – 2000 nm, and 2) fiber-optic cable, and sample compartment. The distance between the fiber optic end and the sample cup was fixed at 3 cm. A 40 mm-diameter plastic cup containing 0.7 g of the turmeric powder with a thickness of 1 mm to ensure that light penetrates to the bottom.

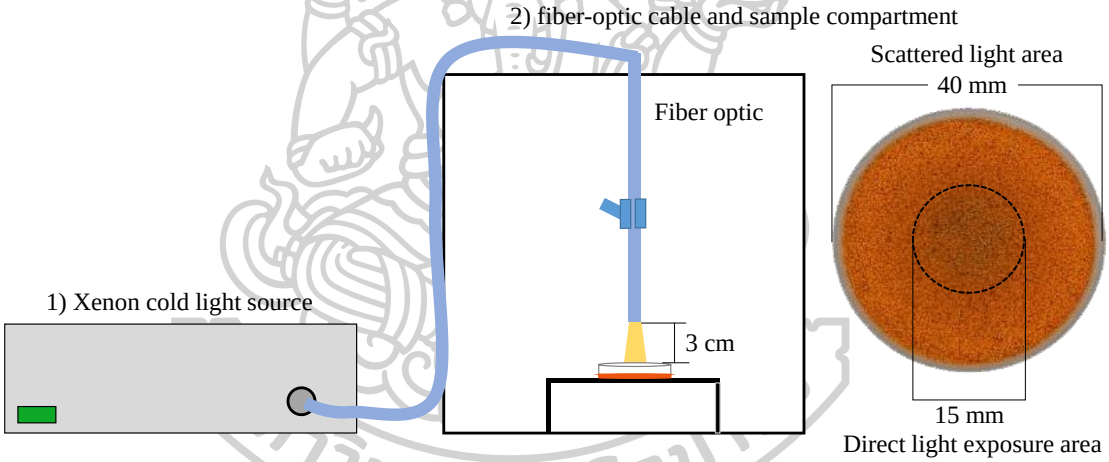


Figure 26 Light exposure experiment instrument.

The sample cup was exposed to the simulated sunlight for 0, 10, 20, 30, and 40 h respected to daily incident sunlight and the common drying period of turmeric slices in Thailand. Light exposure areas were divided into direct light exposure area which received high light intensity (500×10^2 - 600×10^2 lux, represents the intensity of direct sunlight) and scattered light area which received moderate light intensity (130×10^2 – 220×10^2 lux, represents the intensity of ambient daylight) as shown in Figure 26. The powder in the direct light exposure area and scattered light area were separately collected for further analyses.

4.2.3 Color Measurement

The color of turmeric powder from the direct light exposure area and scattered light area was measured by a colorimeter (ColorflexEZ, Hunter Associates Laboratory, VA, USA). The instrument was standardized with a black glass and a calibrated white tile at D65 illumination before measurement (x = 82.03, y = 87.06, z = 91.99). Color values were expressed as L^*, a^*, and b^*. Furthermore, chroma (C^*), hue angle ($h°$), and total color difference (ΔE) were also calculated as follows:

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (4.1)$$

$$h^\circ = tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (4.2)$$

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (4.3)$$

where Δ refers to difference of each parameter between turmeric powder before light exposure and turmeric powder at different exposure times.

4.2.4 Determination of Total Curcuminoids Contents

Total curcuminoids were determined according to Martins et al. (2013) with some modifications. Collected powder from direct light exposure area (0.1 g) or scattered light area (0.25 g) was mixed with 20 mL of methanol in a 50 mL centrifuge tube using a vortex mixer (G560E, Scientific Industries, NY, USA) for 15 s. After that, they were extracted in an ultrasonic bath (Sonorex Digital 10 P, Bandelin, Berlin, Germany) for 30 min (temperature of water was lower than 38 °C). The mixture was filtered through a Whatman No.4 filter paper. The residue was re-extracted for another two times with 10 mL of methanol in the ultrasonic bath for 30 min. The crude extracts were pooled and adjusted to 50 mL in volumetric flask. All the extractions were performed in triplicate. The extract was immediately measured the total curcuminoids contents by UV-Vis spectrophotometer (Genesys 10S UV-Vis, Thermo Fisher Scientific, Waltham, MA, USA). The wavelength was set at 425 nm. A stock solution of standard curcumin (purity > 98%, Merck, Germany) was prepared in methanol at a concentration of 250 mg L^{-1}. The stock solution was diluted to 6 concentrations (0, 0.1, 0.5, 1.0, 2.5, and 5.0 mg L^{-1}). Total curcuminoids contents was expressed as mg curcumin g^{-1} dry matter.

4.2.5 Statistical Analysis

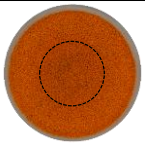
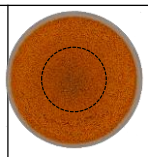
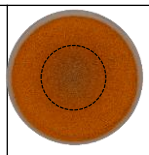
Statistical analyses were performed using PASW Statistics for Windows version 18.0 (SPSS Inc., Chicago, IL, USA). Analysis of variance (ANOVA) and Duncan multiple range test (DMRT) were applied to evaluate the significant difference of color parameters and curcuminoids contents of turmeric powder at different exposure times. The results were assessed at a probability level of ≤ 0.05.

4.3 Results and Discussion

The characteristic orange-yellow color is one of the important factors to indicate the quality of turmeric powder. Table 7 shows that a^*, b^*, and C^* values of turmeric powder obtained from direct light exposure area were significantly lower than scattered light area. This indicated the changes of color shades from orange-yellow to orange-brown ($p \leq 0.05$) after direct light exposure.

Light exposure period significantly affected a^*, b^*, C^*, and $h°$ of turmeric powder in the direct light exposure area ($p \leq 0.05$). The chroma value, C^*, which represents the saturation of color, decreased with the exposure time and therefore it can be seen that the powder in the direct light exposure area was slightly duller after 40 h. The ΔE values which explain the total color difference between turmeric powder before light exposure and turmeric powder at different exposure periods were significantly higher in the the direct light exposure area. However, the light exposure period did not significantly affect the ΔE values of the turmeric powder in both direct light exposure and scattered light areas.

Table 7 Color values of turmeric powder obtained at different exposure times.

Exposure Times	 0 h	 10 h	 20 h	 30 h	 40 h
Direct light exposure area	L^* = 51.49 ± 0.26 a^* = 33.42 ± 0.09^{a} b^* = 63.99 ± 1.10^{a} C^* = 72.19 ± 0.98^{a} $h°$ = 62.42 ± 0.39^{a}	L^* = 50.70 ± 0.67B a^* = 31.85 ± 0.44B^{b} b^* = 59.63 ± 1.38B^{b} C^* = 67.60 ± 1.42B^{b} $h°$ = 61.89 ± 0.25^{ab} ΔE = 1.57 ± 0.12A	L^* = 51.41 ± 0.40 a^* = 31.04 ± 0.05B^{c} b^* = 58.63 ± 1.10B^{b} C^* = 66.34 ± 1.00B^{c} $h°$ = 62.10 ± 0.41^{ab} ΔE = 1.70 ± 0.09A	L^* = 51.61 ± 0.21 a^* = 32.00 ± 0.77^{b} b^* = 59.33 ± 1.46B^{b} C^* = 67.40 ± 1.65^{c} $h°$ = 61.66 ± 0.01^{c} ΔE = 1.60 ± 0.16A	L^* = 51.74 ± 0.02 a^* = 31.15 ± 0.01B^{c} b^* = 57.94 ± 1.19B^{b} C^* = 65.78 ± 1.05B^{d} $h°$ = 61.74 ± 0.48^{c} ΔE = 1.75 ± 0.09A
Scattered light area	L^* = 51.49 ± 0.26^{b} a^* = 33.42 ± 0.09^{bc} b^* = 63.99 ± 1.10 C^* = 72.19 ± 0.98^{ab} $h°$ = 62.42 ± 0.39	L^* = 53.22 ± 0.25A^{a} a^* = 33.68 ± 0.35A^{ab} b^* = 64.28 ± 0.96A C^* = 72.57 ± 1.01A^{ab} $h°$ = 62.35 ± 0.12 ΔE = 1.23 ± 0.05B	L^* = 53.19 ± 0.08^{a} a^* = 33.96 ± 0.22A^{ab} b^* = 64.73 ± 0.06A C^* = 73.10 ± 0.05A^{a} $h°$ = 62.32 ± 0.17 ΔE = 1.22 ± 0.02B	L^* = 53.54 ± 0.46^{a} a^* = 33.06 ± 1.15^{c} b^* = 62.81 ± 2.72A C^* = 70.98 ± 2.94^{b} $h°$ = 62.23 ± 0.21 ΔE = 1.37 ± 0.22B	L^* = 53.41 ± 0.18^{a} a^* = 34.15 ± 0.13A^{a} b^* = 64.72 ± 0.20A C^* = 73.17 ± 0.24A^{a} $h°$ = 62.18 ± 0.02 ΔE = 1.26 ± 0.05B

Significant differences ($p \leq 0.05$) within a row are denoted by different superscript letters. Capital letters are denoted for significant ($p \leq 0.05$) differences between direct light exposure and scatter light area within a color parameter.

In the present study, the total curcuminoids contents of the turmeric powder prior to light exposure was 123.10 ± 1.63 mg curcumin g^{-1} dry matter (12.3%) which was relatively high in comparison to previous reports (Anderson et al., 2000; Nelson et al., 2017).

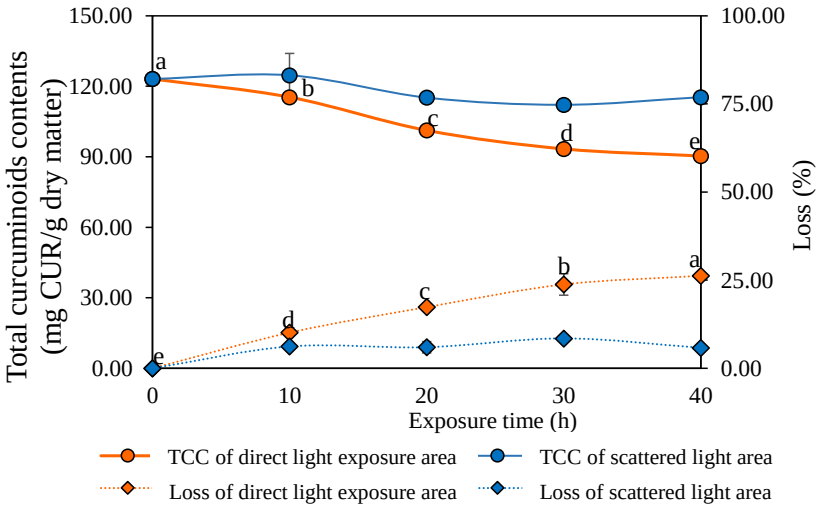


Figure 27 Total curcuminoids contents (TCC) and loss (%) of turmeric powder during the light exposure. Significant differences ($p \leq 0.05$) are denoted by different letters.

The exposure to the simulated sunlight also significantly promoted the curcuminoids degradation ($p \leq 0.05$) (Figure 27). The results indicated that curcuminoids gradually decreased with the exposure time for both areas. Loss of the total curcuminoids in the direct light exposure area, however, was significantly higher than the scattered light area (Figure 27). These results were in agreement with the colour shades of turmeric powder mentioned above. Lee et al. (2013) reported that UV radiation from sunlight might be decomposed orange-yellow color of curcuminoids to dark-brown and produce primarily vanillin, ferulic acid, ferulic aldehyde, and vanillic acid (Nelson et al., 2017). These The present study shows that the loss of total curcuminoids was about 25% in the direct light exposure area, while it was less than 6% in the scattered light area after 40 h. Prathapan et al. (2009) reported that the total curcuminoids in whole turmeric rhizome after sun drying was about 20% lower than that from oven drying at 50 °C. In addition, Khurana and Ho (1988) observed that curcuminoids in turmeric powder were more stable against photodegradation than in solution after an exposure to sunlight for 120 h.

4.4 Conclusion

This study shows that color and total curcuminoids of turmeric powder are susceptible to sunlight. Higher sunlight intensity exhibited stronger effect on curcuminoids degradation than lower intensity. The results suggested that the degradation of curcuminoids can be retarded by avoiding the exposure to sunlight.

4.5 Suggestion

The amounts of turmeric powder used for light exposure experiments should be increased. Degradation of curcumin, demethoxycurcumin, and bisdemethoxycurcumin should be further identified.

CHAPTER 5

Effect of Drying Temperature Together with Light on Drying Characteristics and Bioactive Compounds in Turmeric Slice*

Turmeric is an important source of curcuminoids. It is widely sold in the form of dried slices and powder for production of coloring agents, spices, traditional medicines, and cosmetics. In this study, turmeric slices were dried at five temperatures (40, 50, 60, 70, and 80 °C) under two conditions (without light exposure; noLE and with light exposure; LE) in a laboratory-made hot air dryer. For the LE condition, power and light intensity were 397 ± 29 W m^{-2} and 541 × 10^2 ± 42 × 10^2 lux, respectively. The Midilli and Kucuk model is the best for predicting drying characteristics of turmeric slices. Effective moisture diffusivities (D_{eff}) and the drying rate constants (k) increased with the drying temperature and the light exposure. Light exposure and temperature did not significantly affect the color values of turmeric powder ($p > 0.05$). The three curcuminoids from fresh turmeric identified by HPLC were curcumin (17.88 ± 1.60 mg g^{-1} dry matter), demethoxycurcumin (12.34 ± 0.87 mg g^{-1} dry matter), and bisdemethoxycurcumin (19.84 ± 1.82 mg g^{-1} dry matter). The percentage changes of these curcuminoids after drying under noLE were higher at all temperatures compared to LE condition. Percentage changes of DPPH, ABTS, FRAP, and TPC after drying were not significantly influenced by the drying conditions ($p > 0.05$). The present study suggested that drying at 70 °C without light exposure was the best condition to preserve curcuminoids, color, total phenolic contents, and antioxidant capacity.

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5.1 Introduction

Turmeric (*Curcuma longa*) rhizome is highly demanded for food, beverage, supplement, and pharmaceutical industries. The whole rhizomes are usually processed into dried slices and powder to extend the shelf life and be used in the off-season. Turmeric powder is commonly used as spice in curries and mustards (Nelson et al., 2017) and natural coloring agent in cheese and butter. It is also an important raw material for oleoresin production for use as flavor enhancer in sauces and drinks.

Curcuminoids are the abundant phenolic substances in turmeric rhizomes responsible for yellow color and have been approved to be used as a food ingredient by CODEX (INS No. 100(i)). The three main curcuminoid structures are curcumin, demethoxycurcumin, and bisdemethoxycurcumin (Syed et al., 2015). Curcumin (1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione) is the major active compound with an amount of 2-6% by weight in the rhizome (Yadav et al., 2013). Curcuminoids are also recognized and used for medicines and cosmetics. They contributed numerous pharmacological properties such as anti-inflammatory (Mathew and Hsu, 2018), antitumor, anticancer, and antiviral activities (Zhang et al., 2015). Curcumin also showed a significant anti-HIV effect *in vitro* (Mathew and Hsu, 2018). Therefore, dried turmeric is in great demand on global markets.

Drying is the simplest and cheapest method for food and agricultural processing. The application of drying in food industries is not only to inactivate enzymatic activity or to convert raw plants to a product that is safe, edible, and suitable for storage. It can also improve extractability for industrial extraction by reduction of water content. Thermal energy urges destruction of cell walls and sub cellular compartments which possibly increases the liberation of antioxidant activity in some vegetables (Jiménez-Monreal et al., 2009). Moreover, drying also diminishes the product mass and volume to ease transportation. During the drying process, moisture content of product is reduced by means of heat and subsequent mass transfer to achieve the required product qualities. Heat transfers from drying air toward the moist material to evaporate surface moisture. This cause diffusion of internal moisture to the material surface and keep evaporation going until an equilibrium is reached. Movement of moisture during drying is very complex and involves multiple transport mechanisms including liquid diffusion, vapor diffusion, surface diffusion, and hydrostatic pressure differences (Mujumdar,

2000). The change of moisture content with time is influenced significantly by temperature, humidity, relative air velocity, and pressure. Mathematical modeling of the drying process purposes to design the most suitable operating conditions or drying equipment.

The most common method used to dry turmeric rhizome is sun drying. The whole rhizome could be dried by direct sunlight for about 43 days to reach the final moisture content of 10% (Raza et al., 2018). Sliced turmeric required much shorter time (3-5 days) to reach as low as 7% of moisture content under sun drying at 35-45°C (Chumroenphat et al., 2021). Long drying process could adversely affect curcuminoids content and biological properties as well as product qualities. Chumroenphat et al. (2021) indicated that about 72% of curcuminoids in turmeric slices lost after sun drying. Although, studies on the drying kinetics of turmeric in various solar dryers have been published (Prasad et al., 2006; Borah et al., 2015; Jose and Joy, 2009; Karthikeyan and Murugavelh, 2018; Lakshmi et al., 2018), there were only a few of studies on the degradation of its curcuminoids and bioactive compounds (Jose and Joy, 2009; Lakshmi et al., 2018). Our previous study reported that solar and sun drying significantly degraded curcumin content and color of dried cassumunar ginger (*Zingiber montanum*) slices (Mahayothee et al., 2020).

Experimental results from model system revealed that light exposure accelerates color fading and curcumin loss by photodegradation (Mirzaee et al., 2014; Pricez and Buescher, 1996). It was observed that the degradation rate of curcumin extract in the presence of UV light follows the first-order kinetics with a half-life period of 5 h 50 min (Kumavat et al., 2013). Curcumin in the solution was degraded by both UV and visible light under lamps with emission ranges of 240-600 and 400-510 nm (Tønnensen et al., 1986). The rate constants and half-life for the degradation of 200 ppm curcumin in acetonitrile after irradiation at 400-510 nm were 0.11 h^{-1} and 6.3 h, respectively, whereas 0.1 ppm curcumin in isopropanol was completely decolorized after exposure to continuous radiation at 240-600 nm for 50 min. However, it was stable for at least 24 h at room temperature in the dark (Syed et al., 2015). Obviously, UV light (4 W, 254 nm) adversely affects about 50% loss of curcumin at 8 h which consequently lowers its antioxidant capacities (Lee et al., 2013). Besides the influence of light exposure, curcumin in solution can be also decomposed by thermal processing

(Chen et al. 2014). A study on heat treatment during extraction process indicated that heat treatment at 90°C for 48 h has an impact on color, curcuminoids and antioxidant activity in turmeric extracts (Park et al., 2019). In contrast to lightness value (L^*) of turmeric, which increased, redness (a^*) and yellowness (b^*) values decreased after microwave heating at 900 W for 2 min (Monisha et al., 2016). Loss of curcumin in turmeric was 53% under pressure cooking at 1 bar for 10 min (Suresh et al., 2007).

The literature review indicated that the effect of light was frequently studied in model systems and curcumin extracts. However, a comparative research on the degradation of curcuminoids during the drying with light exposure on turmeric slices has never been reported. Therefore, the main objective of this work was to investigate the drying characteristics, color qualities, and curcuminoids contents of dried turmeric slices after drying at different temperatures using a hot air dryer with and without a simulated sunlight.

5.2 Materials and Methods

5.2.1 Chemical Reagents

Curcumin, demethoxycurcumin, and bisdemethoxycurcumin standards with purity higher than 98%, Folin and Ciocalteu's phenol reagent, 2,2 diphenyl-1-picrylhydrazyl (DPPH), 2,4,6-tri[2-pyridyl]-*s*-triazine (TPTZ), and 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) were purchased from Sigma-Aldrich (St. Louis, Mo, USA). HPLC grade solvents used for quantification of curcuminoids were acquired from Merck (Darmstadt, Germany). Solvents for extraction and determination of antioxidant capacity were of analytical grade from VWR chemicals (Darmstadt, Germany).

5.2.2 Plant materials

Fresh turmeric rhizomes with the maturity of 9-10 months after planting were harvested in Surat Thani province, Thailand. This maturity is commonly used for traditional medicine production. Dirt was brushed off the rhizomes and samples with uniform diameter (1.48 ± 0.23 cm) were selected and packed in net bags. They were carried to the laboratory at the Institute of Agricultural Engineering, University of

Hohenheim, Stuttgart, Germany, and then kept in a refrigerator (Liebherr, Profiline GKv 6410-20, Germany) at 11.0 ± 0.4 °C and relative humidity of 90.4 ± 11.6%. The stored rhizomes were washed under running tap water and then allowed to dry at room temperature before the experiments.

5.2.3 Drying Equipment and Experimental Procedure

Drying experiments were performed at five temperatures, specifically 40, 50, 60, 70, and 80 °C using a laboratory-made hot air dryer with precise controls for temperature and relative humidity. Air velocity was set to 0.5 m s^{-1} in over- and under-flow mode using a centrifugal blower with a frequency converter. Specific humidity of an inlet air was controlled at 25 g water kg^{-1} air, respectively using a Raschig rings packed bed humidifier. Consequently, the relative humidity in the drying chamber at 40, 50, 60, 70, and 80 °C was 50.8, 30.4, 18.8, 12.0, and 7.9%, respectively. Details of the dryer components were described by Argyropoulos et al. (2011). The dryer was warmed up to the required temperature for 2 h before drying. The cleaned rhizomes were sliced into 8 × 40 × 3.5 mm (width × length × height) pieces using a custom made cutter. Two hundred pieces of turmeric sample (approx. 250 g) were placed on an aluminum wire tray in a single layer. Changes in mass were automatically recorded every 15 min using a load cell (Flintec, type PC6, Västerås, Sweden) during the drying at 40 and 50 °C and every 10 min at 60, 70, and 80 °C. Samples were dried until the product mass reached a constant value. Dried product was kept in a jar for 24 h to reach equilibrium prior to analysis. The drying experiments were conducted in duplicate. Initial and final moisture contents were determined using a vacuum dryer (Thermo Scientific, VT 6060 P, Waltham, MA, USA) at 50 °C and 2 kPa for 12 h.

5.2.4 Light Exposure

To evaluate the effect of light during the drying, four Solar Simulation units (Hönle, SOL 500, Munich, Germany) which emit light at wavelengths of 280 - 2750 nm were installed above the drying chamber. The drying chamber was covered by a 1.6 cm thick acrylic sheet which allows both visible and infrared wavelengths to pass through. The distance between the lamps and slice samples was fixed at 40 cm as shown

in Figure 28. Power and light intensity measured above the samples at different points were in the ranges of 397 ± 29 W m^{-2} and 541×10^{2} ± 42×10^{2} lux, respectively.

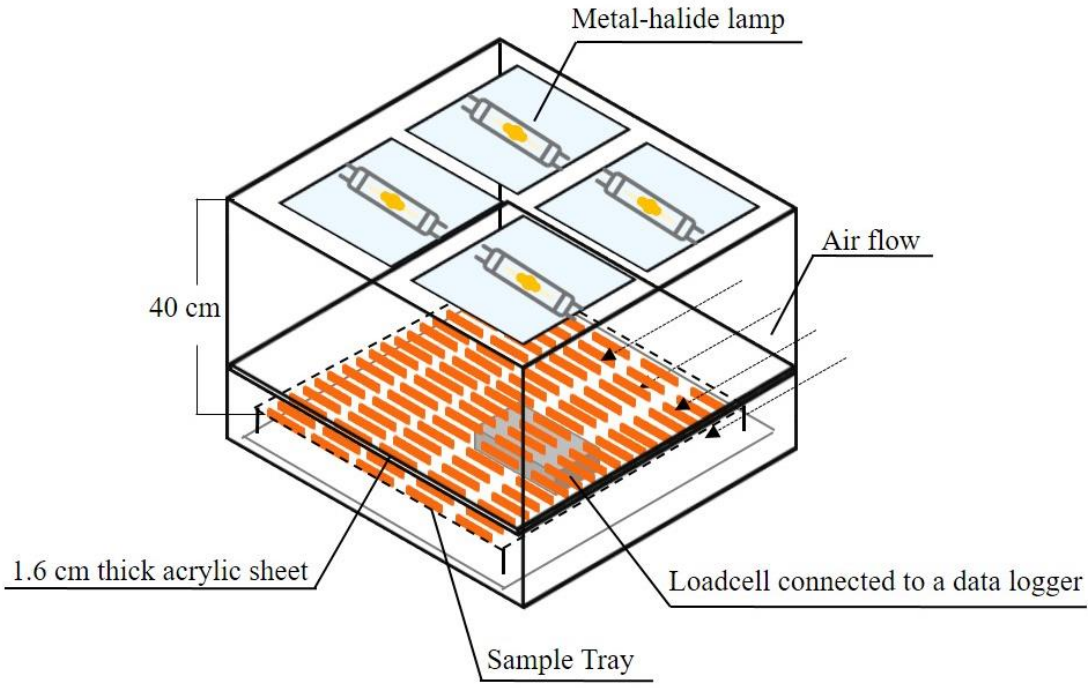

Figure 28 Diagram of the drying chamber and simulated solar light.

5.2.5 Mathematical Modeling for Drying Kinetics

Various mathematical models have been proposed to determine the thin-layer drying characteristics of agricultural products. The Lewis (Eq. (5.1)) (Lewis, 1921), Page (Eq. (5.2)), and Modified Page (Eq. (5.3)) (Overhults et al., 1973) models derived from Newton's law of cooling are widely used as the basis for most semi-theoretical thin-layer models. The models of Henderson and Pabis (1961) (Eq. (5.4)) and Midilli and Kucuk (2003) (Eq. (5.5)) which were derived from Fick's second law of diffusion are more complex than the aforementioned models. All models were fitted to describe the drying kinetics of turmeric slices using non-linear regression analysis in R version 3.5.1 (R Development Core Team, 2008).

$$MR = \exp(-kt) \quad (5.1)$$

$$MR = \exp(-kt^n) \quad (5.2)$$

$$MR = \exp(-kt)^n \quad (5.3)$$

$$MR = a\exp(-kt) \quad (5.4)$$

$$MR = a\exp(-kt^n) + bt \quad (5.5)$$

where *MR* is moisture ratio, *k*, *n*, *a*, and *b* are empirical parameters of the models, and *t* is drying time. The moisture ratio (*MR*) of turmeric slices was determined using following equation:

$$MR = \frac{X_t - X_e}{X_0 - X_t} \quad (5.6)$$

where X_0 is initial moisture content (dry basis), X_t is moisture content (dry basis) at different drying time, and X_e is moisture content (dry basis) at equilibrium which was defined as the final moisture content (dry basis) for each drying condition. The goodness-of-fit of the mathematical model to the experimental data was decided by high coefficient of determination (R^2), low-root-mean squared error (*RMSE*) and low Akaike information criterion (*AIC*) (Akaike, 1974). *AIC* is widely accepted criteria for selecting nonlinear model. R^2, *RMSE*, and *AIC* can be calculated with Eqs. (5.7), (5.8), and (5.9):

$$R^2 = \frac{\text{Residual sum of square}}{\text{Total sum of square}} \quad (5.7)$$

$$= \left[\frac{\sum_{i=1}^{n}(X_{i,exp} - X_{i,pre})^2}{n}\right]^{0.5} \quad (5.8)$$

$$AIC = 2l_i - 2k_i \quad (5.9)$$

where *l* is the maximum value of the log likelihood of the *i* model and *k* is number of parameters of the *i* model.

Drying rate (g water g^{-1} dry solid min^{-1} m^{2-1}) at certain time interval was calculated using Eq. (5.10):

$$\text{Drying rate} = \frac{\Delta X}{\Delta t A} = \frac{X_1 - X_2}{t_2 - t_1} \times \frac{1}{A} \quad (5.10)$$

where X_1 and X_2 are moisture contents (g water g^{-1} dry solid) at different times t_1 and t_2 (min), respectively and *A* is surface area (m^2).

Effective moisture diffusivity (D_{eff}) is defined to explain the rate of moisture movement during drying process of fruit and vegetable especially during falling rate

period. It represents the diffusion phenomenon according to Fick's second law (Touil et al., 2014). The unsteady state diffusion of moisture by Fick's second law is shown in Eq. (5.11):

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \frac{\partial^2 M}{\partial x^2} \tag{5.11}$$

where D_{eff} is the effective moisture diffusivity ($mm^2\ h^{-1}$), M is the moisture content at any time t (kg water kg^{-1} dry matter), and x is the distance of diffusion. Eq. (5.11) can be simplified for a slab geometry of the sample assuming the uniform initial distribution of moisture as expressed in Eq. (5.12) (Crank, 1975):

$$MR = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{\text{eff}} t}{4(h)^2}\right) \tag{5.12}$$

Eq. (5.12) can be simplified as Eq. (5.13) (Crank, 1975):

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{\text{eff}}}{4(h)^2} t \tag{5.13}$$

where D_{eff} is the effective moisture diffusivity ($mm^2\ h^{-1}$), h is the half thickness of slab (mm). D_{eff} was obtained by plotting the graph of ln MR versus time t and the value was calculated using Eq. (5.14) and (5.15):

$$\text{slope} = \frac{-\pi^2 D_{\text{eff}}}{4(h)^2} \tag{5.14}$$

$$D_{\text{eff}} = \text{slope} \times \frac{-4(h)^2}{\pi^2} \tag{5.15}$$

5.2.6 Color Measurement

Color values of fresh and dried samples were measured using a chroma meter (CR-100, Minolta, Tokyo, Japan) in CIE L^*, a^*, b^* coordinates. The instrument was standardized each time with a white calibration plate D65 (Y = 87.5, x = 0.3180, and y = 0.3355). Initial color values were obtained from averaged values of 30 pieces of fresh turmeric slices. The dried sample was ground into powder using an analytical mill (A10, IKA, Wilmington, NC, USA) and then put in a sample holder before measurements. Five replications of dried powder were measured. Chroma (C^*), hue angle ($h°$), and total color change (ΔE) were calculated using Eqs. (5.16), (5.17), and (5.18), respectively:

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{5.16}$$

$$h° = tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{5.17}$$

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (5.18)$$

where Δ refers to difference of each parameter between fresh and dried samples.

5.2.7 Determination of Curcuminoids Contents

Curcumin, demethoxycurcumin, and bisdemethoxycurcumin contents were determined a high performance liquid chromatography method as described by Nelson et al. (2017) with some modifications: Three grams of fresh mashed sample or two grams of dried powder were extracted with 20 mL of methanol in a centrifuge tube using an ultrasonic bath (Sonorex Digital 10 P, BANDELIN, Berlin, Germany) for 30 min. The water temperature in the bath was lower than 35 °C. The mixture was filtered through Whatman grade 4 filter paper and collected in a 50 mL volumetric flask. The residue was re-extracted for another two times with 10 mL of methanol each in the ultrasonic bath for 30 min. The combined extract was adjusted to 50 mL with methanol. The extractions were performed in triplicate. Curcumin, demethoxycurcumin, and bisdemethoxycurcumin contents were determined using a Shimadzu HPLC system (Kyoto, Japan) consisting of a 2IL-20AHT auto sampler, DGU-20A5R degasser, LC-20AD pump, and SPD-M20A diode array detector. Chromatographic separation was achieved on Luna C18 column (250 × 4.6 mm i.d.; 5 μm; Phenomenex, Torrance, CA, USA) operated at 33 °C. Isocratic mode elution was carried out using acetonitrile and 1% acetic acid in water (60/40 v/v) at a flow rate of 1.0 mL min^{-1}. The extract was filtered through 0.45 μm nylon syringe filter before injection. Monitoring of curcuminoids peaks was performed at 425 nm. Solutions of standard curcumin, demethoxycurcumin, and bisdemethoxycurcumin were prepared in methanol at concentrations of 0, 0.5, 1.0, 2.0, 2.5, 5.0, 10.0 and 25.0 mg L^{-1} for preparation of standard curves. Finally, the contents of each component were calculated in mg g^{-1} dry solid. Total curcuminoids content is the sum of the contents of curcumin, demethoxycurcumin, and bisdemethoxycurcumin.

5.2.8 Determination of Total Phenolic Contents and Antioxidant Capacity

Sample extraction was performed as described by Mahayothee et al., 2018; Five hundred milligrams of fresh mashed sample or 0.10 g of dried turmeric powder were

mixed with 10 mL of 60% methanol using a vortex mixer for 15 s and blended using a homogenizer (T25 Ultra Turrax, IKA, Königswinter, Germany) at 8000 rpm for 1 min. The mixture was placed in an ultrasonic bath (780/H 35 kHz, Transsonic, Germany) for 15 min. The water temperature was controlled to lower than 35 °C. The mixture was centrifuged at 11515 × *g* and 4 °C for 10 min (z 326K, Hermle, Tuttlingen, Germany). The supernatant was collected in a volumetric flask and the residue was re-extracted starting from the sonication step for 5 times. The extract was kept in an amber vial at -18 °C for one night before analysis.

Total phenolic content (TPC) was determined using the Folin-Ciocalteu assay (Singleton and Rossi, 1965) with a slight modification: Two hundred microliters of the extract was mixed with 1.0 mL of 10 fold diluted Folin and Ciocalteu reagent in an amber vial. The mixture was allowed to stand for 5 min, then 1.6 mL of 7.5% $NaCO_3$ solution were mixed in. The final mixture was kept in the dark for 120 min. The absorbance of the mixture was measured at 765 nm using a UV-Vis spectrophotometer (DR6000, Hach Lange, Düsseldorf, Germany). Gallic acid solutions at concentrations of 0, 20, 40, 60, 80, and 100 mg L^{-1} were used to prepare a standard curve. TPC was calculated in mg gallic acid equivalent (GAE) 100^{-1} g^{-1} dry solid.

Determination of antioxidant capacity was based on electron transfer reaction methods, namely DPPH radical scavenging assay (DPPH), ferric reducing antioxidant potential (FRAP), and ABTS radical scavenging capacity assay (ABTS). Standard Trolox solutions at concentrations of 0, 12.5, 25.0, 62.5, 125.0, 187.7, and 250.0 mg L^{-1} were used to prepare calibration curves. The results were calculated in mg Trolox equivalent g^{-1} dry solid.

DPPH assay was done as described by Brand-Williams et al. (1995) with some modifications: One hundred microliters of the final extract was mixed with 3.9 mL of 0.6 mM DPPH solution. One hundred microliters of 60% methanol was used as a control. The reaction was carried out in the dark for 120 min before measuring the absorbance at 517 nm.

FRAP assay was done as described by Benzie and Strain (1996) with some modifications: One hundred and fifty microliters of the extract was mixed with 2850 μL of FRAP solution. After standing for 10 min the absorbance at 593 nm was measured.

ABTS assay was done as described by Arnao et al. (2001) with some modifications: Five milliliters of each 7 mM ABTS solution and 2.6 mM $K_2S_2O_8$ was mixed and incubated in the dark for 16 h to obtain ABTS radical cation ($ABTS^{\bullet+}$) solution. The $ABTS^{\bullet+}$ solution was diluted with 300 mL of 60% methanol to reach an absorbance value of 1.100 ± 0.020 at 734 nm prior to use. One hundred and fifty microliters of the final extract was mixed with 2850 μL of $ABTS^{\bullet+}$ solution and allowed to react in the dark for 120 min. The absorbance was measured at 734 nm.

5.2.9 Statistical Analysis

Analysis of variance (ANOVA) and Duncan's multiple range test were performed to evaluate the difference of each response variable using the sample lots as blocks. The results were assessed at a probability level of $p = 0.05$. Statistical analysis was performed using SPSS (Version 17, Chicago, IL, USA).

5.3 Results and Discussion

5.3.1 Drying Kinetics of Turmeric Slices

The drying behaviors of turmeric slices are shown in Figure 29. Drying curves (Figure 29a) represent the reduction of moisture ratio as a function of time at 40, 50, 60, 70, and 80 °C with light exposure (LE) and without light exposure (noLE). Fresh samples with an initial moisture content of 77.34 ± 0.87% (w.b.) were continuously dried until their mass reached constant value. The final moisture contents and water activities were in the ranges of 10.40 – 13.26% (w.b.) and 0.259 – 0.444, respectively (Table 8).Constant rate period was not observed in all curves (Figure 29).

The drying rate is clearly influenced by the drying air temperature and light exposure. As a result, the drying times taken to reach the final moisture content were shorter at higher air temperatures and ranged between 3.67 h (at 80 °C) and 37 h (at 40 °C). Thin layer drying models were used to describe the experimental data. Noted that only data from the initial time to the beginning of constant weight (15.52, 9.52, 5.53, 3.83, and 2.67 h and 11.52, 8.52, 5.00, 3.17, and 2.33 h for 40, 50, 60, 70, and 80 °C under noLE and LE, respectively) were used for kinetic modeling to avoid the effect of long constant weight data on model parameters estimation. For both noLE and LE

conditions the Midilli and Kucuk model gave the lowest *RMSE* and *AIC* values, which are used to evaluate fitness of non-linear models (data not shown). Therefore, it was considered as the most appropriate model to describe the drying kinetics of turmeric slices with R^2 higher than 0.998 and *RMSE* lower than 0.008 (Table 8).

The Midilli and Kucuk model was derived from the Henderson and Pabis model by adding an extra "*b*" parameter and therefor contains 4 empirical parameters. The equation combines both an exponential term and a linear term which are suitable to describe both constant rate periods and falling rate periods. It was successfully applied for other herbs and sliced samples, such as chili, pepper, apple, pumpkin and persimmon slices (Onwude et al., 2016). Our results show that the drying rate constants (*k*) from the Midilli and Kucuk model significantly increased with drying temperature and light exposure ($p \leq 0.05$). At the lower temperatures, the effect of light was more prominent. For example, the *k* value for the drying with light was about 2.5 times of that without light at 40 °C while it was only 1.1 times at 80 °C.

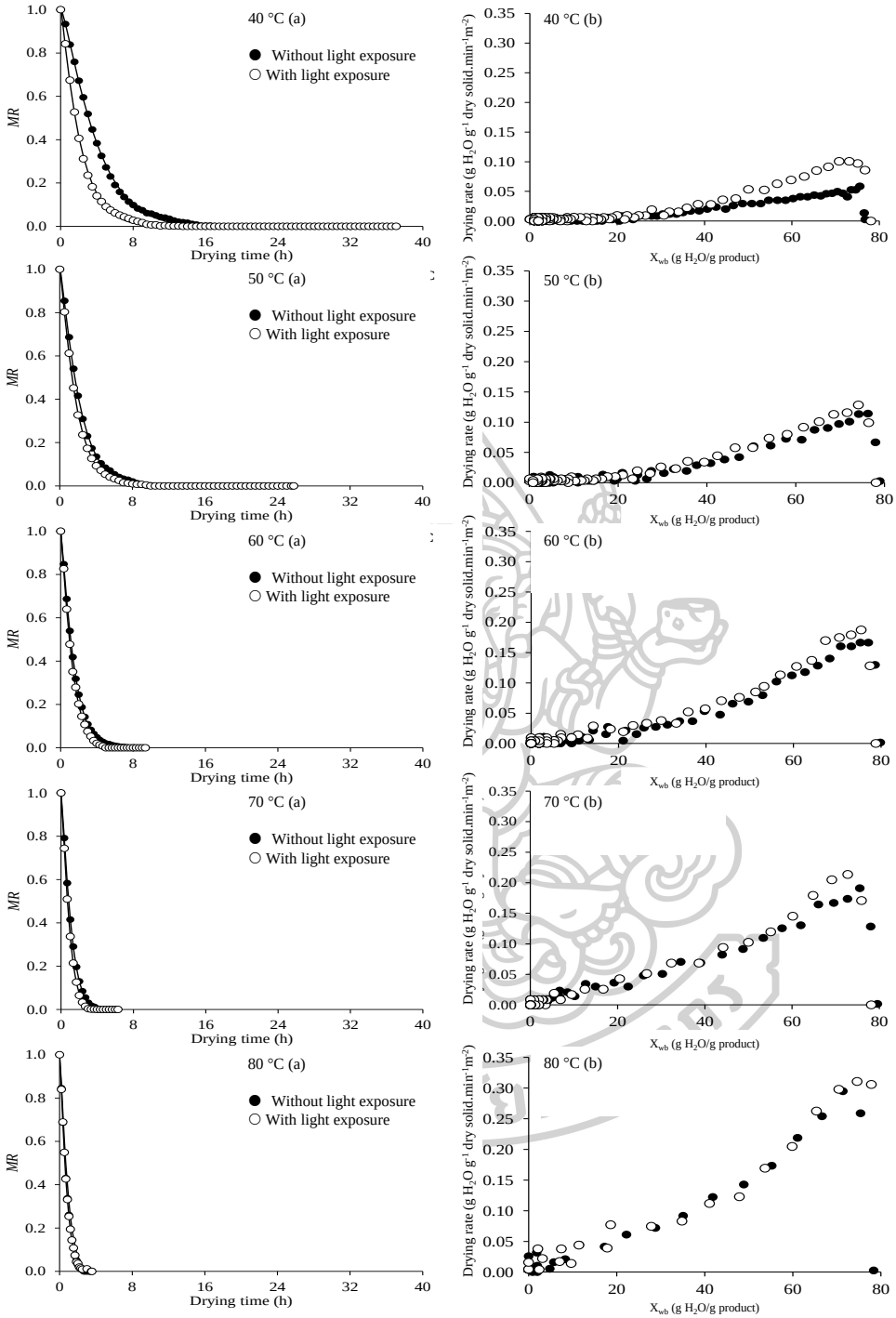

Figure 29 Drying behaviors of turmeric slices as affected by drying conditions; (a) Drying curves, (b) Drying rate curves. Drying conditions are indicated by ● without light exposure and ○ with light exposure. Lines are drawn using Midilli and Kucuk model.

Table 8 Drying time, moisture content, water activity, and drying rate constants of turmeric slices obtained at different conditions.

Conditions		Drying time	MC (%)	a_w	Midilli and Kucuk model					
Temperature (°C)	Light exposure	(h)	After drying	After drying	k (h^{-1})	n	a	b	R^2	$RMSE$
40	No	37.00	$13.26±.055^{a}$	$0.444±0.039^{a}$	0.1636^{e}	1.2921	1.0026	0.0009	0.9996	0.0055
	Yes		$11.64±1.25^{A}$	$0.349±0.040^{A}$	0.4151^{E}	1.1240	1.0140	0.0010	0.9989	0.0087
50	No	26.00	$12.98±0.82^{ab}$	$0.418±0.112^{ab}$	0.3908^{d}	1.2009	1.0129	0.0015	0.9993	0.0071
	Yes		$11.29±0.50^{AB}$	$0.308±0.091^{AB}$	0.5467^{D}	1.1632	1.0092	0.0008	0.9993	0.0069
60	No	9.72	$11.07±0.81^{ab}$	$0.248±0.001^{b}$	0.6483^{c}	1.2025	1.0051	0.0015	0.9998	0.0040
	Yes		$10.94±0.46^{AB}$	$0.275±0.018^{B}$	0.7211^{C}	1.1685	1.0114	-0.0010	0.9992	0.0071
70	No	6.28	$10.58±0.62^{b}$	$0.262±0.020^{b}$	0.8598^{b}	1.2305	1.0044	-0.0009	0.9999	0.0034
	Yes		$.1040±0.63^{B}$	$0.259±0.047^{B}$	1.0532^{B}	1.2265	1.0007	-0.0055	0.9999	0.0036
80	No	3.65	$10.56±0.22^{b}$	$0.232±0.049^{b}$	1.3139^{a}	1.266	1.0003	-0.0070	0.9999	0.0037
	Yes		$10.79±1.59^{B}$	$0.259±0.001^{B}$	1.4390^{A}	1.2492	0.9983	-0.0044	0.9997	0.0046

Data are expressed as mean ± standard deviation (n = 2). Different lower case letters and different capital letters indicate a significant ($p \leq 0.05$) difference among different drying temperatures at noLE and LE conditions, respectively.

The effects of drying temperature and light exposure on the drying rate are presented in Figure 29(b). At the beginning of the drying process the moisture content was approximately 77% (w.b.) and the drying rate rapidly rose to a maximum value. This phase is known as warm-up period. In this period the turmeric slices are heated from an initial temperature of 26.13 ± 0.34 °C to the respective drying air temperatures (Figure 30)

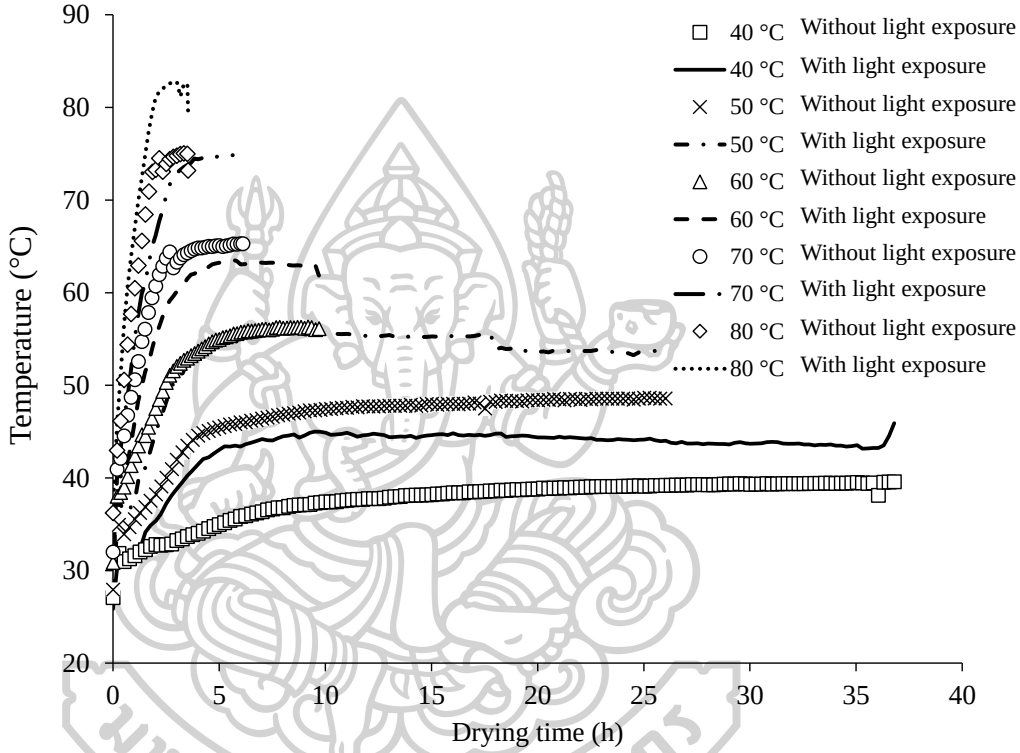

Figure 30 Product temperature of turmeric slices during drying at different conditions.

The warm-up period was relatively short. Higher temperatures reduced warm-up periods which were 30 min at 40 and 50 °C, 20 min at 60 and 70 °C, and 10 min at 80 °C for both noLE and LE conditions. In this period, the moisture on the surface started to evaporate which resulted in an increasing of the drying rate until the moisture content was reduced to approximately 70 – 75% (w.b.). The falling rate period began when the free moisture at the surface was deficient for continuous evaporation. The rate of evaporation decreased rapidly leading to an increase in the surface temperature. Crust was formed at the surface of the sample which resulted in visible shrinkage and created a barrier for moisture diffusion.

Figure 30 shows that sample temperature under LE was higher by approximately 5 °C than under noLE at the same drying air temperature. This was due to absorption of infrared radiation from the light by the samples which was converted into thermal energy and increased the sample temperature. Therefore, the drying process under LE conditions was faster than under noLE conditions (Figure 29).

D_{eff} values increased with temperature and light exposure as shown in Figure 31. The values of D_{eff} were also estimated using the data from the initial time to the beginning of constant weight as described above. The obtained values were 0.39, 0.65, 0.99, 1.55, and 2.42 $mm^2\ h^{-1}$ at 40, 50, 60, 70, and 80 °C, respectively for noLE and 0.60, 0.89, 1.30, 2.09, and 2.66 $mm^2\ h^{-1}$ at 40, 50, 60, 70, and 80 °C, respectively for LE. Borah et al. (2015) reported an average D_{eff} value of 0.67 $mm^2\,h^{-1}$ for turmeric slices in a solar conduction dryer with drying temperature around 39 – 51 °C. Drying at 80 °C under both noLE and LE conditions yielded the highest D_{eff} values. Higher drying temperature provides higher moisture diffusivity ($p \leq 0.05$) which were consistent with the drying rate constant from the Midlli and Kucuk model ($R^2 = 0.989$). This was due to an increase in temperature which promotes the mass transfer of moisture from inside to the turmeric surface. Light exposure also increased the D_{eff} values ($p \leq 0.05$) because it slightly increased the product temperatures (Figure 31). The interactions of temperature and light were not significant for D_{eff} ($p > 0.05$). However, moisture diffusivity in agricultural products differs due to moisture content, variation of composition, microstructure, and drying variables. The results from Akanbi et al. (2006) established the D_{eff} in the range 13.39– 44.17 mm^2h^{-1} for the first, send, and third periods for drying of tomato slices at 45 – 75 °C. Jayatunga and Amarasinghe (2019) reported that increase in D_{eff} with increasing drying temperature. The highest D_{eff} of 7.31 mm^2h^{-1} was obtained at a hot air temperature of 75 °C for black pepper.

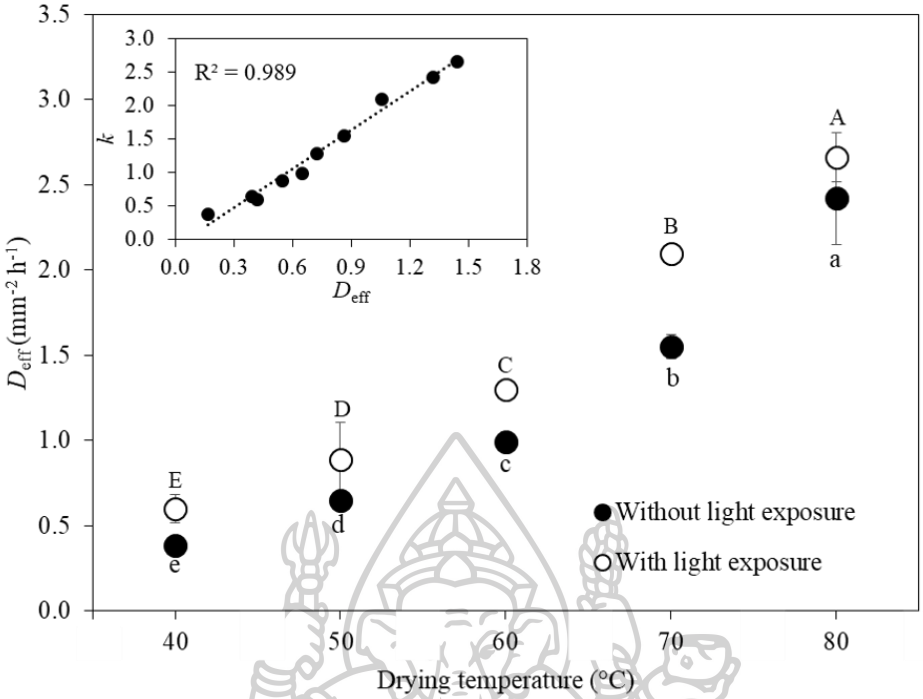

Figure 31 Moisture diffusivity (D_{eff}) of turmeric slices as affected by drying conditions indicated by ● without light exposure and ○ with light exposure. Inset: Relationship between drying rate constant (k) from Midlli and Kucuk model and D_{eff}. Different lower case letters and different capital letters indicate a significant difference ($p \leq 0.05$) among different drying temperatures at noLE and LE conditions, respectively.

Light exposure also increased the D_{eff} values ($p \leq 0.05$) because it slightly increased the product temperatures (Figure 31). The interactions of temperature and light were not significant for D_{eff} ($p > 0.05$).

5.3.2 Effect of Drying on Color

Color is the first parameter to determine the quality of turmeric because it is often regarded as an indicator of curcuminoids content. The light exposure caused color fading of turmeric slices at all temperatures, especially on the upper side which was directly exposed to the light. The upper side of samples from 40 and 50 °C under LE condition were palest because of the long exposure to light (37 and 26 h, respectively). This indicated that the light exposure accelerated the loss of curcuminoids on the surface which is responsible for yellow color in turmeric. Mahayothee et al. (2020)

reported that the yellow color of dried cassumunar ginger slices from sun and solar drying was largely diminished especially on the upper side. In this study, however, it was observed that the color of the internal part of slices did not significantly changed under every condition.

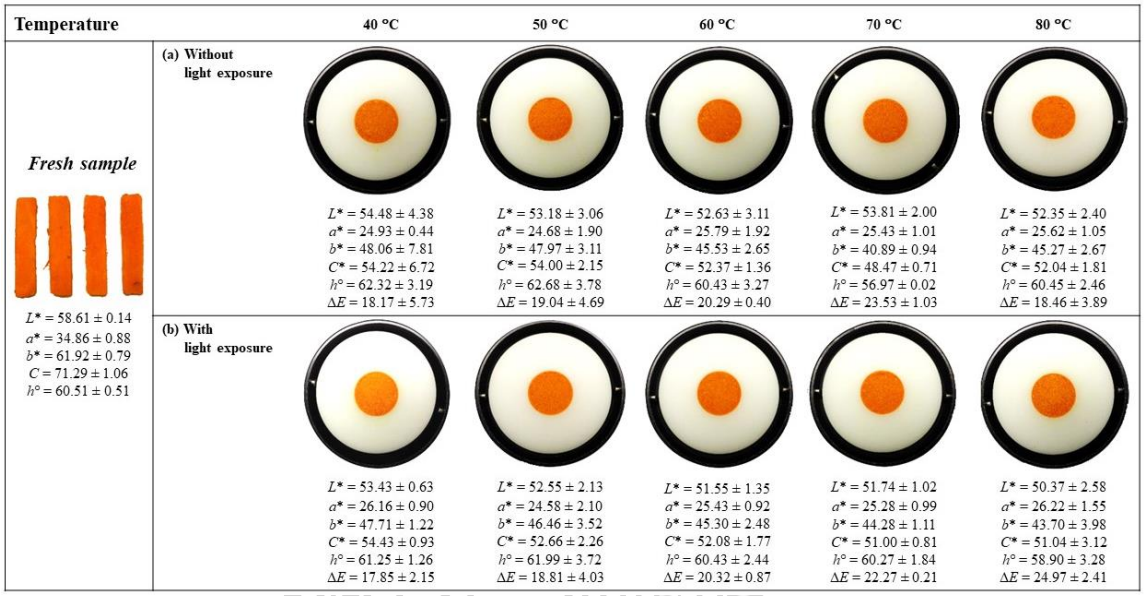

Figure 32 Appearance and color values of fresh turmeric slices and dried turmeric powder under different drying conditions.

Figure 32 shows the measured color values L^*, a^*, b^*, chroma (C^*), hue angle ($h°$), and total color difference (ΔE) of the turmeric powder obtained under various conditions. It should be noted that the color values of turmeric powder were not significantly affected by the drying temperature and light exposure ($p > 0.05$). The $h°$ values of turmeric flesh and powder were in a range 57 - 63 which indicates a characteristic orange-yellow color. ΔE value was used to describe the total color difference between fresh turmeric and turmeric powder. The result showed that the drying temperature and light also did not affect the ΔE values. This agreed with the appearances of the powder (Figure 32).

5.3.3 Effect of Drying on Curcuminoids

Curcuminoids from fresh turmeric identified by HPLC were curcumin (5.63 ± 0.82 mg g^{-1} fresh weight (FW) or 17.88 ± 1.60 mg g^{-1} dry matter), demethoxycurcumin (2.52 ± 0.60 mg g^{-1} FW or 12.34 ± 0.87 mg g^{-1} dry matter), and bisdemethoxycurcumin (4.09 ± 1.45 mg g^{-1} FW or 19.84 ± 1.82 mg g^{-1} dry matter). HPLC chromatograms of curcumin, demethoxycurcumin, and bisdemethoxycurcumin are shown in Figure 33.

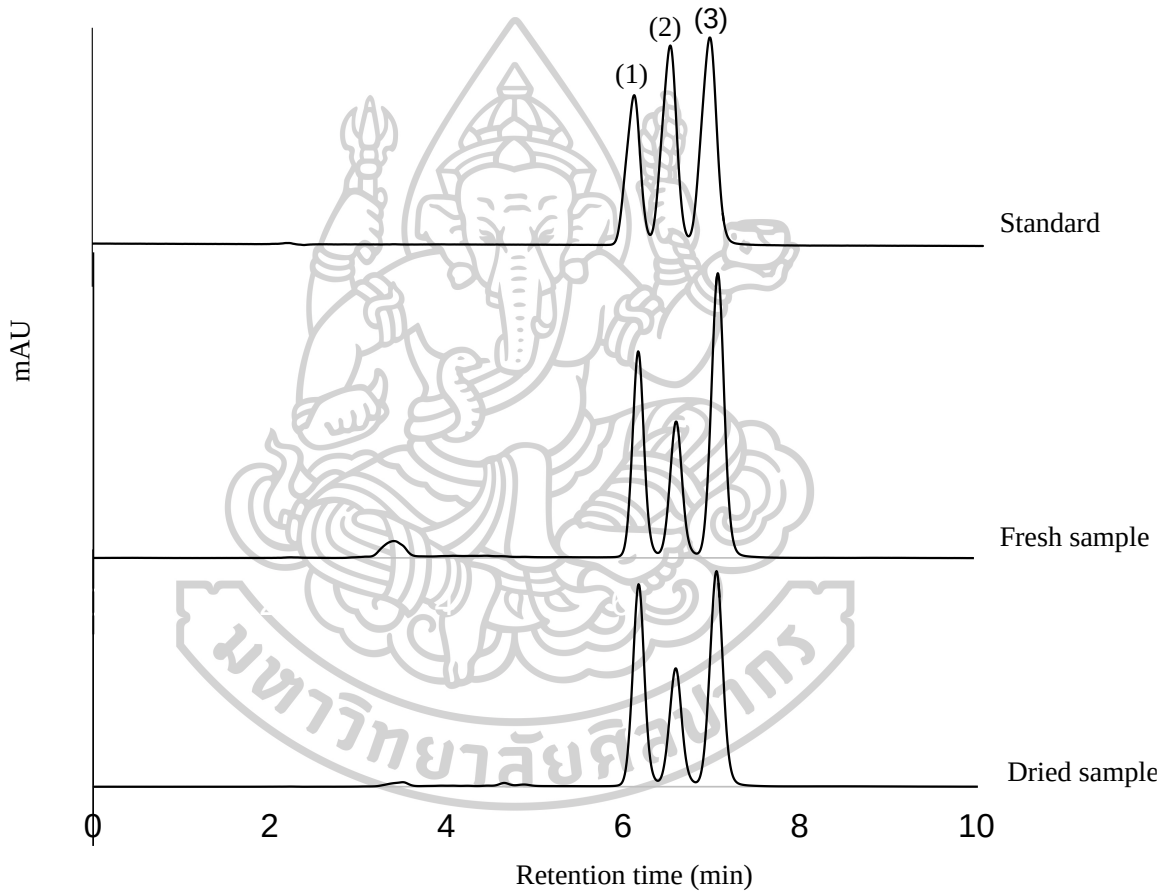

Figure 33 HPLC chromatogram of bisdemethoxycurcumin (1), demethoxycurcumin (2) and curcumin (3) from drying at 60°C.

Total curcuminoids contents, which were the sum of those 3 components, of fresh and dried turmeric were in the ranges of 52.63 – 69.41 and 62.40 – 74.40 mg g^{-1} dry matter, respectively. The contents of total curcuminoids in this study were similar to a turmeric powder from China and India, which were approximately 44 and 56 mg

g^{-1} dry matter, respectively (Li et al., 2011; Pal et al., 2020). Pothitirat and Gritsanapan, (2005) reported that the curcuminoids contents of turmeric powder planting in Surat Thani province, Thailand analyzed by TLC was 44.89 mg g^{-1} dry matter. Curcumin was the major compound in the fresh sample with a ratio of 47.03% of total curcuminoids, followed by bisdemethoxycurcumin (32.45% of total curcuminoids) and demethoxycurcumin (20.52% of total curcuminoids) (Table 9) which is consistent with previous report (Pothitirat and Gritsanapan, 2005).

Table 9 also indicates that the ratios of both curcumin and demethoxycurcumin were slightly lower after drying while the bisdemethoxycurcumin ratio increased by approximately 1-2% of total curcuminoids under every drying condition. However, there was no significant difference ($p > 0.05$) in the ratio of curcumin and bisdemethoxycurcumin between dried products obtained under different drying conditions.

Table 9 Effects of drying temperature and light exposure on curcuminoids ratio (%) in turmeric powder compared to fresh turmeric.

Conditions		Curcuminoids ratio (%)					
Temperature (°C)	Light exposure	Curcumin		Demethoxycurcumin		Bisdemethoxycurcumin	
		Fresh^{ns}	Dried^{ns}	Fresh	Dried	Fresh^{ns}	Dried^{ns}
40	No	47.62±8.14A	45.70±5.70B	20.65±0.66A^{ab}	20.45±0.64B^{ab}	31.73±7.48B	33.85±5.13A
	Yes	46.99±5.92A	43.78±4.90B	20.74±0.19A^{ab}	20.67±0.25A^{a}	32.27±5.73B	35.55±4.65A
50	No	46.98±6.59A	45.61±6.53B	20.81±0.17A^{ab}	20.06±0.36B^{b}	32.21±6.76B	34.33±6.17A
	Yes	46.12±5.75A	43.72±5.74B	20.56±0.96A^{abc}	20.37±0.50B^{ab}	33.33±4.79B	35.91±5.23A
60	No	47.43±6.48A	46.47±6.54B	20.88±0.63A^{a}	20.24±0.55B^{ab}	31.69±5.85B	33.88±6.82A
	Yes	44.73±5.07A	44.38±5.25B	20.81±0.68A^{a}	20.45±0.20B^{ab}	34.46±4.39B	34.58±4.22A
70	No	47.77±7.42A	44.09±4.55B	20.38±0.47A^{bc}	20.05±0.30B^{b}	31.85±6.95B	35.86±4.84A
	Yes	47.39±6.82A	45.02±6.57B	20.39±0.02A^{abc}	20.39±0.53A^{ab}	32.22±6.84B	34.59±6.04A
80	No	47.78±7.50A	45.57±7.14B	19.95±0.04A^{c}	20.22±0.81A^{ab}	32.27±7.54B	34.21±6.33A
	Yes	47.49±7.20A	44.50±4.36B	20.01±0.35A^{c}	20.32±0.19A^{ab}	32.51±6.85B	35.19±4.17A

Data are expressed as mean ± standard deviation (n = 2). Significant ($p \leq 0.05$) differences within a column are denoted by different superscript letters. Capital letters are denoted for significant ($p \leq 0.05$) differences between fresh and dried samples within a condition.

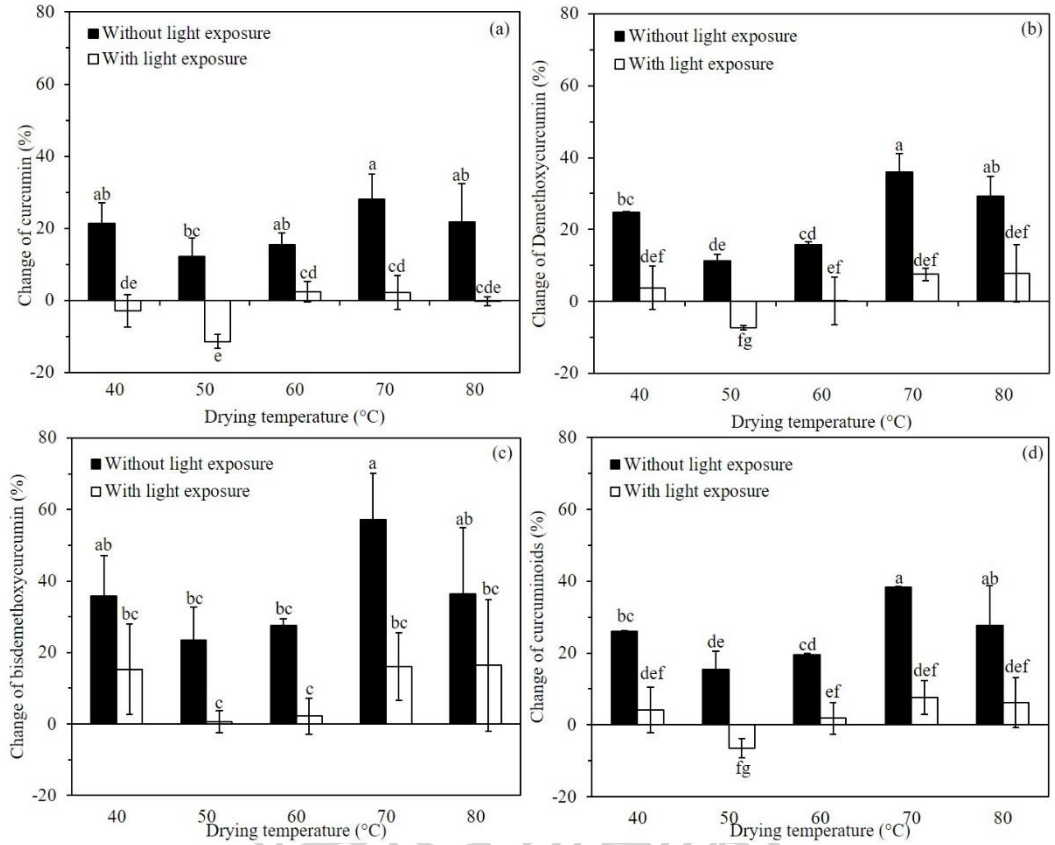

Figure 34 Changes of (a) curcumin, (b) demethoxycurcumin, (c) bismethoxycurcumin, and (d) curcuminoids (%) of dried products as affected by drying conditions indicated by ■ without light exposure and □ with light exposure. Significant differences ($p \leq 0.05$) within all conditions are denoted by different letters.

The effects of temperature and light on curcuminoids contents for drying at various conditions are shown in Figure 34. Percentage changes of curcumin, demethoxycurcumin, bisdemetoxycurcumin, and total curcuminoids contents of dried products obtained from different drying conditions compared to fresh samples were calculated to illustrate the degradation. The contents of each curcuminoid in dried products obtained under noLE condition were higher than those in fresh sample, especially at 70 and 80 °C. This might be attributed to the fact that drying improves the extractability of compounds due to destruction of cell walls which increases solvent migration during extraction (Herminia et al., 2017). Green et al. (2008) also observed higher curcuminoids content in turmeric dried in a hot air dryer without light exposure

(55.5% w/w) than in fresh sample (47.1% w/w). However, unchanged curcuminoids contents for turmeric samples that were immersed into hot water before drying was reported in another study (Prathapan et al., 2009).

Figure 34 also shows that the temperature and light exposure significantly affected ($p \leq 0.05$) the percentage change of each curcuminoid. At 40 and 50 °C under LE condition, curcumin content degraded due to longer exposure to heat and light compared to 60 and 70 °C. The same applies to demethoxycurcumin content at 50 °C under LE. The results were in agreement with the study of Raza et al. (2018) which found that the very long time sun drying (43 days) and solar tunnel drying (37 days) resulted in the lowest curcumin content with the values of 1.40 and 1.68%, respectively. While the highest contents of 2.97% was found during the hot-air drying at 70 °C temperature, and the values decreased at higher temperatures (80 and 90 °C). The degradation of curcumin in the present study was also observed after drying at 80 °C which indicated that the high temperature accelerated degradation of curcumin under LE condition even in shorter time. In contrast, degradation was not found at 80 °C under noLE condition. These results were in consistent with the appearances of turmeric powder shown in Figure 34. The degradation of curcumin is well-recognized but not yet fully understood. It has been reported that photodegradation of curcumin by sunlight produces vanillin, ferulic acid, ferulic aldehyde, and vanillic acid (Nelson et al., 2017). Previous study also reported that curcumin was less stable than demethoxycurcumin (Sandur et al., 2007). Bisdemethoxycurcumin content was higher after drying under all conditions (Figure 34). Heffernan et al. (2017) reported that bisdemethoxycurcumin is about 4 times more stable than curcumin and demethoxycurcumin when exposed to sunlight. In our experiment the degradation of total curcuminoids content after drying was less than 8%. In addition, the degradation of curcumin was less than 12% which was much lower than degradation of pure curcumin observed in other studies (Kharat et al., 2017; Gordon et al., 2015). This might be because the structure of turmeric cell protects the loss of curcumin from thermal and light exposure.

5.3.4 Total Phenolic Content and Antioxidant Capacities

The DPPH, ABTS, FRAP, and TPC values of fresh turmeric rhizomes were in the ranges of 110.8 – 143.8 mg Trolox g^{-1} dry matter, 752.6 – 838.7 μM Trolox g^{-1} dry matter, 292.9 – 348.9 μM Trolox g^{-1} dry matter, and 34.9 – 53.4 mg GAE g^{-1} dry matter, respectively (Table 10).The presence of several phenolic compounds and curcuminoids might contribute to the antioxidant capacities of the turmeric mainly gallic acid, protocatechuic acid, p-hydroxybenzoic acid, vanillic acid, caffeic acid, p-coumeric acid, feruric acid, and sinapic acid (Chumroenphat et al., 2021). They are well known for their strong antioxidant activities (Jayaprakasha et al., 2006). It was found that antioxidant capacities were unchanged or slightly lower after the drying under all conditions (Table 10). However, the percentage changes of DPPH, ABTS, FRAP, and TPC between different drying conditions were not significantly different ($p > 0.05$). Even though, there were both increase and decrease of curcumionoids after drying under some conditions, changes of antioxidant capacities by these various methods were not significantly different. This might be explained by the fact that there are several classes of antioxidants in turmeric which might also contribute to the overall antioxidant capacities. Phenolic compounds found in turmeric are including gallic acid, curcumin, ferulic acid, epicatechin, catechin, cinnamic acid, protocatechuic acid, chlorogenic acid, coumarin, rutin, genistein, and coumarin (Chumroenphat et al., 2021; Yang et al., 2020). Changing in antioxidant capacities in dried product is not a simple phenomenon. Both decreasing and increasing of antioxidant capacities after drying have been often reported. Chumroenphat et al. (2021) reported the large decreases in TPC, DPPH, and FRAP in turmeric slices after sun drying while ABTS was significantly increased. Due to the differences in major and minor compositions of raw materials and drying conditions, several compounds may be changed into higher or lower antioxidant activity compounds during drying and therefore varying of antioxidant activities of the dried turmeric slices could be expected.

Table 10 Effects of drying temperatures and light exposure on total phenolic content and antioxidant capacities in dried turmeric.

Drying conditions		DPPH (mg Trolox g^{-1} dry matter)		ΔTEAC (%)^{ns}	ABTS (μM Trolox g^{-1} dry matter)		ΔTEAC (%)^{ns}	FRAP (μM Trolox g^{-1} dry matter)		ΔFRAP (%)^{ns}	TPC (mg GAE g^{-1} dry matter)		ΔTPC (%)^{ns}
Temp. (°C)	Light exposure	Fresh	Dried		Fresh	Dried		Fresh	Dried		Fresh	Dried	
40	No	131.7±28.1	125.8±26.9	-4.5	836.8±54.6^{a}	785.2±43.8^{b}	-6.2	317.0±35.2	316.0±35.6	-0.3	48.1±4.7	50.6±6.9	5.2
	Yes	130.6±16.8^{a}	117.3±17.1^{b}	-10.2	878.7±45.1^{a}	751.6±27.7^{b}	-14.5	348.0±65.3^{a}	307.7±46.8^{b}	-11.6	47.6±3.5	44.3.±5.4	-6.9
50	No	101.1±19.2	124.3±19.3	22.9	792.7±21.0^{a}	755.7±23.3^{b}	-4.7	311.8±36.9	303.9±46.6	-2.5	45.8±4.9	45.9±3.8	0.2
	Yes	128.6±23.6	122.5±19.8	-4.7	824.9±44.6^{a}	744.5±23.6^{b}	-9.7	323.1±46.7	304.3±31.5	-5.8	46.1±5.0	49.6±7.1	7.6
60	No	109.5±58.5	130.6±27.7	19.3	720.3±353.2	752.2±30.9	-9.5	336.4±52.8	321.7±30.2	-4.4	47.8±6.5	48.3±6.9	1.0
	Yes	138.4±16.6^{a}	124.8±22.0^{b}	-9.8	908.5±64.1^{a}	749.6±38.8^{b}	-17.5	344.9±77.2^{a}	306.2±58.1^{b}	-11.2	53.4±3.3^{a}	46.3±4.1^{b}	-13.3
70	No	143.8±27.2^{a}	132.9±24.3^{b}	-7.6	902.7±39.9^{a}	758.4±23.7^{b}	-16.0	344.4±65.4^{a}	337.4±72.4^{b}	-2.0	52.8±3.2	49.2±8.3	-6.8
	Yes	123.1±25.9	127.9±26.4	3.9	774.9±71.8	719.4±23.7	-7.2	299.7±29.8	319.7±49.5	6.7	36.6±12.0^{b}	42.1±9.3^{a}	15
80	No	128.1±20.9	125.3±22.7	-2.2	748.2±37.4	720.9±19.7	-3.6	293.0±60.8	307.9±52.0	5.1	39.2±7.0	42.3±8.9	7.9
	Yes	110.8±7.3	131.2±26.2	18.4	752.6±45.9	733.7±18.0	-2.5	292.9±77.0^{b}	323.8±58.1^{a}	10.5	34.9±4.3^{b}	45.1±8.5^{a}	29.2

Data are expressed as mean ± standard deviation (n = 2). Significant ($p \leq 0.05$) differences between fresh sample and dried product in each condition are denoted by different superscript letters.

5.4 Conclusion

In this study, the drying kinetics of turmeric slices under the controlled light, temperatures, specific humidity, and air velocity were determined for the first time. It was found that light affected the drying rate constant and the effective moisture diffusivity of turmeric slices by increasing the product temperature. Additionally, the curcuminoids contents were clearly susceptible to light while the color of the powder was insignificantly changed. The drying conditions did not significantly affect the percentage change of antioxidant capacities. In conclusion, the results suggested that turmeric can be dried at 70 °C while avoiding light exposure to accelerate the drying process without an adverse impact on color, curcuminoids contents, and antioxidant capacity. The knowledges obtained from this study can be used for improving a solar drying for commercial drying of turmeric and other curcuminoids containing plants.

5.5 Suggestion

Phenolic compounds profile should be studied for better understanding on phenolic compounds and antioxidant activities relationship.

CHAPTER 6

Degradation of Curcuminoids and Color in Dried Turmeric Slices as Affected by Drying Temperature with Light Exposure under Different Cover Materials*

Dried turmeric is used as a spice and traditional medicine. The common drying methods for turmeric (*Curcuma longa* L.) are sun drying and solar drying. In this study, turmeric slices with a thickness of 2 mm were dried at 40, 50, 60, and 70 °C in a laboratory hot-air dryer with a simulated solar radiation applied through transparent polycarbonate cover (UV impermeable) and PMMA cover (UV permeable). Air velocity and relative humidity of drying air were fixed at 1.0 m s^{-1} and 25 g H_2O kg^{-1} dry air, respectively. Light significantly increased the sample temperature under both covers. Page was the best model to predict the drying characteristics of turmeric slices. Drying rate correlated with the effective moisture diffusivity, which increased at higher temperature. The hue angle (*h*°) of turmeric was distinctly lower at 70 °C under both covers. The dried products were of intensive orange color. Curcumin, demethoxycurcumin, and total curcuminoids were affected by the cumulated thermal load (*CTL*). The lowest curcumin content was found at 40 °C under PMMA (highest *CTL*). The optimum drying condition was 70 °C under polycarbonate cover due to shorter drying time and better preservation of color and curcuminoids in the dried product.

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6.1 Introduction

Solar dryers are using solar radiation as an energy source for drying agricultural products in a simple construction and have been extensively implemented in tropical and subtropical regions due to their affordability and cost-effectiveness (Esper and Mühlbauer, 1998; Müller and Mühlbauer, 2012; Udomkun et al., 2020). Several types of solar dryers were developed to overcome drawbacks of direct sun drying, such as cabinet solar dryers (Prasad et al., 2006; Ssemwanga et al., 2020), solar tunnel dryers (Janjai et al., 2009; Kumar et al., 2014), and greenhouse solar dryers (Janjai et al., 2007; Nabnean and Nimnuan, 2020). These dryers provide temperatures higher than the ambient temperature which results in faster drying compared to open-air sun drying. One of the most important components of a solar dryer is the transparent cover material which traps solar radiation and induces the greenhouse effect inside the solar dryer (Janjai et al., 2007).

Various types of cover materials such as polyethylene, glass, polycarbonate, and poly(methyl methacrylate) sheets have been used for solar dryers (Condorí et al., 2001; Elkhadraoui et al., 2015; Serm Janjai et al., 2011; Rodríguez-Ramírez et al., 2021; Singh and Kumar, 2012). Polyethylene is a widely used cover material for greenhouse dryers (Rodríguez-Ramírez et al., 2021). Although it is made of UV stabilized plastic, it lasts for only 3 to 4 months under strong UV radiation in tropical regions (Janjai and Keawprasert, 2006). Clear glass transmits up to 90% of visible light and 72% of UV radiation (Serrano and Moreno, 2020), but its weak points are heavy weight and low shatter resistance. Polycarbonate has been used frequently because of its high resistance to impact (Serrano and Moreno, 2020) and effective UV radiation blocking (Rodríguez-Ramírez et al., 2021). The drying air temperature in a polycarbonate-covered greenhouse dryer reaches up to 65 °C in an environment with an ambient temperature of 35 °C (Janjai, 2012). Poly(methyl methacrylate), also known as PMMA or plexiglass, transmits both UV and visible radiation with a transmittance up to 92%. Both polycarbonate and PMMA can be used for many years. Cover materials influence the drying temperature and solar radiation inside the drying chamber, which may compromise the quality attributes and nutritional compositions of dried products (Devan et al., 2020; Mohammed et al., 2020).

Turmeric (*Curcuma longa* L.) is in the ginger family. The benefits of turmeric rhizomes are more than being used as a condiment, spice, coloring agent, or flavor boost because it is rich in curcuminoids (curcumin, demethoxycurcumin, and bisdemethoxycurcumin) and medicinal compounds (Nelson et al., 2017). Curcuminoids, orange-yellow pigments, are the most biologically active compounds in turmeric which make up 2 - 6% of the rhizome's dry mass (Sandur et al., 2007). The basic structures of curcuminoids are diarylheptanoid links between two aromatic rings (Suksamrarn et al., 2008) and exhibit keto-enol tautomerism (Mondal et al., 2016).

Light promotes the degradation of curcumin (Lee et al., 2013; Tønnensen et al., 1986). The chromophore group of curcumin absorbs strongly the visible light spectrum, making it susceptible to photochemical degradation which yields vanillin, vanillic acid, 4-vinylguaiacol, ferulic acid, and ferulic aldehyde (Heger et al., 2014). The degradation causes fading of yellow color of curcumin (Lee et al., 2013). Curcumin in turmeric rhizomes is reduced by direct and indirect solar radiation. Raza et al. (2018) reported lower curcumin contents of dried rhizomes from sun drying and solar tunnel drying than that from shade drying. Mahayothee et al. (2020) also reported that drying in a solar greenhouse dryer covered with polycarbonate sheet reduced curcumin contents in cassumunar ginger.

However, the study of cover materials on bioactive compounds of dried products is still limited. The main objective of this study was to investigate the effect of solar radiation exposure under two cover materials, one UV permeable and one UV impermeable, and different drying temperatures on drying characteristics, color, and curcuminoids contents of dried turmeric slices using a hot air dryer. Simulated solar radiation was employed to obtain consistent light intensity throughout the study, which is impossible in outdoor solar drying experiments.

6.2 Materials and Methods

6.2.1 Materials

Organic solvents used in the study were HPLC grade. Methanol (99.95%) and acetonitrile (99.9%) were from Geyer GmbH (Stuttgart, Germany) and abcr GmbH (Karlsruhe, Germany), respectively. Curcumin (purity ≥ 99.5%, CAS No. 458-37-7),

demethoxycurcumin (purity ≥ 98%, CAS No. 22608-11-3), and bisdemethoxycurcumin (purity ≥ 98%, CAS No. 33171-05-0) were purchased from Sigma-Aldrich Chemie GmbH (Taufkirchen, Germany).

6.2.2 Turmeric Rhizomes

Turmeric (*C. longa* L.) rhizomes at the maturity of nine months were harvested from a plantation in Surat Thani province, Thailand. Rhizomes of uniform size, diameter (1.36 ± 0.18 cm) and weight (13.76 ± 3.70 g) were selected. Soil was brushed off the rhizomes before being packed in net bags. Thirty kilograms of the clean rhizomes were sent to the laboratory at the Institute of Agricultural Engineering, University of Hohenheim, and then kept in a refrigerator (Profiline GKv 6410-20, Liebherr, Biberach, Germany) at a temperature of 11.0 ± 0.4 °C and relative humidity of 90.7 ± 11.6%. The initial moisture content of the fresh rhizomes was 84.42 ± 0.70% (wet basis, w.b.). The stored rhizomes were washed under running tap water and allowed to drain at room temperature prior to drying experiments.

6.2.3 Simulated Light Exposure during Drying Experiments

6.2.3.1 Experimental Set Up

Drying experiments were conducted at 40, 50, 60, and 70 °C using the over- and under-flow chamber of a laboratory-made hot air dryer with precise controls for temperature and relative humidity. A detailed description of the drying system can be found in Argyropoulos et al. (2011).The air velocity was fixed at 0.5 m s^{-1} using a centrifugal blower. Specific humidity of the drying air was adjusted to 25 g water kg^{-1} air using a Raschig rings packed bed humidifier. Corresponding relative humidity 40, 50, 60, and 70 °C was 50.8, 30.4, 18.8, and 12.0%, respectively. To evaluate the effect of light exposure during the drying experiments, a solar light generator was installed above the drying chamber (Figure 35). Four solar simulation units (SOL 500, Dr. Hönle AG, Starnberg, Germany) were used to simulate natural sunlight emitting at wavelengths of 280 – 2750 nm. Each unit has a supply voltage of 230 V/50 Hz and maximum power consumption of 430 W. The distance between the light bulbs and slice samples was fixed at 40 cm.

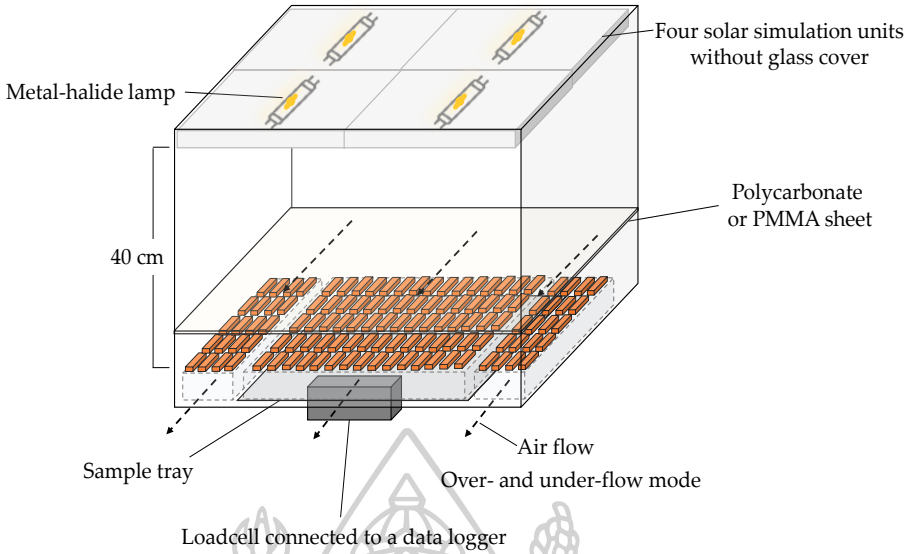

Figure 35 Depiction of the drying chamber and simulated solar light applied through the cover materials.

A 6 mm thick transparent double wall polycarbonate sheet with UV protection was used as UV impermeable transparent cover (Twinlite® Gen 2.0, PT Impack Pratama Industri Tbk, Jakarta, Indonesia). According to manufacturer's specification, transmittance is starting above a wavelength of 390 nm and the shortwave and longwave transmittance are 87 and 60%, respectively.

A 3 mm thick transparent PMMA sheet with high resistance to UV light was used as UV permeable transparent cover (Plexiglas® GS clear 2548, Röhm GmbH, Darmstadt, Germany). According to manufacturer's specification transmittance is starting above a wavelength of 250 nm and shortwave radiation transmittance is in the range of 90 – 92%. Either the polycarbonate or PMMA sheet was used to cover the drying chamber (Figure 35)

Prior to experiments, the dryer and light generator were warmed up to the required condition for an hour. Solar radiation above sample surfaces was measured using a solar radiation sensor with spectral range of 360 – 1120 nm (SRS-200, Pace Scientific, Mooresville, NC, USA). Photon flux density under the polycarbonate and PMMA sheets was 1325 ± 125 μmol m^{-2} s^{-1} and 1557 ± 177 μmol m^{-2} s^{-1}, respectively. UV radiation was measured using a UV radiometer with spectral range of 250 – 400 nm (SUVAB, GEOVES, Conegliano, Italy). The UV radiation under the polycarbonate

and PMMA sheets were in the ranges of 0.6 – 0.9 W m^{-2} and 100 – 147 W m^{-2}, respectively.

6.2.3.2 Drying Experiment

The rhizomes were sliced using an adjustable hand slicer (mean thickness of 2.16 ± 0.28 mm). The slices were cut to a size of 10 mm × 40 mm using a handmade cutter. The samples (240 pieces, *ca.* 200 g) were placed on a perforated aluminum main tray in a single layer. Additional 100 pieces were placed on two side trays to create a homogeneous airflow in the drying chamber. The product temperature was measured by inserting thin mantle thermocouples in two pieces when the samples were placed in the drying chamber. The product temperature was recorded during the process as well. The main tray was automatically weighed every 15 min using a load cell (Flintec, type 123 PC6, Västerås, Sweden) over the course of drying at 40 and 50 °C and every 10 min at 60 and 70 °C. Once the product mass approached a constant value, samples from the side trays were randomly taken to measure the water activity (a_w) using a water activity meter (HP23 AW-A, Rotronic, Bassersdorf, Switzerland) in order to confirm that the a_w value of the product has reached 0.360, which corresponds to moisture content of the FAO recommendation (FAO, 2004). The dried product was kept in a jar for 24 h to reach equilibrium prior to chemical analysis. Initial and final moisture contents were determined using a vacuum dryer (VT 6060 P, Thermo Scientific, Waltham, MA, USA) at 50 °C and 2 kPa for 12 h. The drying experiment was performed in duplicate.

6.2.4 Evaluation of Drying Characteristics

Moisture contents at different times on wet basis and dry basis were calculated. The initial mass was obtained by measuring the mass of turmeric slices before drying. Dry solid mass of the sample was calculated from final moisture content of dried products.

The drying rate (*DR*) (g water g^{-1} dry solid h^{-1} m^{-2}) was then calculated using Eq. (6.1):

$$DR = \frac{\Delta M_{db}}{\Delta t \cdot A} = \frac{M_{1,db} - M_{2,db}}{t_2 - t_1} \cdot \frac{1}{A} \quad (6.1)$$

where $M_{1,db}$ and $M_{2,db}$ are moisture contents (g water g^{-1} dry solid) at times t_1 and t_2 (h), respectively and A is surface area (m^2).

The moisture ratio (MR) of turmeric slices during the drying experiment was calculated using Eq. (6.2):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (6.2)$$

where M_0 and M_t are the initial moisture content and the moisture content at a specific time (g water g^{-1} dry solid), respectively. The equilibrium moisture content (M_{eq}) was defined as the final moisture content (g water g^{-1} dry solid) for each drying condition.

Effective moisture diffusivity (D_{eff}) is used to describe drying characteristics of foodstuffs by the diffusion phenomenon. Due to the slab shape of the sliced turmeric, Fick's second law was used to determine D_{eff} by Eq. (6.3) (Crank, 1975):

$$MR = \frac{8}{\pi^2} \cdot \exp\left(\frac{-\pi^2 \cdot D_{eff} \cdot t}{4 \cdot h^2}\right) \quad (6.3)$$

where D_{eff} is the effective moisture diffusivity ($mm^2\ h^{-1}$) and h is the half thickness of the slab (mm). Eq. (6.3) can be written in a logarithmic form as Eq. (6.4) (Crank, 1975):

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 \cdot D_{eff}}{4 \cdot h^2} \cdot t \quad (6.4)$$

The slope value was obtained from the plot of ln MR versus time t (Eq. (6.4)). D_{eff} was calculated using Eq. (6.5):

$$D_{eff} = \text{slope} \cdot \frac{-4 \cdot h^2}{\pi^2} \quad (6.5)$$

Activation energy (E_a) was estimated to describe the relation between the D_{eff} and temperature by an Arrhenius-type equation as shown in Eq. (6.6) (Özdemir and Onur Devres, 1999):

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad (6.6)$$

where D_0 is the pre-exponential factor ($mm^2\ h^{-1}$), E_a is the activation energy for the moisture diffusion (kJ mol^{-1}), R is the ideal gas constant (kJ mol^{-1} K), and T is the drying temperature (K). Eq. (6.6) can be written in a logarithmic form as Eq. (6.7):

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \quad (6.7)$$

E_a was obtained from the plot of ln D_{eff} versus 1/T. The slope of the fitted straight line is -E_a/R.

6.2.5 Thin Layer Drying Models

Thin-layer drying equation is important for drying kinetics analysis. It gives some understanding of the water transportation process during drying. *MR* from experimental data were fitted with various thin-layer drying models. The Lewis model (Eq. (6.8)) is derived from Newton's law of cooling (Lewis, 1921):

$$MR = \exp(-k \cdot t) \quad (6.8)$$

where k is the drying constant (h^{-1}) and t is the drying time (h).

Page model (Page, 1949) (Eq. (6.9)) and Modified Page model (Overhults et al., 1973) (Eq. (6.10)) were modified from Lewis to obtain more accuracy by adding a parameter n as a power of t and of *(-kt)*, respectively:

$$MR = \exp(-k \cdot t^n) \quad (6.9)$$

$$MR = \exp(-k \cdot t)^n \quad (6.10)$$

Henderson and Pabis model (Eq. (6.11)) was derived from the model of Fick's second law of diffusion by adding a shape parameter a. The Logarithmic model (Eq. (6.12)) was modified from Henderson and Pabis model with a parameter b (Overhults et al., 1973).

$$MR = a \cdot \exp(-k \cdot t) \quad (6.11)$$

$$MR = a \cdot \exp(-k \cdot t) + b \quad (6.12)$$

Midilli and Kucuk model (Midilli and Kucuk, 2003) (Eq. (6.13)) was obtained by adding both a parameter n as a power of t and another term with a parameter b (h^{-1}) multiplied with t to the Henderson and Pabis model:

$$MR = a \cdot \exp(-k \cdot t^n) + b \cdot t \quad (6.13)$$

The models were evaluated by the coefficient of determination (R^2), the root mean square error (*RMSE*), and the Akaike information criterion (*AIC*) (Akaike, 1974) as given in Eq. (6.14) – (6.16). High R^2, low *RMSE* and *AIC* are preferable.

$$R^2 = \frac{Residual\ sum\ of\ square}{Total\ sum\ of\ square} \quad (6.14)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{i,exp} - MR_{i,pre}\right)^2}{n}} \quad (6.15)$$

$$AIC = -2 \cdot \ln(L) + 2 \cdot k \quad (6.16)$$

where MR_{exp} is the experimental moisture ratio, MR_{pre} is the moisture ratio predicted by the thin layer models, n is the number of observations, L is the maximum value of the likelihood for the model, and k is the number of parameters of the model. All models were fitted using a non-linear regression analysis in R version 3.5.1 (R Development Core Team, 2008). To evaluate the effect of time and temperature during the drying process, the thermal energy received by the sample was estimated using the cumulated thermal load (CTL, K h) according to Jödicke et al. (2020) (Eq. (6.17)):

$$CTL = \sum_{n=0} \frac{(T_n - T_o) + (T_{n+1} - T_o)}{2} \cdot (t_{n+1} - t_n) \quad (6.17)$$

where T_n is the product temperature (K) at measurement event n, T_0 is the initial product temperature (33.8 °C), and t_n is the drying time (h) at measurement event n.

6.2.6 Color Measurement

Chroma meter (CR-400, Minolta, Tokyo, Japan) was used to measure the color of fresh turmeric in the CIE L^* a^* b^* color space for each drying condition from 30 fresh turmeric slices (2 positions per piece). The dried sample was ground into powder using a knife mill (Grindomix GM 200, Retsch, Haan, Germany) at 10,000 min^{-1} for 30 s. The process was paused for an interval time of 10 s after each 10 s of grinding. The ground powder was passed through a sieve No. 35 (pore size 500 μm). The sample was filled in a CR-A50 granular material attachment before color measurements. Five replications were measured. Chroma (C^*), hue angle ($h°$), and total color change (ΔE) were calculated using Eq. (6.18) – (6.20), respectively:

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (6.18)$$

$$h^* = tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (6.19)$$

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (6.20)$$

where Δ refers to difference of each parameter between fresh turmeric and turmeric powder.

6.2.7 Methanolic Extraction

Three grams of mashed fresh turmeric or 1.5 g of powder was extracted in 20 mL of methanol using an ultrasonic bath (Transsonic T-780/h, Elma, Stuttgart, Germany) for 30 min. The water temperature was controlled to be lower than 35 °C. The mixture was centrifuged at 11,530 × *g* for 15 min at 4 °C (Z326K, Hermle, Gosheim, Germany). The supernatant was collected in a 100 mL volumetric flask and the residue was re-extracted another two times with 20 mL of methanol each. The pooled supernatant was adjusted to 100 mL with methanol and then filtered through a 0.45 µm nylon syringe filter before the analysis. The extractions were performed in triplicate.

6.2.8 Chromatographic Analysis of Curcuminoids

The curcumin, demethoxycurcumin, and bisdemethoxycurcumin contents were immediately determined using a Shimadzu HPLC system (Kyoto, Japan) consisting of a 2IL-20AC HT autosampler, DGU-20A5R degasser, LC-20AT pump, SPD-M20A diode array detector, and CTO-20A column heater. Chromatographic separation was conducted using a Luna C18 column (250 × 4.6 mm i.d.; 5 µm; Phenomenex, Torrance, CA, USA) operated at 30 ◦C. The autosampler temperature was 4 °C. The mobile phases A and B were acetonitrile and 1% acetic acid solution, respectively. The gradient mode elution was carried out as follows: a linear decrease from 60 to 50% B in 30 min, 50 to 35% B in 5 min, 35 to 30% B in 5 min and maintained at 30% for 8 min, 30–0% B in 3 min, and 0–60% B in 7 min at a flow rate of 1.0 mL min^{-1}. The injection volume was 10 µL. Curcuminoid peaks were monitored at 425 nm. Standard curcumin, demethoxycurcumin, and bisdemethoxycur- cumin in methanol at concentration range of 1.0–75.0 mg L^{-1} were used for preparation of standard curves. The contents of each component were calculated in mg g^{-1} dry solid. Total curcuminoids content was the sum of the contents of curcumin, demethoxycurcumin, and bisdemethoxycurcumin.

6.2.9 Statistical Analysis

Analysis of variance (ANOVA) and Duncan's multiple range test were performed to evaluate the difference of each response variable. The results were

assessed at a probability level of 0.05. Statistical analysis was performed using SPSS Statistics 17.0 (IBM, Chicago, IL, USA).

6.3 Results and Discussion

6.3.1 Drying Characteristics

Turmeric slices with an initial moisture content of 84.24 ± 0.70% (w.b.) were dried to final moisture content and water activity in the ranges of 6.23–8.54% (w.b.) and 0.331–0.365 (Table 11) which were in accordance with the requirements for dried turmeric (FAO, 2004).

The drying curves at 40, 50, 60, and 70 °C for both polycarbonate and PMMA covers are presented in Figure 36. *MR* reduced rapidly at the beginning of the drying process and the highest drying rates were also observed in this period (Figure 37).

Table 11 Drying time, final moisture content (*MC*), and water activity (a_w) of dried products, and cumulated thermal load (*CTL*) during drying at various drying conditions.

Temperature (°C)	Drying time (h)	Cover materials	*MC* (% w.b.)^{ns}	$a_w{}^{ns}$	*CTL* (K h)
40	14.22 h	Polycarbonate	8.06 ± 1.84	0.331 ± 0.029	219.25 ± 5.21^{b}
		PMMA	8.54 ± 0.40	0.365 ± 0.013	233.89 ± 10.51^{a}
50	7.50 h	Polycarbonate	7.30 ± 1.23	0.363 ± 0.016	158.13 ± 7.92^{d}
		PMMA	6.53 ± 1.24	0.350 ± 0.047	173.20 ± 4.00^{c}
60	4.75 h	Polycarbonate	7.08 ± 0.81	0.331 ± 0.017	136.68 ± 1.65^{e}
		PMMA	7.13 ± 1.47	0.347 ± 0.019	140.33 ± 1.17^{e}
70	3.17 h	Polycarbonate	6.23 ± 0.94	0.336 ± 0.004	107.71 ± 1.56^{f}
		PMMA	6.51 ± 0.18	0.334 ± 0.021	110.23 ± 1.21^{f}

Values are given as the mean ± standard deviation. Different superscript letters in columns indicate significant differences ($p \leq 0.05$). ns: not significant.

The MR reduction was, on a small scale, faster under the polycarbonate cover due to the slightly higher product temperatures (Figure 38). The drying time required to reach the constant moisture content was shorter at higher temperatures (Table 11). It ranged between 3.17 h (at 70 °C) and 14.22 h (at 40 °C). The *CTL* values show the amount of heat assimilated by the samples throughout the drying process (Table 11). Because *CTL* reflects the combined effect of time and temperature, longer drying times can result in higher *CTL* values even at lower drying temperatures. At 40 and 50°C, drying under PMMA cover showed higher *CTL* values than polycarbonate cover corresponding to higher product temperatures (Figure 38). However, cover materials did not significantly affect the *CTL* values at 60 and 70 °C. The lowest *CTL* values were found at 70°C.

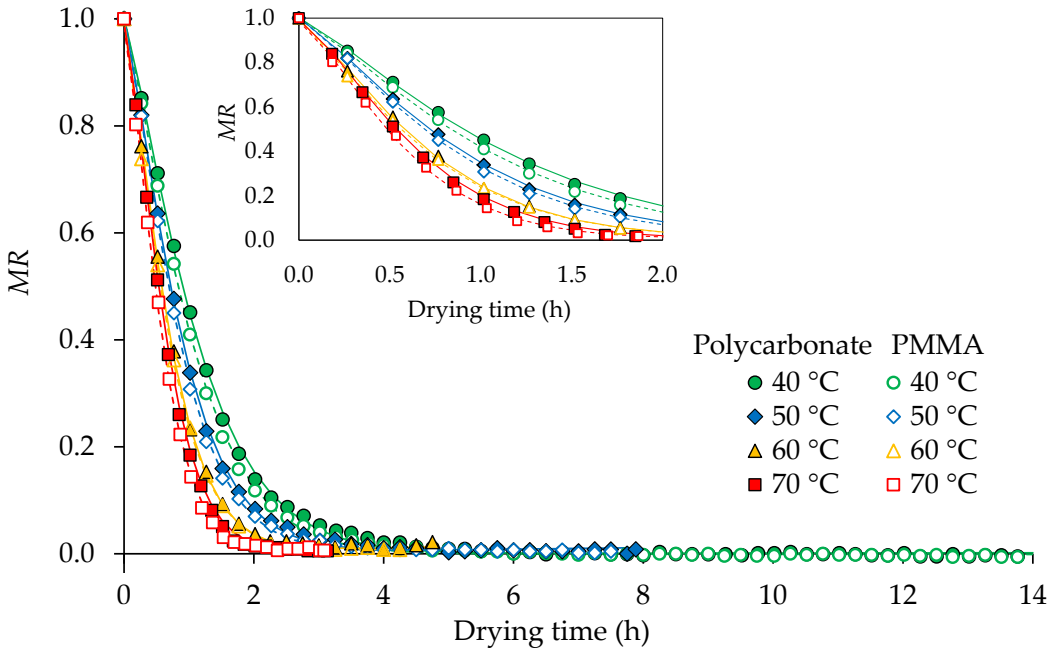

Figure 36 Drying curves of turmeric slices as affected by temperature and different cover materials. The lines show the predicted moisture ratio (*MR*) from the Page model using generalized *k* values from Eq. (6.21) and (6.22).

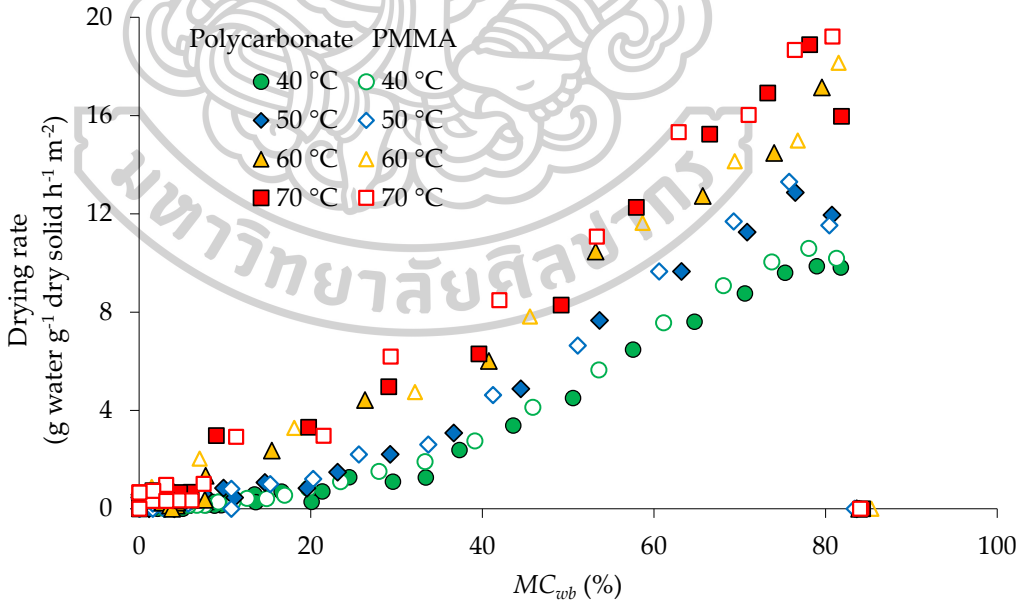

Figure 37 Drying rate of turmeric slices as affected by temperature and different cover materials. MC_{wb}: Moisture content (wet basis).

Figure 38 shows average temperatures inside the product during drying. The initial temperature of fresh turmeric slices was 33.8 °C. At the beginning of the drying process, the product temperatures were lower than the drying air temperatures and rose rapidly due to heat transfer from the hot air to the samples. The drying rate increased swiftly to its maximum value as the product temperature increased (Figure 38). The initial moisture content of fresh turmeric slices was reduced from approximately 84% to 81% (w.b.) within 15 min at 40 and 50 ◦C and 10 min at 60 and 70 °C for both covers. This phase is known as the warm-up period. Drying at higher temperatures led to a shorter warm-up period. The rates of drying were higher at higher temperatures, which were caused by the higher energy available to vaporize free water off the turmeric surfaces. The falling-rate period started when the moisture content of the samples reached a critical moisture content of approximately 80% (w.b.) (Figure 37). In this period, the free surface water was insufficient for continuous evaporation, resulting in case hardening and shrinkage of the sample surface. This also led to an increase in surface temperature and a decrease in mass transfer driving force. Figure 38 indicates that the product temperatures rose to the set drying air temperatures in an hour and exceeded these by approximately 10 °C within 3 h for both cover materials. This temperature difference could be explained by the absorption of solar radiation by the samples which was converted into thermal energy. After 3 h of drying, the product temperature under the PMMA cover was slightly higher (≈1 °C) than under the polycarbonate cover. This can be attributed to the higher light transmittance of the PMMA cover compared to polycarbonate.

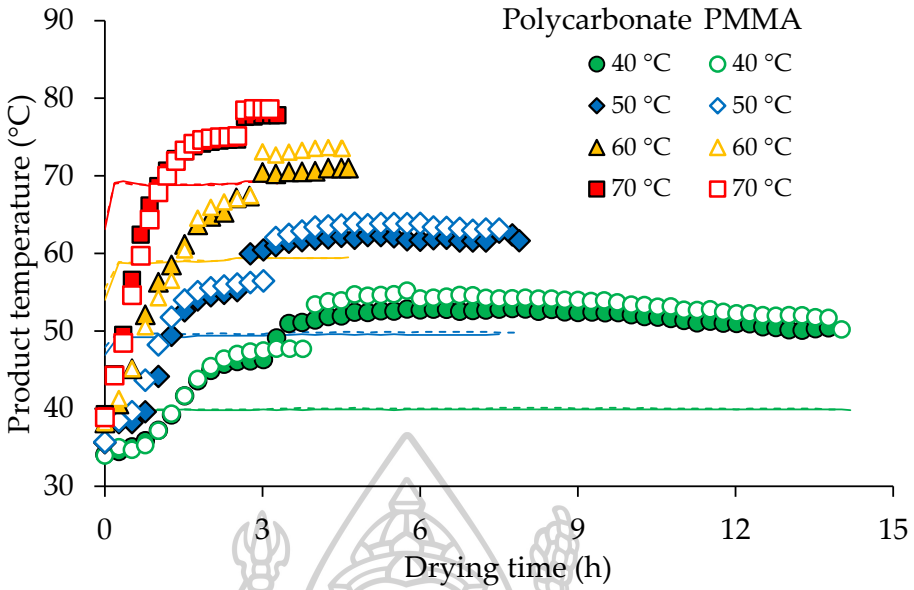

Figure 38 Product temperature under polycarbonate and PMMA cover; lines and dotted lines show the drying air temperature in the drying chamber under polycarbonate and PMMA cover, respectively.

The thin layer models (Lewis, Page, Modified Page, Henderson and Pabis, and Midilli and Kucuk) were fitted to the MR from the initial time to the beginning of constant weight (at 5.00, 4.00, 2.75, 2.00 and 4.75, 3.75, 2.50, 2.00 h for 40, 50, 60, and 70 °C under polycarbonate and PMMA covers, respectively) to avoid errors from long constant weight data in parameter modeling.

Table 12 Drying constants and statistical results for drying of turmeric slices at different conditions.

Temperature (°C)	Cover materials	Newton				Page					Modified Page				
		k	R^2	*RMSE*	*AIC*	*k*	*n*	R^2	*RMSE*	*AIC*	*k*	*n*	R^2	*RMSE*	*AIC*
40	Polycarbonate	0.8547	0.9899	0.0295	-84.34	0.7930	1.2225	0.9986	0.0110	-123.82	0.8272	1.2225	0.9986	0.0110	-123.82
	PMMA	0.9344	0.9888	0.0306	-83.90	0.8778	1.2462	0.9987	0.0080	-130.62	0.9007	1.2462	0.9987	0.0080	-130.62
50	Polycarbonate	1.0205	0.9888	0.0320	-64.80	0.9823	1.2446	0.9987	0.0108	-101.84	0.9858	1.2446	0.9987	0.0108	-101.84
	PMMA	1.1373	0.9882	0.0331	-59.70	1.1218	1.2423	0.9992	0.0086	-100.88	1.0948	1.2679	0.9992	0.0086	-100.88
60	Polycarbonate	1.3935	0.9884	0.0340	-43.50	1.4431	1.2703	0.9996	0.0065	-80.88	1.3473	1.2703	0.9996	0.0065	-80.88
	PMMA	1.4653	0.9885	0.0343	-38.58	1.5248	1.2545	0.9990	0.0103	-63.46	1.3998	1.2545	0.9990	0.0103	-63.46
70	Polycarbonate	1.5337	0.9788	0.0468	-41.98	1.6728	1.3594	0.9997	0.0054	-100.26	1.4601	1.3593	0.9997	0.0054	-100.26
	PMMA	1.6571	0.9828	0.0413	-48.44	1.8220	1.3223	0.9988	0.0108	-81.18	1.5741	1.3223	0.9988	0.0108	-81.18

Temperature (°C)	Cover materials	Henderson and Pabis					Midilli and Kucuk						
		k	*a*	R^2	*RMSE*	*AIC*	*a*	*k*	*n*	*b*	R^2	*RMSE*	*AIC*
40	Polycarbonate	0.9002	1.0576	0.9931	0.0245	-90.14	0.9992	0.8021	1.2700	0.0037	0.9994	0.0074	-136.32
	PMMA	0.9842	1.0587	0.9921	0.0256	-78.74	0.9994	0.8874	1.2803	0.0030	0.9995	0.0049	-146.10
50	Polycarbonate	1.0731	1.0566	0.9920	0.0271	-68.48	1.0012	1.0076	1.2946	0.0051	0.9996	0.0060	-117.86
	PMMA	1.1946	1.0561	0.9914	0.0284	-62.60	1.0018	1.1488	1.3039	0.0042	0.9998	0.0045	-117.38
60	Polycarbonate	1.4463	1.0434	0.9905	0.0308	-43.10	0.9965	1.4594	1.2940	0.0026	0.9997	0.0057	-79.90
	PMMA	1.5122	1.0370	0.9901	0.0319	-38.96	0.9956	1.4715	1.2233	-0.0063	0.9994	0.0081	-64.80
70	Polycarbonate	1.6294	1.0706	0.9841	0.0405	-44.04	0.9968	1.6522	1.3542	-0.0021	0.9998	0.0050	-98.54
	PMMA	1.7370	1.0555	0.9861	0.0372	-43.48	0.9885	1.8189	1.3479	0.0007	0.9989	0.0103	-78.46

The Page, Modified Page, and Midilli and Kucuk models yielded the highest R^2, lowest *RMSE*, and *AIC* values, as shown in Table 12. Therefore, the Page model (Eq. (6.9)), which is simple and widely used, was considered to be the best model for drying turmeric slices. The modeling results showed that k increased significantly with drying temperature ($p \leq 0.05$). However, no significant differences of k between polycarbonate and PMMA covers were found. Therefore, it can be concluded that temperature has the largest impact on the drying rate. Temperature affects the drying rate by the acceleration of evaporation, diffusivity, and heat transfer during drying and the subsequent increase in water migration from inside the product to the drying air (Ibrahim and Zamfirescu, 2016).

The k values from the Page model changed with the drying temperature. They could be well described by the exponential equation with the high R^2 values. The generalized equations describing the k values as a function of drying temperature (TC, ◦C) for the drying under the polycarbonate and PMMA sheets are shown in Eq. (6.21) and (6.22).

Polycarbonate (R^2 = 0.9734): $k = 0.2766 \cdot \exp(0.0262 \cdot T)$ (6.21)

PMMA (R^2 = 0.9907): $k = 0.3256 \cdot \exp(0.0250 \cdot T)$ (6.22)

On the other hand, the n values at different drying temperatures were almost constant and the average values of 1.2742 and 1.2629 were obtained for polycarbonate and PMMA covers, respectively. The calculated k values from the generalized equations (Eq. (6.21) and (6.22)) and the average n values were used to predict changes in the moisture ratio during drying (Lines in Figure 36). It was found that the model could well explain the drying behavior of turmeric slices at different temperatures with a high R^2 (0.9187 – 0.9759) and low *RMSE* (0.0052 – 0.0176).

The moisture movement in the sample during the falling-rate period is described by molecular diffusion (Jayas et al., 1991). Figure 39(a) shows that the effective moisture diffusivity (D_{eff}) values of turmeric slices during drying significantly increased with the rising temperature ($p \leq 0.05$). D_{eff} was linearly proportional to the drying rate k (from the Page equation) with R^2 = 0.9898 (Figure 39(a) inset). The obtained D_{eff} values were 0.45, 0.54, 0.86, and 1.07 $\text{mm}^2\ \text{h}^{-1}$ at 40, 50, 60, and 70 °C, respectively for polycarbonate covering and 0.51, 0.61, 0.92, and 1.14 $\text{mm}^2\ \text{h}^{-1}$, respectively for PMMA covering. D_{eff} was obviously affected by drying temperature.

However, the statistical analysis showed a non-significant difference of D_{eff} between polycarbonate and PMMA covers at the same temperature. Figure 39(b) illustrates the effect of temperature under different cover materials by the Arrhenius-type relationship. Activation energies were 21.55 ± 2.75 kJ mol^{-1} for polycarbonate cover and 21.20 ± 1.72 kJ mol^{-1} for PMMA cover.

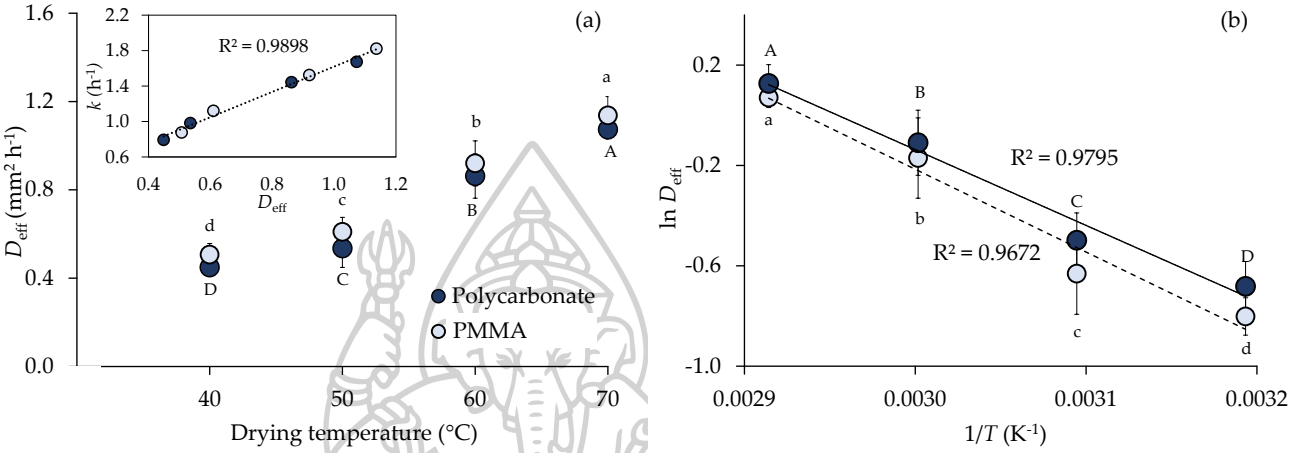

Figure 39 Effective moisture diffusivity (D_{eff}) of turmeric slices as affected by temperature and different cover materials (a) and Arrhenius relationship between ln D_{eff} and reciprocal temperature (1/T) (b). Different letters indicate significantly different (D_{eff}) at $p \leq 0.05$. Drying conditions are indicated by ● polycarbonate and ○ PMMA. k: drying rate.

6.3.2 Appearance and Color Measurement

Figure 40 shows appearances of fresh and dried turmeric slices obtained from various drying conditions. The fresh turmeric was of intense orange color. Drying temperatures and different covers affected the appearance of the dried products. For both covers, higher temperature resulted in less color fading on the surfaces due to shorter light exposure. The most brownish surfaces were found from polycarbonate cover at 40 and 50 °C and PMMA cover at 40 °C. The underside of the products at 50 and 60 °C under both covers was somewhat brighter than the exposed side. The dried product at 70 ◦C under polycarbonate cover showed the most intense orange on both sides, while the slices dried under PMMA cover at the same temperature were darker. This difference could be the effect of higher UV intensity under PMMA.

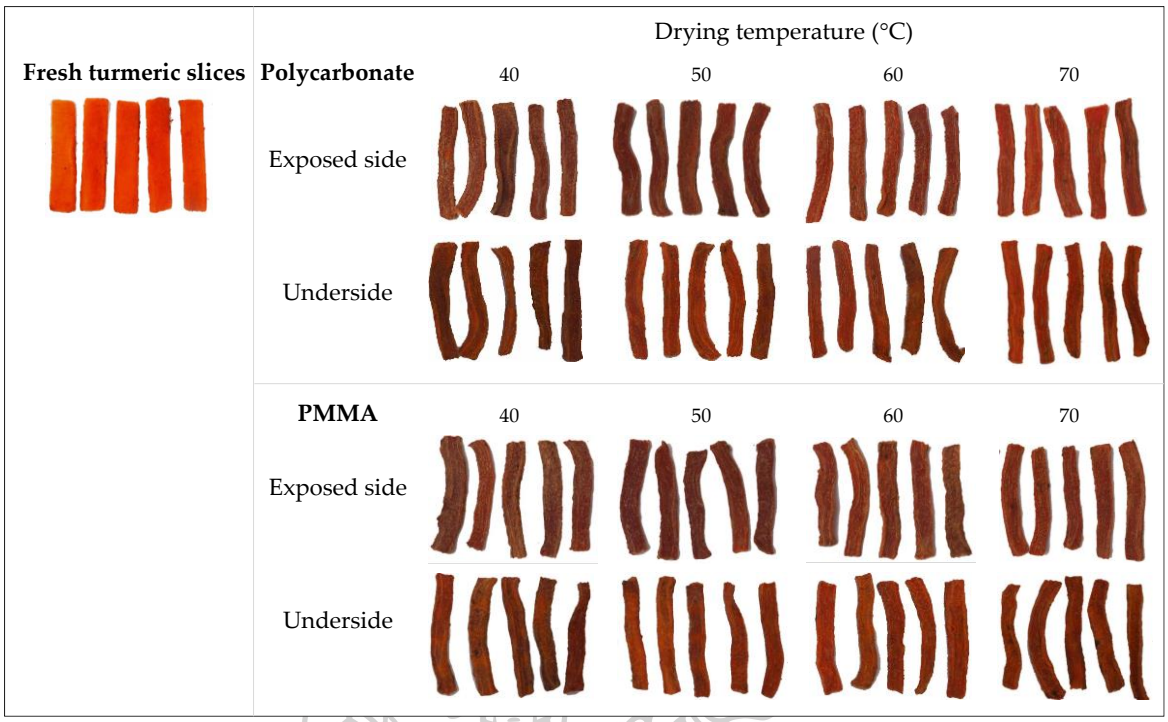

Figure 40 Appearance of fresh and dried turmeric slices on both exposure side and underside after drying under polycarbonate and PMMA covers, respectively.

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Table 13 Appearance and color values of the fresh sample and dried turmeric powder obtained from various drying conditions.

		Drying temperature (°C)							
		40		50		60		70	
Color values	Fresh sample	Polycarbonate	PMMA	Polycarbonate	PMMA	Polycarbonate	PMMA	Polycarbonate	PMMA
									
*L**	53.37 ± 0.46	54.59 ± 0.12^{a}	51.36 ± 2.86^{a}	54.09 ± 1.91^{a}	53.10 ± 0.16^{a}	54.24 ± 0.37^{a}	52.02 ± 4.37^{a}	49.67 ± 0.37^{b}	47.80 ± 1.08^{b}
*a**	38.34 ± 1.00	26.32 ± 0.76^{bcd}	25.85 ± 1.39^{cd}	27.99 ± 0.08^{abc}	27.37 ± 0.33^{abc}	28.46 ± 1.07^{ab}	26.46 ± 0.10^{abc}	28.63 ± 0.44^{a}	24.18 ± 1.55^{d}
*b**	47.47 ± 1.58	34.43 ± 0.04^{a}	28.59 ± 4.68^{ab}	34.41 ± 3.32^{a}	32.27 ± 0.08^{a}	34.29 ± 0.17^{a}	30.60 ± 5.59^{a}	26.99 ± 0.53^{ab}	22.94 ± 2.04^{b}
*C**	61.09 ± 1.51	43.34 ± 0.42^{a}	38.57 ± 4.40^{ab}	44.39 ± 2.52^{a}	42.32 ± 0.15^{a}	44.58 ± 0.56^{a}	40.54 ± 4.16^{a}	39.35 ± 0.64^{ab}	33.34 ± 2.48^{b}
h°	50.02 ± 1.04	52.61 ± 0.84^{a}	47.71 ± 3.15^{ab}	50.80 ± 2.79^{a}	49.70 ± 0.40^{a}	50.31 ± 1.20^{a}	48.87 ± 5.30^{ab}	43.31 ± 0.36^{b}	43.45 ± 1.07^{b}
Δ*E*	-	16.46 ± 2.96^{c}	22.86 ± 2.98^{abc}	16.56 ± 1.92^{c}	18.59 ± 2.09^{bc}	18.08 ± 0.03^{bc}	21.25 ± 4.47^{bc}	23.68 ± 2.50^{ab}	27.94 ± 1.01^{a}

Values are given as the mean ± standard deviation. Different superscript letters indicate significant differences ($p \leq 0.05$). Δ*E*: Total color change.

Table 13 shows the color values of turmeric powder from various conditions. Drying temperature and covers significantly affected a^* values of the powder ($p \leq 0.05$), which signifies the redness of turmeric flesh. The a^* value was lowest at 40 °C under polycarbonate and PMMA and at 70 °C under PMMA. This corresponded with the appearance of the dried products. Pal et al. (2020) showed that the a^* value was an important indicator of the quality of turmeric rhizomes. The L^*, b^*, and C^* values of the dried powder were lowest at 70 °C under both covers. The powder from these conditions was of dark orange color.

The lower b^* values indicated less yellowness in the powder dried at 70 °C under both covers and at 60 °C under PMMA. The $h°$ value of the turmeric powder was in the range of 43.31–52.61 (Table 13). It was found that drying at 70 °C under both covers resulted in the lowest h° value ($p \leq 0.05$), which represented the intensive orange color and corresponded with the appearance of the dried products. ΔE values describe the overall color difference between fresh turmeric and turmeric powder (Table 13). Drying at 70 °C under both covers resulted in the highest ΔE values ($p \leq 0.05$). PMMA slightly increased ΔE at the same temperature ($p > 0.05$). However, The ΔE values were not consistent with the reduction of curcuminoids in turmeric powder.

6.3.3 Degradation of Curcuminoids

The orange color of turmeric is due to the curcuminoid pigments. Fresh turmeric slices used in this study had a total curcuminoids content of 8.06 ± 0.11 g 100 g^{-1} fresh sample. Three curcuminoids were identified by HPLC-DAD as curcumin (64.75%), demethoxycurcumin (16.65%), and bisdemethoxycurcumin (18.60%). Wichitnithad et al. (2009) reported that the curcuminoids in most commercial turmeric extracts consisted of 60 – 80% curcumin, 15 – 30% demethoxycurcumin, and 2 – 6% bisdemethoxycurcumin. The curcumin, demethoxycurcumin, and bisdemethoxycurcumin contents of the fresh samples were in the ranges of 197.03 – 224.95, 51.31 – 56.71, and 57.09 – 64.13 mg g^{-1} dry solid, respectively (Table 14). HPLC chromatogram of curcuminoids in dried turmeric is shown in Figure 41.

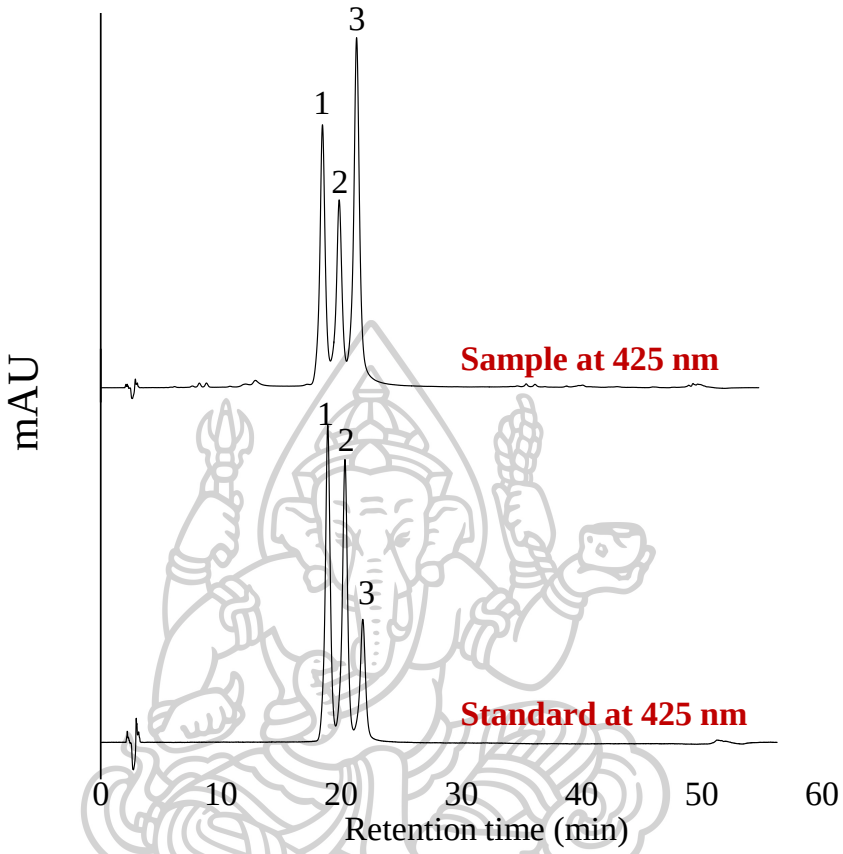


Figure 41 HPLC chromatogram of curcuminoids in standard curcumin and dried turmeric from drying at 40 °C, (1) bisdemethoxycurcumin (2) demethoxycurcumin (3) curcumin.

It was found that the drying process reduced curcumin, demethoxycurcumin, and total curcuminoids contents under all conditions, except at 70 °C under polycarbonate cover. Curcumin contents of the turmeric powder were in the range of 182.50 – 213.72 mg g^{-1} dry solid. The bisdemethoxycurcumin contents at 40 °C under polycarbonate and PMMA covers were not significantly different from the fresh sample. At 50, 60, and 70 °C the bisdemethoxycurcumin contents increased under both covers.

The ratios between each curcuminoid in turmeric powder and fresh turmeric are plotted against the logarithm of the cumulated thermal load (log *CTL*) values (Figure

42). In this study, the *CTL* value is used to explain the amount of heat assimilated by the samples throughout the drying process on degradation of curcuminoids at different drying temperatures. A ratio above unity indicates an increase in curcuminoids in the obtained turmeric powder compared to fresh turmeric, while a ratio lower than unity indicates the degradation of curcuminoids. All curcuminoids ratios rapidly decreased when the log *CTL* increased from 2.02 to 2.37 and then tended to gradually decrease afterwards (Figure 42). The highest degradation of all curcuminoids was found at 40 °C under PMMA. This is likely because of the long drying time and exposure to light (14.22 h). The results were in agreement with the study of Komonsing et al. (2022) which found that curcuminoids in turmeric slices were degraded by temperature and light under the long time drying, while the curcuminoids contents of the products obtained from drying in the dark were higher than those of the fresh sample. At 40 °C, the drying under polycarbonate cover, which can protect UV radiation, showed less degradation of curcuminoids. Few studies observed that the photodegradation of curcuminoids was strongly caused by exposure to UV radiation (Chumroenphat et al., 2021; Priyadarsini, 2009). Degradation of bisdemethoxycurcumin was found only at 40 °C under PMMA cover. This suggests higher stability of bisdemethoxycurcumin towards solar radiation compared to curcumin, which was the most sensitive, and demethoxycurcumin.

Table 14 Curcumin, demethoxycurcumin, and bisdemethoxycurcumin of turmeric slices obtained from various drying conditions.

Temperature (°C)	Cover materials	Curcumin (mg g^{-1} dry solid)		Demethoxycurcumin (mg g^{-1} dry solid)		Bisdemethoxycurcumin (mg g^{-1} dry solid)		Total curcuminoids content (mg g^{-1} dry solid)	
		Fresh	Dried	Fresh	Dried	Fresh	Dried	Fresh	Dried
40	Polycarbonate	197.03 ± 3.09^{a}	182.50 ± 3.67^{b}	51.31 ± 1.08^{a}	47.27 ± 0.48^{b}	57.09 ± 0.39^{a}	57.75 ± 0.03^{a}	305.44 ± 4.56^{a}	287.52 ± 4.12^{b}
	PMMA	211.97 ± 3.20^{a}	184.99 ± 2.89^{b}	54.67 ± 0.03^{a}	49.06 ± 0.71^{b}	62.56 ± 1.57^{a}	60.37 ± 1.61^{a}	329.03 ± 1.60^{a}	294.42 ± 0.58^{b}
50	Polycarbonate	217.13 ± 4.00^{a}	202.11 ± 3.92^{a}	56.48 ± 0.19^{a}	53.47 ± 1.16^{a}	62.25 ± 1.64^{a}	65.42 ± 2.34^{a}	335.86 ± 2.16^{a}	321.00 ± 7.42^{a}
	PMMA	206.10 ± 5.48^{a}	195.62 ± 6.44^{a}	53.13 ± 1.46^{a}	51.77 ± 2.64^{a}	59.41 ± 1.82^{a}	63.76 ± 4.64^{a}	318.64 ± 8.75^{a}	311.16 ± 13.72^{a}
60	Polycarbonate	224.95 ± 3.78^{a}	210.48 ± 0.66^{b}	56.71 ± 1.93^{a}	54.85 ± 0.25^{a}	64.13 ± 3.02^{a}	68.15 ± 1.51^{a}	345.79 ± 8.72^{a}	333.49 ± 2.24^{a}
	PMMA	202.76 ± 1.82^{a}	200.17 ± 3.45^{a}	52.98 ± 1.34^{a}	52.86 ± 1.33^{a}	57.76 ± 3.63^{a}	63.87 ± 3.81^{a}	313.50 ± 6.79^{a}	316.90 ± 8.59^{a}
70	Polycarbonate	200.22 ± 14.42^{a}	213.72 ± 2.84^{a}	52.09 ± 3.56^{a}	56.97 ± 1.00^{a}	59.44 ± 5.81^{a}	70.69 ± 2.17^{a}	311.75 ± 23.78^{a}	341.20 ± 0.33^{a}
	PMMA	216.86 ± 5.95^{a}	202.62 ± 1.88^{a}	55.83 ± 1.87^{a}	53.55 ± 2.24^{a}	63.28 ± 0.27^{a}	65.56 ± 3.46^{a}	335.96 ± 8.09^{a}	321.71 ± 7.59^{a}

Values are given as the mean ± standard deviation. Different superscript letters indicate significant differences between fresh and dried sample for each compound ($p \leq 0.05$).

Figure 42 also suggests that the type of cover material (polycarbonate or PMMA) did not significantly ($p > 0.05$) affect the curcuminoids ratio at 50 and 60 °C. However, a significant difference was found at 70 °C (lowest log *CTL*). Drying under PMMA led to the degradation of curcumin (0.93) and demethoxycurcumin (0.91) in the powder, which might be due to the combination of UV radiation and high temperature accelerating the degradation of these curcuminoids. By contrast, the powder from polycarbonate showed higher curcumin and demethoxycurcumin contents after drying. The increase in curcuminoids contents at 70 °C under polycarbonate might be due to the lowest log *CTL* together with the absence of UV radiation. Souza et al. (1997) found that the combination of light and hot air was more detrimental to curcumin than only one of both factors. Lee et al. (2013) reported that curcumin is decolorized when exposed to UV light. The structure of curcuminoids, which are chromophores, can absorb UV radiation, which results in auxochromes exhibiting brown color (Suyitno et al., 2018). UV induced about 50% of fading of the yellow color of curcumin solution within 8 h However, the photodegradation of curcuminoids has not been well elucidated. It is likely that curcumin acts as a photosensitizer and decomposes in the process (Tønnesen and Karlsen, 1985). The degraded products might be ferulic aldehyde, ferulic acid, 4- vinylguaiacol, vanillin, and vanillic acid. The result agreed with Rodríguez-Ramírez et al. (2021) who reported that cover materials (polycarbonate and polyethylene) influenced the drying temperature and UV radiation inside the solar drying chamber. They found that dried strawberries obtained from polyethylene cover (UV permeable) showed lower total phenolic contents due to higher temperature compared to polycarbonate (UV impermeable) cover. The degradation of anthocyanin contents was also lower in the absence of UV.

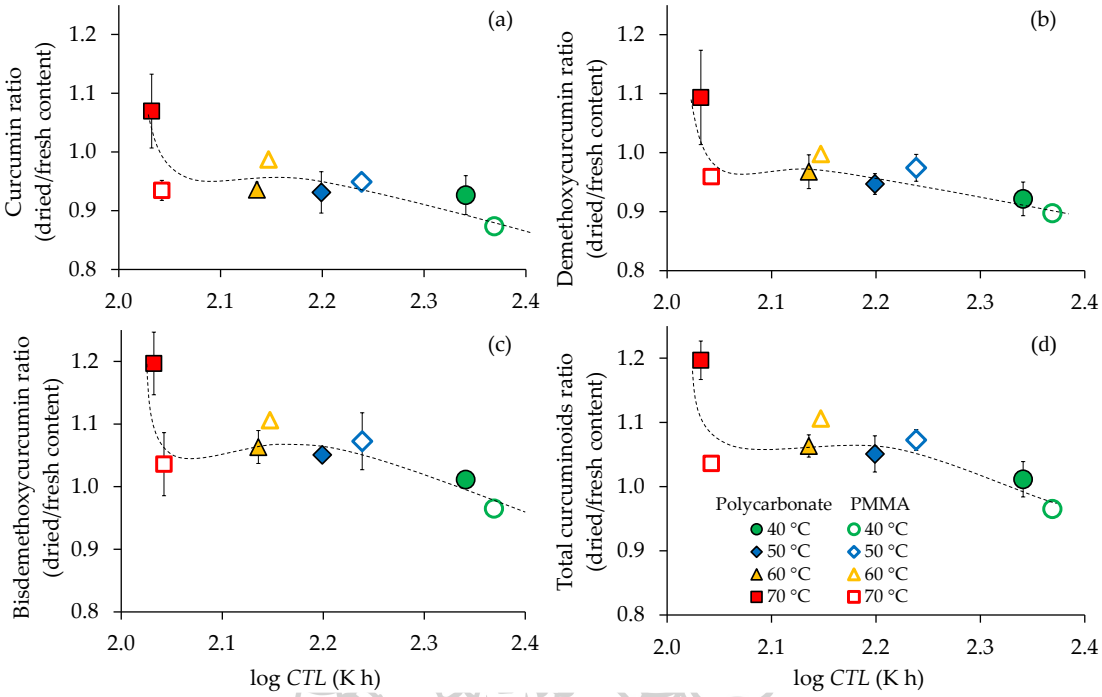


Figure 42 Degradation of curcuminoids in function of cumulated thermal load (*CTL*); (a) curcumin, (b) demethoxycurcumin, (c) bisdemethoxycurcumin, and (d) total curcuminoids.

6.4 Conclusions

This study was conducted to imitate solar drying under transparent polycarbonate cover (UV impermeable) and PMMA covers (UV permeable). Light increased product temperature, which increased in drying rates and effective moisture diffusivity. The combined time-temperature effect was presented as cumulated thermal load (*CTL*), which could be used to describe the degradation of curcuminoids. In addition, UV radiation transmitted through PMMA increased the degradation of curcuminoids. In conclusion, the best quality of dried products in terms of color and curcuminoids contents were achieved by drying at 70 °C under polycarbonate cover. Drying under these conditions resulted in shorter drying time without negative impact on curcuminoids contents. This knowledge can be applied for the optimization of the drying process for turmeric slices in a solar dryer.

6.5 Suggestion

Base on the results of the study, drying process of turmeric should be done in short time to reduce exposure time to solar radiation. However, there are still many aspects which should be investigated such as essential oils, phenolic compounds, and antioxidant capacities. Degradation products during light exposure should be also investigated.

CHAPTER 7

Summary

This thesis has contributed to the understanding of the influences of drying temperature, light, and cover material on the drying behavior and quality of dried turmeric.

Temperature affects the drying characteristics of turmeric slices. Turmeric slices are dried completely in the falling-rate period. Page model is the most suitable and simple model to describe the drying behavior of turmeric slices. Drying rate changes with the drying temperature and can be described well by an exponential equation. Drying at high temperature results in shorter drying time due to increased mass transfer of moisture from inside to the slice surface. The generalized Page model equations can be applied for prediction of drying rate and moisture content of turmeric slices during drying at different temperatures. Product dried at high temperature shows intensive yellow color. The most brownish surface is found after drying at low temperatures (40 and 50 °C) which may be caused by enzymatic browning reactions.

Light affects the drying rate constant and the effective moisture diffusivity of turmeric slices by increasing the product temperature due to absorption of infrared radiation. Color and curcuminoids of turmeric powder are susceptible to sunlight and higher sunlight intensity exhibits stronger effect on curcuminoids degradation. From the study, it can be seen clearly that light has more influence on curcuminoids than drying temperature.

The combination of light and drying temperature has impact on the drying behavior of turmeric slices. However, drying conditions do not significantly affect the percentage change of antioxidant capacities. Drying rate of turmeric slices under poly(methyl metacrylate) cover, also known as PMMA or plexiglass, is slightly higher than under polycarbonate cover due to higher light transmittance properties of PMMA. UV radiation transmitted through PMMA increases the degradation of curcuminoids. However, visible radiation also degrades curcuminoids. Drying at low temperature leads to high degradation of all curcuminoids due to long drying time and extensive

exposure to light. As a result, the following drying conditions for turmeric slices are recommendable:

- Drying should be conducted at a temperature as high as 70 °C to obtain the best quality of dried products in terms of color and curcuminoids contents.
- UV impermeable cover material such as polycarbonate reduces transmission of solar radiation, thus, leading to better preservation of curcuminoids.
- In order to reduce the surface area and the exposure of the product to solar radiation, the slices should not be too thin.

LIST OF PUBLICATIONS

Komonsing, N., Tholha, W., Boonrod, Y., Khuwijitjaru, P., Janjai, S., and Mahayothee, B. (2017). Effect of drying temperatures and drying methods on color of dried turmeric slices. Proceedings in The 44th National Graduate Research Conference "Graduate Research Driven Thailand 4.0", 19-20th October 2017. U-Place Hotel, Ubon Ratchathani, Thailand.

Komonsing, N., Khuwijitjaru, P., Sangjan, S., and Mahayothee, B. (2019). Effect of light on curcuminoids content in turmeric powder. Proceedings in 7th European Drying Conference (EuroDrying'2019), 10-12 th July 2019, Torino, Italy..

Komonsing, N., Khuwijitjaru, P., Nagle, M., Müller, J., and Mahayothee, M. (2022). Effect of drying temperature together with light on drying characteristics and bioactive compounds in turmeric slice. Journal of Food Engineering, 317, 110695. https://doi.org/10.1016/j.jfoodeng.2021.110695

Komonsing, N., Reyer, S., Khuwijitjaru, P., Mahayothee, B., and Müller, J. (2022). Drying behavior and curcuminoids changes in turmeric slices during drying under simulated solar radiation as influenced by different transparent cover materials. Foods, 11(5), 696. DOI: 10.3390/foods11050696

APPENDIX

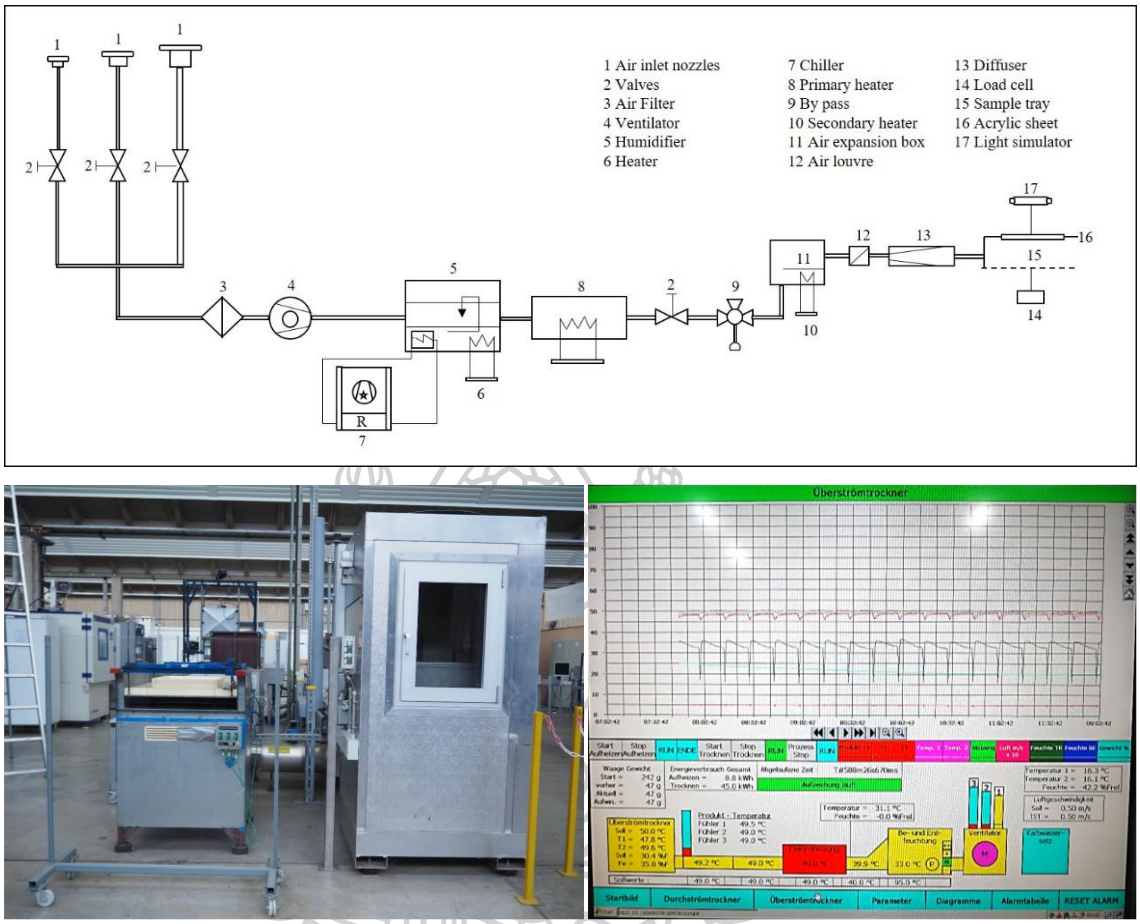


Figure A1 Schematic diagram of the laboratory-made hot air dryer, drying compartment, and controlling program used in the experiments.

Figure A2 Light hot air laboratory dryer hot air laboratory dryer.

In Chapter 5

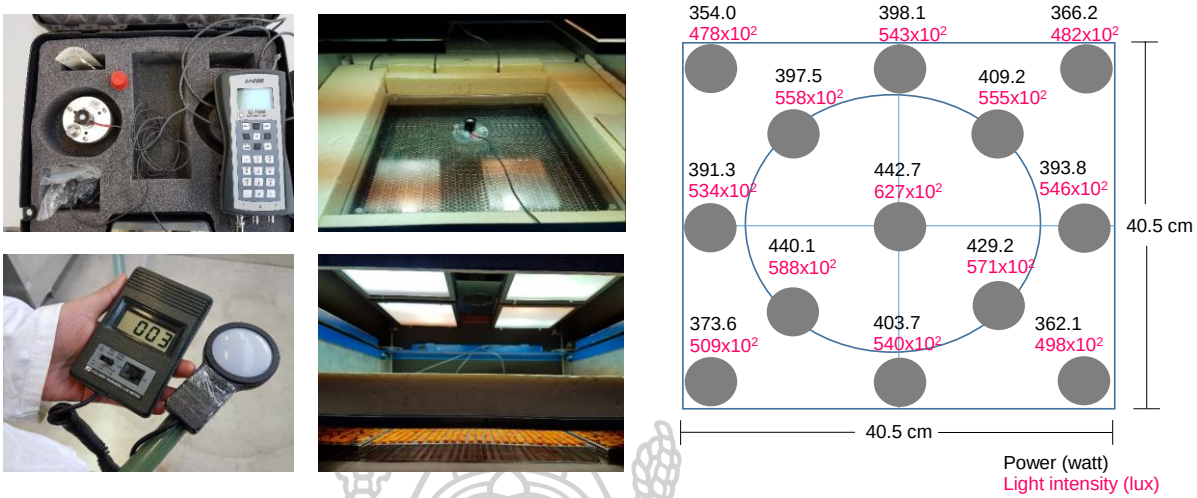


Figure A3 Measurement of light intensity in different position.

1. Determination of Total Phenolic Content (TPC)

Total phenolic contents (TPC) was determined using a Folin - Ciocalteu assay as described by Singleton and Rossi (1965) with a slight modification.

1.1 Chemical reagents

- 10% Folin and Ciocalteu's phenol reagent

Pipette 10 mL of Folin and Ciocalteu's phenol reagent into a 100 mL volumetric flask and adjust volume with distilled water.

- 7.5% (w/v) Na_2CO_3 solution

Dissolve 7.5 g Na_2CO_3 with distilled water and adjust volume to 100 mL in a volumetric flask.

- A stock standard gallic solution (1000 mg L^{-1})

Weight 0.1000 ± 0.0010 g gallic acid (record the certain weight). Dissolve in 60% methanol and adjust volume to 50 mL. Prepare Gallic standard at different concentration in 10 mL volumetric flask as shown in Table A1.

Table A1 Preparation of standard gallic acid.

Concentration (mg L^{-1})	Stock standard gallic acid solution (mL)
0	0
20	0.2
40	0.4
60	0.6
80	0.8
100	1.0

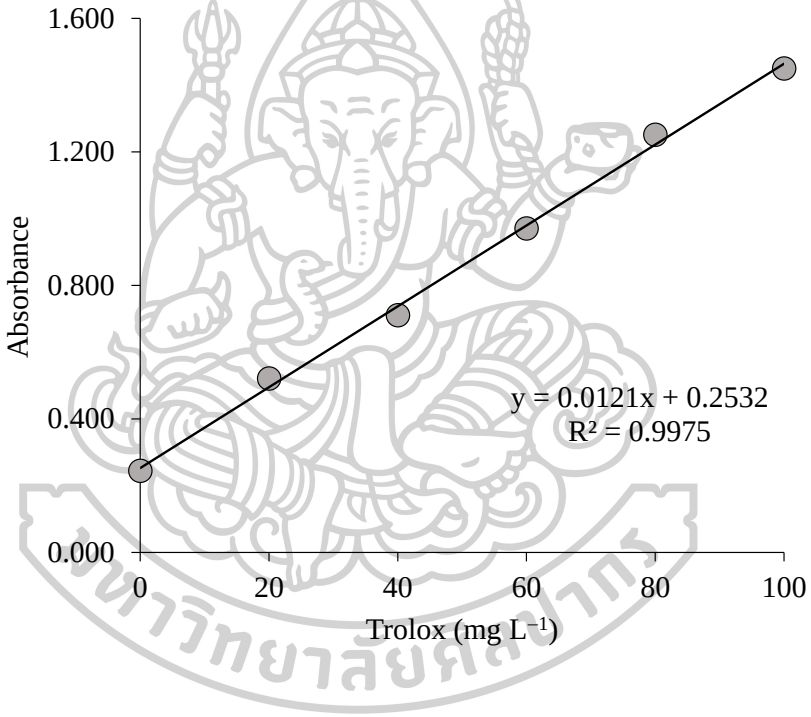
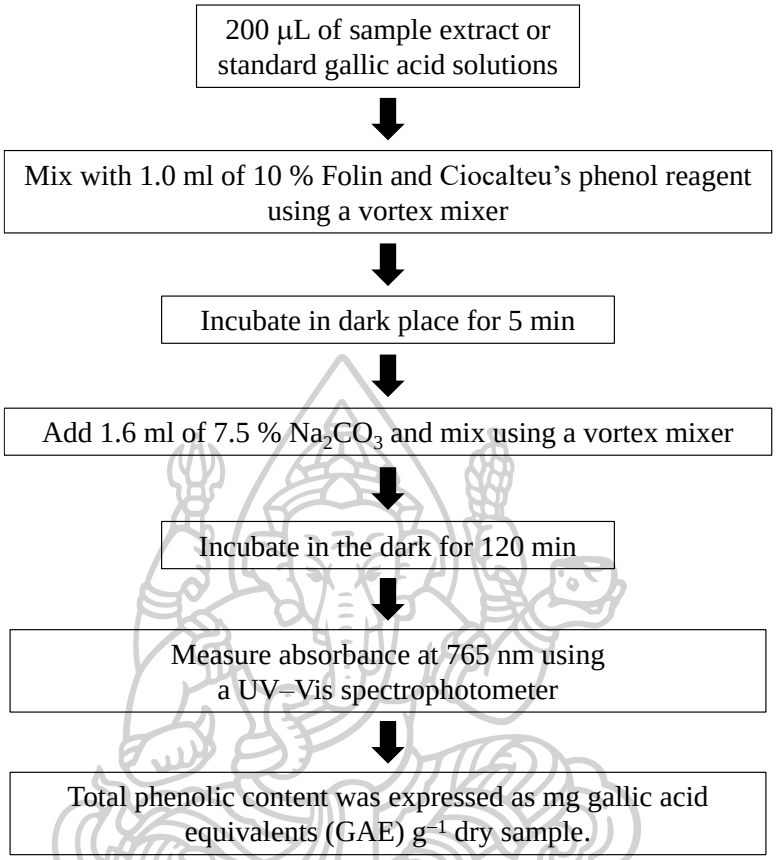


Figure A4 Gallic calibration curve for total phenolic content assay.

1.2 Procedure



2. Determination of Antioxidant Activity

Determination of antioxidant capacity was based on electron transfer reaction methods, namely DPPH radical scavenging assay (DPPH), ferric reducing antioxidant potential (FRAP), and ABTS radical scavenging capacity assay (ABTS).

2.1 DPPH radical scavenging assay

DPPH assay was done as described by Brand-Williams et al. (1995) with some modifications.

2.1.1 Chemical reagents

- 6 x 10^{-5} M 1,1-diphenyl-2-picrylhydrazyl (DPPH)

Weight 0.0118 g of DPPH and dissolve in 20 mL of methanol, stir using a stirring rod. Wait for few minutes until DPPH dissolves completely, then transfer to a volumetric flask and adjust the volume to 500 mL, (prepare before use).

- A stock standard trolox solution (250 mg L^{-1})

Weight 0.0250 ± 0.0010 g trolox (record the certain weight). Dissolve with 60% methanol and adjust the volume to 100 mL in a volumetric flask. Prepare trolox standard at 6 concentrations in a 10 mL volumetric flask.

Table A2 Preparation of standard trolox solution.

Concentration (mg L^{-1})	Stock standard trolox solution (mL)
0	0
20	0.8
50	2.0
100	4.0
150	6.0
250	10.0

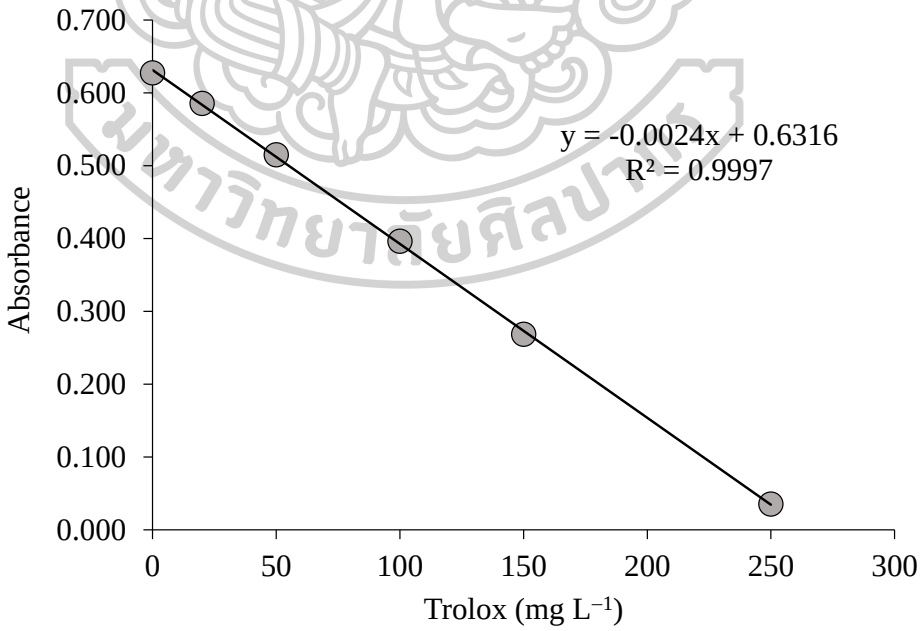
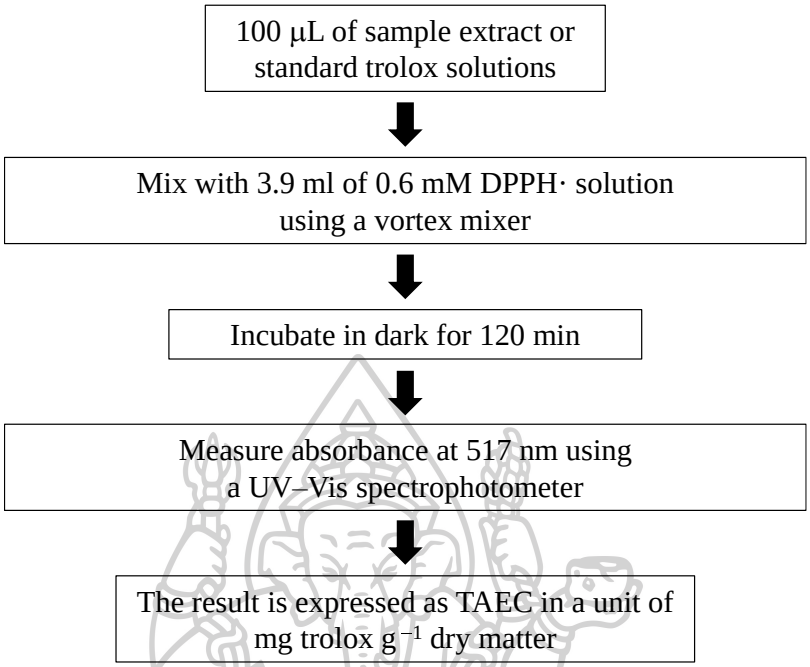


Figure A5 Trolox calibration curve for DPPH assay.

2.1.2 Procedure



2.2 Ferric reducing antioxidant potential

Ferric reducing antioxidant potential (FRAP) assay as described by (Benzie and Straint, 1996) with some modifications.

2.2.1 Chemical reagents

- 300 mM Acetate buffer pH 3.6

Dissolve 3.1 g sodium acetate trihydrate ($CH_3COONa.3H_2O$) in 16 mL glacial acetic acid and adjust the volume to 1000 mL with ionized water, then store at 4 °C.

- 40 mM Hydrochloric acid solution

Prepare 0.1 N HCl, pipette 8.3 mL of 37% HCl and adjust the volume with ionized water to 1000 mL. Then pipette 40 mL of 0.1 N HCl and adjust the volume with ionized water to 100 mL to obtain 40 mM HCl.

- 10 mM TPTZ (2,4,6-tri[2-pyridyl]-s-triazine)

Dissolve 0.0312 g TPTZ with 1 mL of 40 mM HCl in water bath at 50 °C. Then adjust the volume to 10 mL (prepare before use).

- 20 mM Ferric (II) Chloride ($FeCl_2.6H_2O$)

Dissolve 0.054 g $FeCl_2.6H_2O$ in ionized water and adjust the volume to 10 mL (prepare before use).

- FRAP reagent

Mix 100 mL of 300 mM Acetate buffer pH 3.6, 10 mL of 10 mM TPTZ, 10 mL of 20 mM $FeCl_2.6H_2O$, and 12 mL of ionized water in a Duran bottle. Warm in a water bath at 37 °C, the color of FRAP reagent should be straw color.

- A stock standard trolox solution (1000 μM) was prepared as in Table A3.

Table A3. Preparation of standard trolox.

Concentration (μM)	stock standard trolox solution (mL)
0	0
50	0.25
100	0.50
250	1.25
500	2.50
750	3.75
1000	5.00

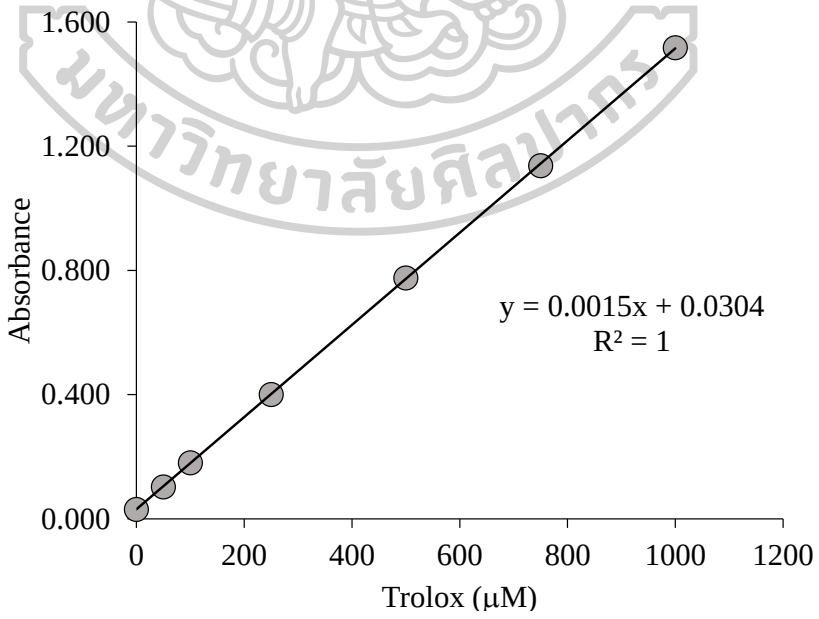
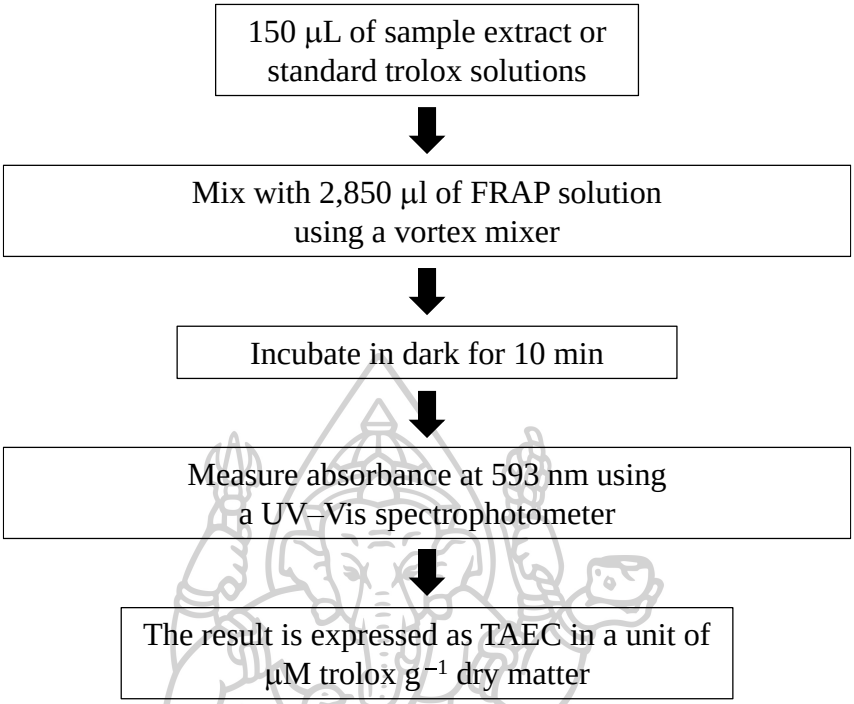


Figure A6 Trolox calibration curve for FRAP assay.

2.2.2 Procedure



2.3 ABTS radical scavenging capacity assay

ABTS assay was done as described by Arnao et al. (2001).

2.3.1 Chemical reagents

- 7 mM 2, 2′-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt or ABTS solution (Molecular weight = 548.70 g mol^{-1})

  Dissolve 0.01920 g ABTS in distilled water and adjust the volume to 5 mL.

- 2.6 mM potassium persulphate (Molecular weight = 270.32 g mol^{-1})

  Dissolve 0.0070 g potassium persulphate in distilled water and adjust the volume to 10 mL.

- $ABTS^{\bullet+}$ radical solution ($ABTS^{\bullet+}$)

  Mix 5 mL of 7 mM $ABTS^{\bullet+}$ solution and 5 mL of 2.6 mM potassium persulphate (1:1) and then keep in the dark for 12-16 hr.

- $ABTS^{\bullet+}$ Working solution

  Mix 9 mL of $ABTS^{\bullet+}$ radical solution with 300 mL of 60% methanol to get the working solution with an absorbance of 1.100 ± 0.02 at 734 nm.

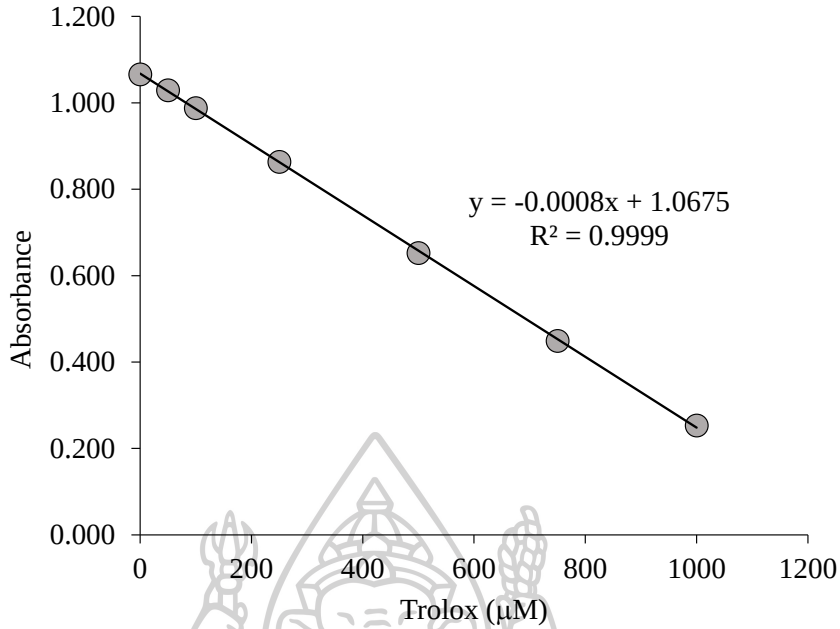


Figure A7 Trolox calibration curve for ABTS assay

2.3.2 Procedure

150 µL of sample extract or standard trolox solutions

↓

Mix with 2,850 µl of $ABTS^{\bullet+}$ working solution using a vortex mixer

↓

Incubate in dark for 120 min

↓

Measure absorbance at 734 nm using a UV–Vis spectrophotometer

↓

The result is expressed as TAEC in a unit of µM trolox g^{-1} dry matter

3. Curcuminoids contents

Curcumin, demethoxycurcumin, and bisdemethoxycurcumin contents were determined using a high performance liquid chromatography (HPLC) method as described by Nelson et al. (2017) with some modifications.

3.1 Chemical reagents

- A stock standard curcumin solution (250 mg L^{-1})

Dissolve 5 mg curcumin standard with 2 mL ethanol, rinse, and adjust volume to 20 mL in a volumetric flask with ethanol. Preparation of curcumin standard is shown in Table A4.

Table A4 Preparation of standard curcumin.

Concentration (mg L^{-1})	Stock curcumin solution (mL)
0	0
1.0	0.02
2.5	0.05
5.0	0.10
10.0	0.20
25.0	0.50

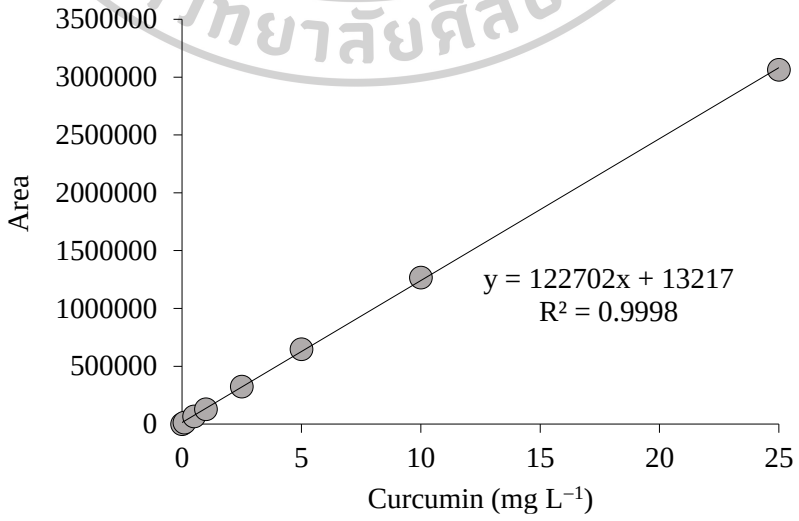


Figure A8 Curcumin standard curve.

- A stock standard demethoxycurcumin solution (250 mg L^{-1})

Dissolve 5 mg demethoxycurcumin standard with 2 mL ethanol, rinse, and adjust volume to 20 mL in a volumetric flask. Preparation of demethoxycurcumin standard is shown in Table A5.

Table A5 Preparation of standard demethoxycurcumin.

Concentration (mg L^{-1})	Stock demethoxycurcumin solution (mL)
0	0
1.0	0.02
2.5	0.05
5.0	0.10
10.0	0.20
25.0	0.50

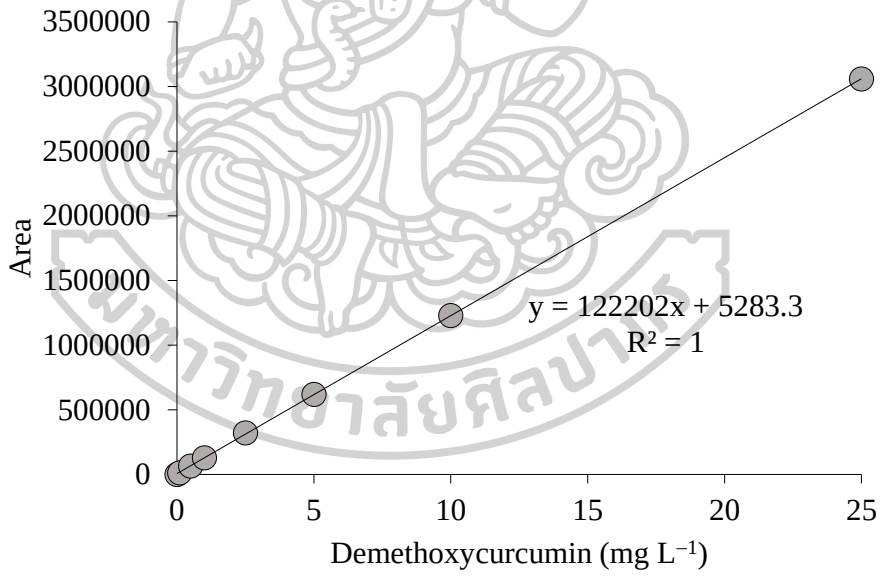


Figure A9 Demethoxycurcumin standard curve.

- A stock standard bisdemethoxycurcumin solution (250 mg L^{-1})

Dissolve 5 mg bisdemethoxycurcumin standard with 2 mL ethanol, rinse, and adjust the volume to 20 mL in volumetric flask. Preparation of demethoxycurcumin standard is shown in Table A6.

Table A6 Preparation of standard bisdemethoxycurcumin.

Concentration (mg L^{-1})	Stock bisdemethoxycurcumin solution (mL)
0	0
1.0	0.02
2.5	0.05
5.0	0.10
10.0	0.20
25.0	0.50

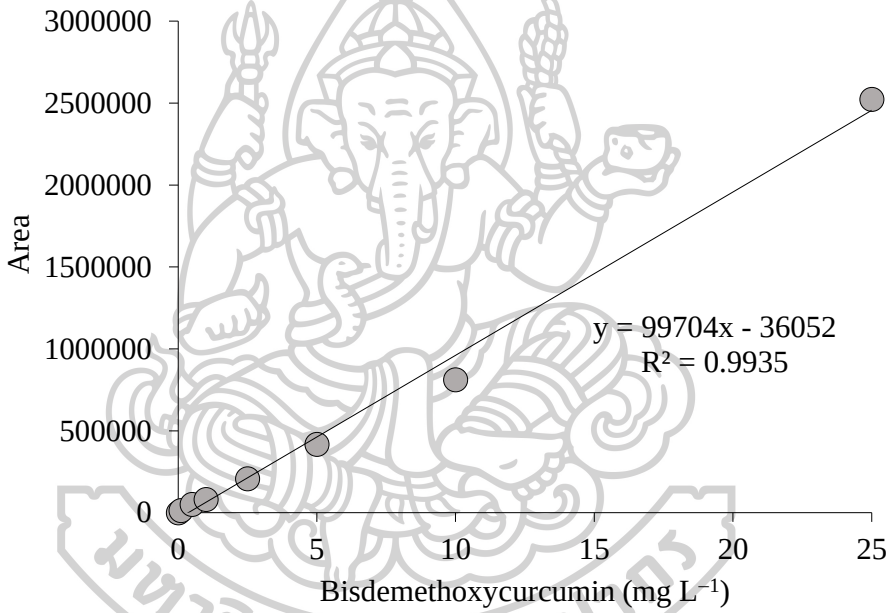
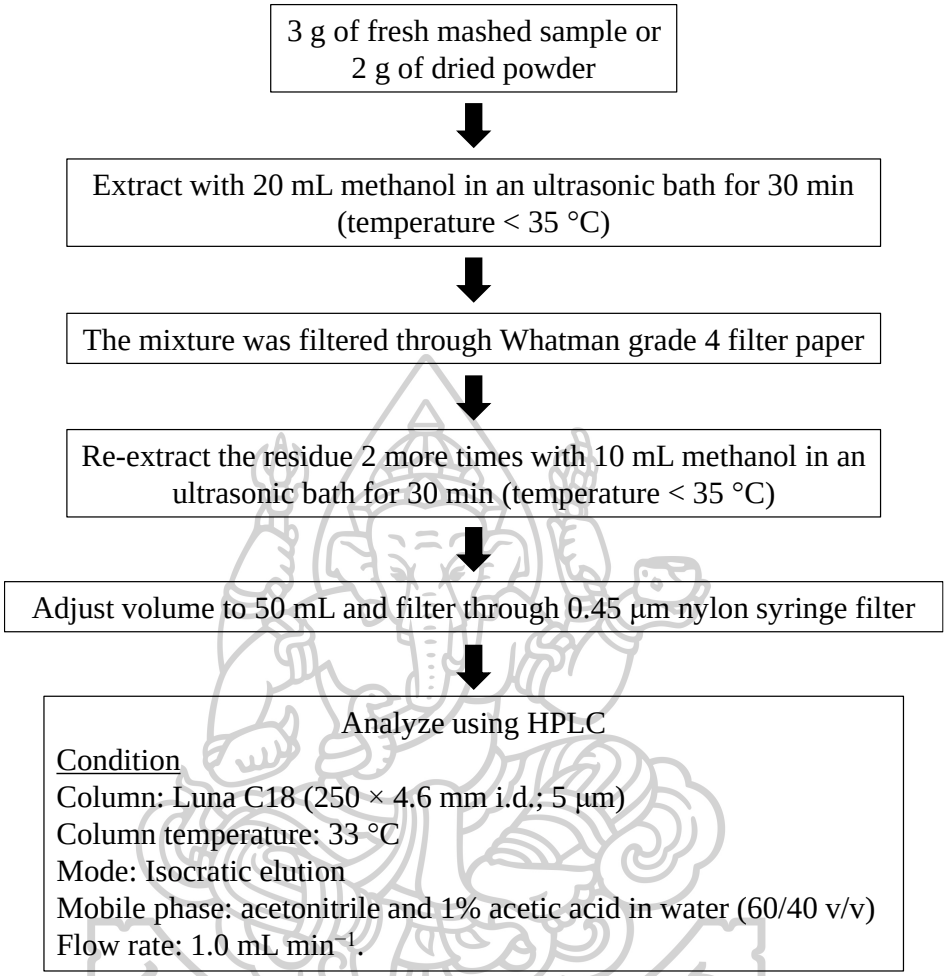


Figure A10 Bisdemethoxycurcumin standard curve.

3.2 Procedure



4. Results

Table A7 The physical properties of fresh turmeric before drying.

Parameters	Min - Max	Mean ± SD
color parameter		
*L** (lighness)	57.81 ± 1.07 - 59.33 ± 0.24	58.63 ± 0.45
*a** (+redness)	33.62 ± 2.07 - 35.96 ± 2.09	34.66 ± 0.80
*b** (+yellowness)	60.62 ± 0.64 - 65.07 ± 3.97	62.45 ± 1.23
*C**	69.50 ± 1.60 - 74.73 ± 2.53	71.65 ± 1.36
h°	59.93 ± 2.43 - 62.09 ± 0.35	60.86 ± 0.68
moisture content (%wet basis)	76.10 ± 4.05 - 78.97 ± 1.38	77.34 ± 0.87
water activity^{ns} (temp. = 23 °C)	0.958 ± 0.012 - 0.972 ± 0.005	0.965 ± 0.005

Table A8 The chemical properties of fresh turmeric before drying.

Parameter	Min – Max	Mean ± SD
Contents (mg g^{-1} fresh sample)		
Curcumin	4.12 ± 0.11 - 9.29 ± 0.18	29.53 ± 4.87
Demethoxy curcumin	1.85 ± 0.16 - 4.02 ± 0.16	12.17 ± 3.11
Bisdemethoxy curcumin	2.17 ± 0.15 - 6.17 ± 0.38	17.31 ± 5.90
Total curcuminoids contents (mg curcumin g^{-1} fresh sample)	12.65 ± 0.78 - 20.81 ± 0.77	71.03 ± 7.52
DPPH (mg trolox g^{-1} fresh sample)	19.54 ± 1.03 - 40.59 ± 0.21	128.87 ± 22.02
FRAP (μM trolox g^{-1} fresh sample)	52.79 ± 3.99 - 87.49 ± 3.29	321.01 ± 56.77
ABTS (μM trolox g^{-1} fresh sample)	139.22 ± 2.66 - 220.36 ± 1.64	828.43 ± 72.61
TPC (mg gallic acid g^{-1} fresh sample)	5.04 ± 0.81 - 13.61 ± 1.10	45.18 ± 8.27

Table A9 Appearance of fresh turmeric slices under different drying conditions.

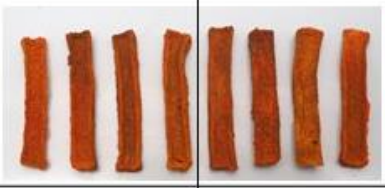
Drying conditions	Without light exposure		Light exposure	
Fresh sample				
	Upper side	**Down side**	**Exposure side**	**Down side**
40 °C				
50 °C				
60 °C				
70 °C				
80 °C				

Table A10 Effects of drying temperatures and light exposure on DPPH in dried turmeric lot 1.

Drying conditions		DPPH (mg Trolox g^{-1} dry matter)		ΔDPPH (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	106.28	101.58	-4.42
	Yes	116.38	101.87	-12.47
50	No	107.54	106.99	-0.51
	Yes	107.47	104.57	-2.70
60	No	112.43	106.03	-5.69
	Yes	123.48	105.04	-14.93
70	No	119.36	110.79	-7.18
	Yes	99.75	104.05	4.31
80	No	109.60	104.69	-4.48
	Yes	106.80	112.17	5.02

Table A11 Effects of drying temperatures and light exposure on DPPH in dried turmeric lot 2.

Drying conditions		DPPH (mg Trolox g^{-1} dry matter)		ΔDPPH (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	156.99	150.06	-4.41
	Yes	144.88	132.76	-8.37
50	No	142.02	141.51	-0.36
	Yes	149.67	140.48	-6.14
60	No	159.78	155.12	-2.91
	Yes	153.32	144.54	-5.72
70	No	168.25	154.98	-7.89
	Yes	146.54	151.77	3.57
80	No	146.62	145.86	-0.51
	Yes	114.88	154.74	34.70

Table A12 Effects of drying temperatures and light exposure on ABTS in dried turmeric lot 1.

Drying conditions		ABTS (μM Trolox g^{-1} dry matter)		ΔABTS (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	804.20	773.23	-3.85
	Yes	906.54	710.06	-21.67
50	No	787.37	774.76	-1.60
	Yes	801.18	763.87	-4.66
60	No	861.65	779.74	-9.51
	Yes	962.00	783.91	-18.51
70	No	892.04	777.15	-12.88
	Yes	710.78	710.06	-0.10
80	No	730.88	723.30	-1.04
	Yes	746.39	742.40	-0.53

Table A13 Effects of drying temperatures and light exposure on ABTS in dried turmeric of lot 2.

Drying conditions		ABTS (μM Trolox g^{-1} dry matter)		ΔABTS (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	869.45	766.16	-11.88
	Yes	850.75	729.86	-14.21
50	No	814.24	736.62	-9.53
	Yes	848.57	725.22	-14.54
60	No	868.54	728.75	-16.10
	Yes	855.00	715.31	-16.34
70	No	913.31	739.66	-19.01
	Yes	839.04	728.77	-13.14
80	No	765.45	718.47	-6.14
	Yes	758.87	724.95	-4.47

Table A14 Effects of drying temperatures and light exposure on FRAP in dried turmeric lot 1.

Drying conditions		FRAP (μM Trolox g^{-1} dry matter)		ΔFRAP (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	346.66	340.55	-1.76
	Yes	405.26	350.04	-13.69
50	No	338.59	344.85	1.85
	Yes	358.38	332.74	-7.15
60	No	374.19	349.01	-6.73
	Yes	413.87	358.58	-13.36
70	No	400.55	364.05	-9.11
	Yes	321.9	349.03	8.43
80	No	346.67	353.06	1.84
	Yes	361.53	376.55	4.15

Table A15 Effects of drying temperatures and light exposure on ABTS in dried turmeric lot 2.

Drying conditions		FRAP (μM Trolox g^{-1} dry matter)		ΔFRAP (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	287.38	285.24	-0.74
	Yes	290.75	265.35	-8.74
50	No	271.55	263.00	-3.15
	Yes	287.72	275.92	-4.10
60	No	279.79	294.35	5.20
	Yes	275.93	253.80	-8.02
70	No	288.17	274.26	-4.83
	Yes	277.59	270.33	-2.61
80	No	239.32	262.68	9.76
	Yes	224.25	270.96	20.83

Table A16 Effects of drying temperatures and light exposure on TPC in dried turmeric lot 1.

Drying conditions		TPC (mg GAE g^{-1} dry matter)		ΔTPC (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	44.52	41.04	-7.81
	Yes	45.92	39.54	-13.89
50	No	42.95	42.66	-0.66
	Yes	44.62	43.85	-1.74
60	No	46.69	42.04	-9.95
	Yes	53.05	42.60	-19.69
70	No	53.82	41.77	-22.40
	Yes	25.74	33.68	30.86
80	No	33.94	34.32	1.11
	Yes	31.31	37.46	19.65

Table A17 Effects of drying temperatures and light exposure on TPC in dried turmeric lot 2.

Drying conditions		TPC (mg GAE g^{-1} dry matter)		ΔTPC (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	51.68	56.67	9.65
	Yes	49.38	49.25	-0.26
50	No	50.12	49.14	-1.95
	Yes	47.55	54.57	14.75
60	No	52.06	54.54	4.78
	Yes	53.73	49.98	-6.98
70	No	51.82	56.50	9.04
	Yes	47.36	50.56	6.74
80	No	44.46	50.24	13.01
	Yes	38.58	52.70	36.62

Table A18 Effects of drying temperatures and light exposure on curcumin in dried turmeric lot 1.

Drying conditions		curcumin (mg curcumin g^{-1} dry matter)		Δcurcumin
Temp. (°C)	Light exposure	Fresh	Dried	(%)
40	No	28.16	33.03	17.27
	Yes	27.11	27.19	0.30
50	No	27.20	31.48	15.74
	Yes	32.29	28.16	-12.80
60	No	26.98	31.76	17.71
	Yes	25.89	27.05	4.48
70	No	26.00	32.05	23.27
	Yes	26.01	27.44	5.50
80	No	23.75	30.71	29.26
	Yes	29.24	29.40	0.56

Table A19 Effects of drying temperatures and light exposure on curcumin in dried turmeric lot 2.

Drying conditions		curcumin (mg curcumin g^{-1} dry matter)		Δcurcumin
Temp. (°C)	Light exposure	Fresh	Dried	(%)
40	No	23.87	29.94	25.45
	Yes	28.89	27.11	-6.14
50	No	32.54	35.30	8.48
	Yes	31.31	28.15	-10.07
60	No	27.64	31.29	13.20
	Yes	30.25	30.35	0.36
70	No	23.90	31.80	33.07
	Yes	29.00	28.68	-1.11
80	No	27.42	31.36	14.36
	Yes	30.05	29.70	-1.18

Table A20 Effects of drying temperatures and light exposure on demethoxycurcumin in dried turmeric lot 1.

Drying conditions		demethoxycurcumin (mg curcumin g^{-1} dry matter)		Δdemethoxycurcumin (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	10.65	13.27	24.58
	Yes	10.91	11.79	8.08
50	No	11.03	12.42	12.59
	Yes	12.79	11.80	-7.79
60	No	10.60	12.34	16.35
	Yes	10.90	11.42	4.82
70	No	9.83	13.73	39.62
	Yes	10.17	11.06	8.75
80	No	8.95	11.92	33.20
	Yes	10.99	12.46	13.44

Table A21 Effects of drying temperatures and light exposure on demethoxycurcumin in dried turmeric lot 2.

Drying conditions		demethoxycurcumin (mg curcumin g^{-1} dry matter)		Δdemethoxycurcumin (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	12.04	15.04	24.91
	Yes	14.09	14.02	-0.51
50	No	15.91	17.50	9.98
	Yes	15.81	14.71	-6.96
60	No	13.76	15.87	15.35
	Yes	15.65	14.94	-4.53
70	No	11.64	15.44	32.59
	Yes	13.89	14.75	6.22
80	No	12.86	16.09	25.14
	Yes	14.36	14.67	2.17

Table A22 Effects of drying temperatures and light exposure on bisdemethoxycurcumin in dried turmeric lot 1.

Drying conditions		bisdemethoxycurcumin (mg curcumin g^{-1} dry matter)		Δbisdemethoxycurcumin (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	13.95	20.05	43.71
	Yes	14.95	18.57	24.21
50	No	14.45	18.78	30.00
	Yes	19.28	18.99	-1.50
60	No	14.31	18.06	26.23
	Yes	16.80	17.77	5.79
70	No	13.21	21.97	66.29
	Yes	13.64	16.75	22.79
80	No	12.07	18.04	49.47
	Yes	15.39	19.91	29.39

Table A23 Effects of drying temperatures and light exposure on bisdemethoxycurcumin in dried turmeric lot 2.

Drying conditions		bisdemethoxycurcumin (mg curcumin g^{-1} dry matter)		Δbisdemethoxycurcumin (%)
Temp. (°C)	Light exposure	Fresh	Dried	
40	No	21.11	26.96	27.75
	Yes	24.55	26.12	6.40
50	No	28.44	33.32	17.12
	Yes	27.34	28.12	2.84
60	No	23.12	29.79	28.85
	Yes	27.61	27.26	-1.29
70	No	20.66	30.57	47.96
	Yes	25.26	27.61	9.33
80	No	24.27	29.94	23.34
	Yes	26.47	27.35	3.35

In Chapter 6

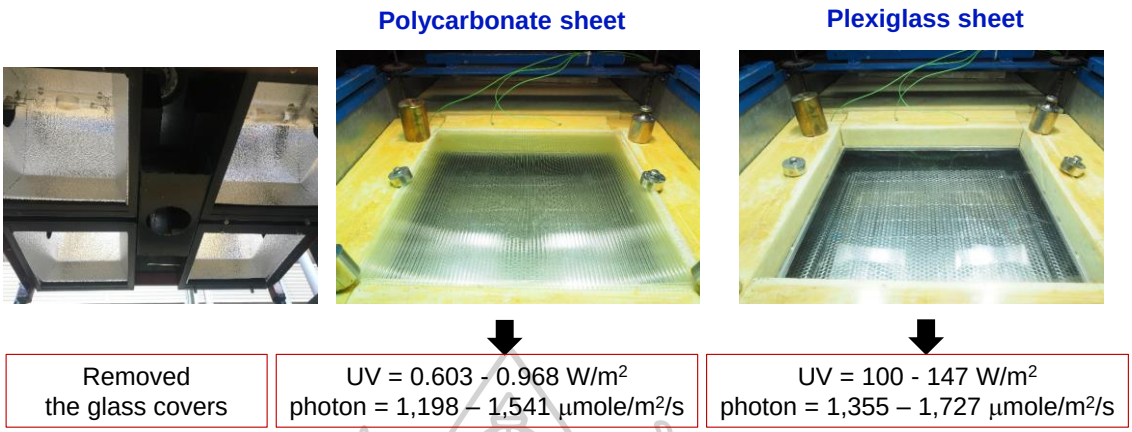


Figure A11 light simulation applied through the cover materials.

1. Determination of curcuminoids contents

Curcumin, demethoxycurcumin and bisdemethoxycurcumin were identified using Monton et al. (2016) with some modifications.

1.1 Chemical reagents

Standards:

- Curcumin matrix substance for MALDI-MS, ≥99,5% (HPLC), Sigma Aldrich, 78246-100MG, PCode:101699392, CAS No.: 458-37-7
- Demethoxycurcumin, ≥ 98% (HPLC), Sigma Aldrich, D7696-5MG, CAS No.: 22608-11-3
- Bisdemethoxycurcumin, ≥ 98% (HPLC) solid, Sigma Aldrich, B6938-5MG, CAS No.: 33171-05-0
- A stock standard curcumin solution (500 mg L^{-1})
    - Dissolve 100 mg curcumin standard in 200 mL methanol.
- A stock standard demethoxycurcumin solution (250 mg L^{-1})
    - Dissolve 5 mg demethoxycurcumin standard in 20 mL methanol.
- A stock standard bisdemethoxycurcumin solution (250 mg L^{-1})
    - Dissolve 5 mg bisdemethoxycurcumin standard in 20 mL methanol.

Table A24 Mix- standard preparation for calibration curve.

Standard No.	Concentration (mg L^{-1})	Curcumin (mL)	Demethoxy curcumin (mL)	Bisdemethoxy curcumin (mL)	MeOH (mL)
1	1	0.5	1	1	250
2	2.5	0.25	0.5	0.5	50
3	5	0.5	0.5	0.5	25
4	10	0.5	1	1	25
5	25	0.5	1	1	10
6	50	0.5	1	1	5
7	75	1.5	3	3	10
8	150 ppm Curcumin, 87.5 ppm Demethoxycurcumin, 87.5 ppm Bisdemethoxycurcumin	3.0	3.5	3.5	-

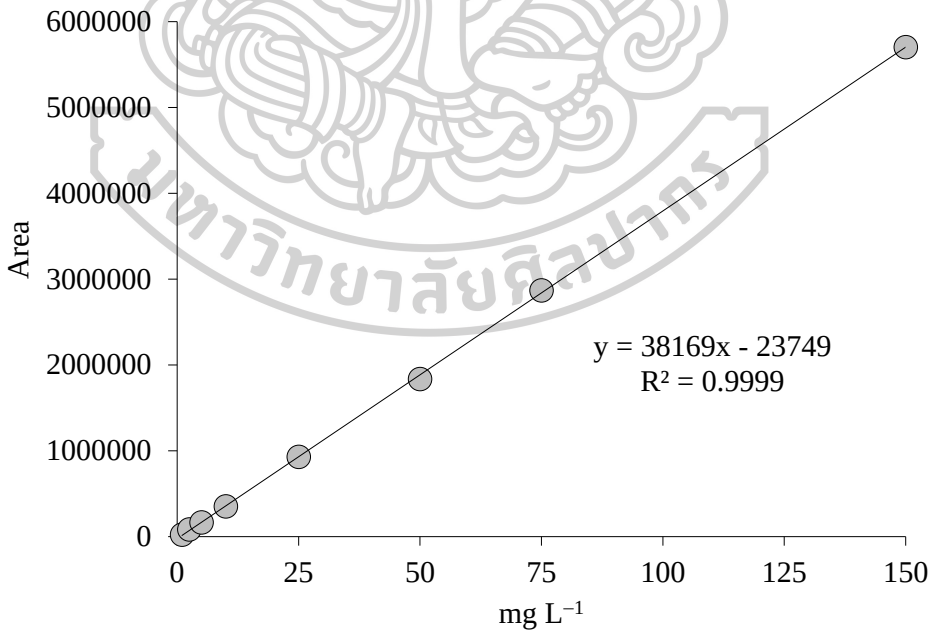


Figure A12 Calibration curve of curcumin.

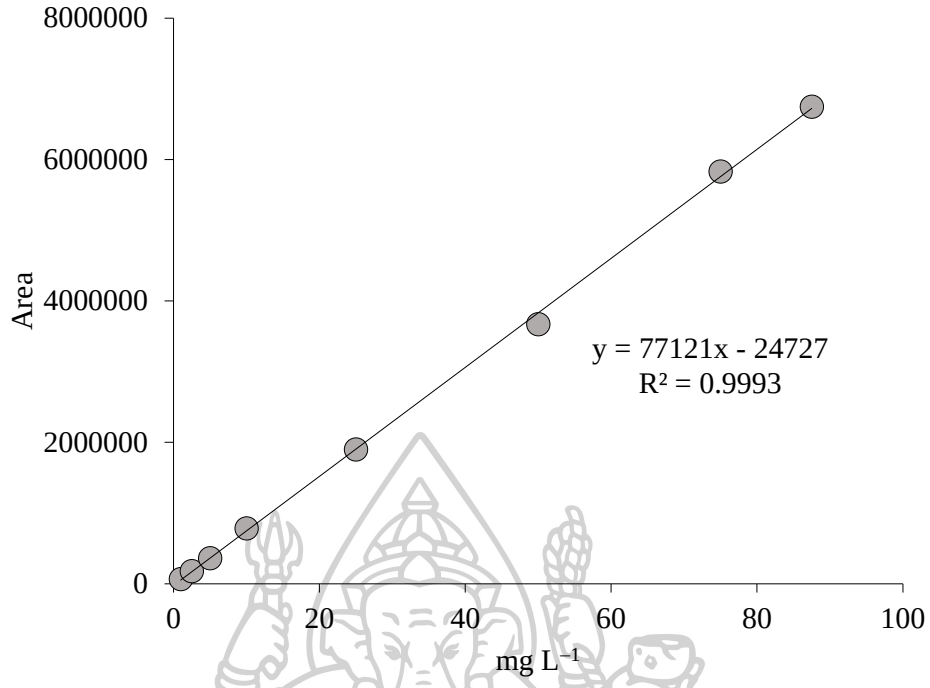


Figure A13 Calibration curve of demethoxycurcumin.

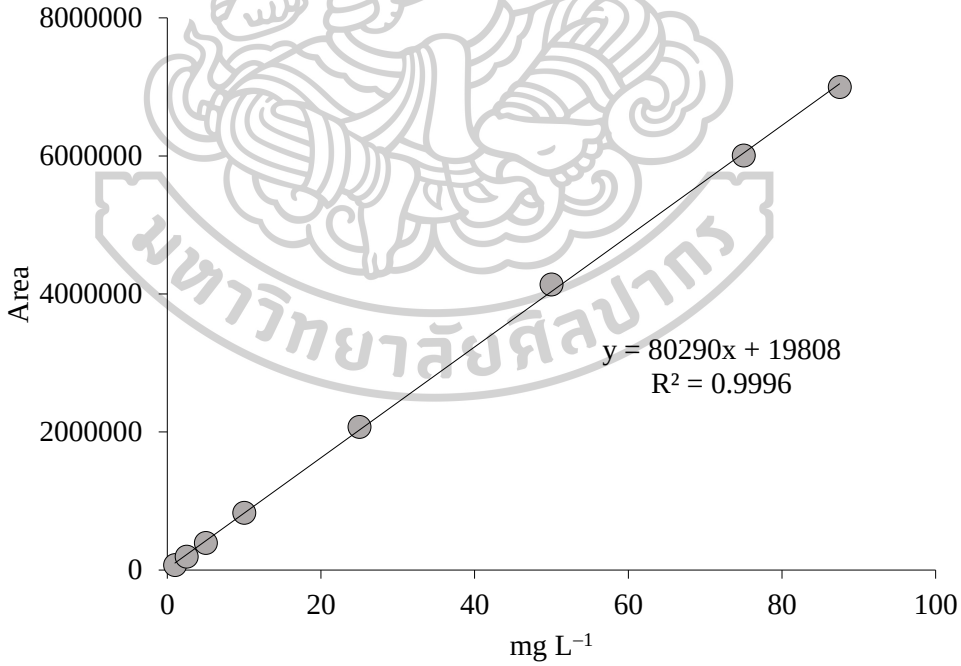


Figure A14 Calibration curve of bisdemethoxycurcumin.

1.2 Procedure

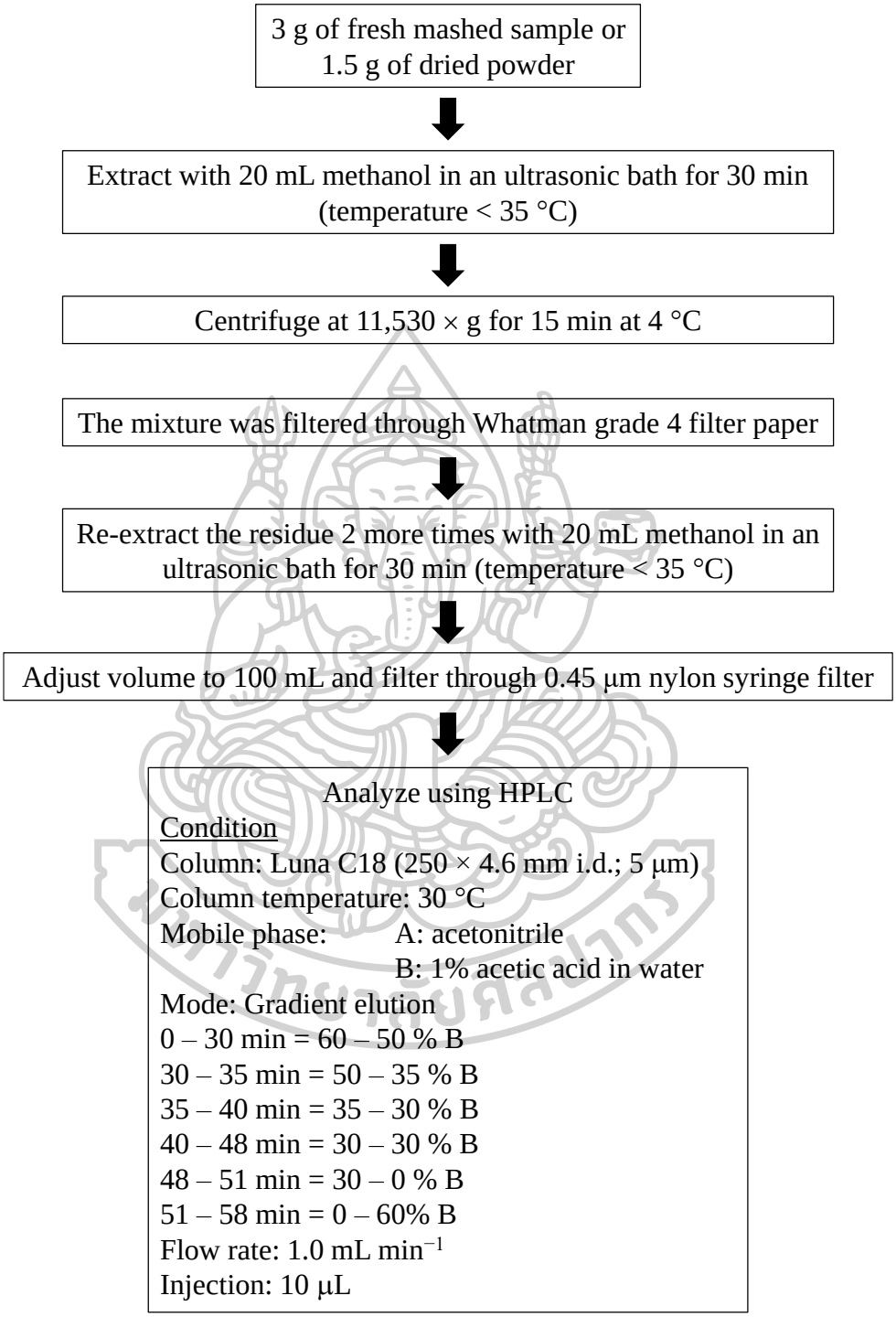


Table A25 Physical and chemical properties of fresh turmeric before drying.

Parameters	Mean ± SD
color parameter	
*L** (lightness)	53.25 ± 0.44
*a** (+redness)	38.42 ± 0.89
*b** (+yellowness)	47.41 ± 1.45
*C**	61.09 ± 1.32
h°	50.93 ± 1.01
moisture content (%wet basis)	84.35 ± 0.83
water activity (temp. = 24 °C)	0.959 ± 0.009
Curcuminoids content (g g^{-1} 100 fresh sample)	8.06 ± 0.11

Table A26 Curcumin (CUR), dimethoxycurcumin (DCUR), bisdemethoxycurcumin (BCUR), and total curcuminoids (TCUR) contents and change (%) of turmeric from the replication of drying experiment.

Temp. (°C)	Cover material	Drying Rep.	Content (mg g^{-1} dry matter)											
			Fresh sample				Dried sample				Change (%)			
			CUR	DCUR	BCUR	TCUR	CUR	DCUR	BCUR	TCUR	CUR	DCUR	BCUR	TCUR
40	Polycarbonate	1	199.22	52.07	57.37	308.66	179.91	46.94	57.77	284.61	-9.69	-9.86	0.69	-7.79
		2	194.85	50.55	56.82	302.22	185.10	47.61	57.72	290.43	-5.00	-5.81	1.59	-3.90
	PMMA	1	214.06	54.65	61.45	330.16	187.04	48.56	59.23	294.83	-12.62	-11.15	-3.61	-10.70
		2	209.53	54.70	63.67	327.90	182.94	49.56	61.51	294.01	-12.69	-9.38	-3.41	-10.33
50	Polycarbonate	1	219.95	56.34	61.09	337.38	199.34	52.65	63.77	315.75	-9.37	-6.55	4.38	-6.41
		2	214.30	56.61	63.41	334.33	204.88	54.30	67.08	326.25	-4.40	-4.09	5.78	-2.41
	PMMA	1	209.97	54.16	60.70	324.83	200.17	53.64	67.05	320.86	-4.66	-0.97	10.46	-1.22
		2	202.23	52.09	58.13	312.45	191.07	49.91	60.48	301.46	-5.52	-4.19	4.04	-3.52
60	Polycarbonate	1	222.28	55.35	62.00	339.63	210.02	54.68	67.08	331.78	-5.52	-1.21	8.21	-2.31
		2	227.62	58.08	66.27	351.96	210.94	55.03	69.23	335.20	-7.33	-5.24	4.47	-4.76
	PMMA	1	201.47	52.04	55.19	308.70	197.73	51.92	61.18	310.83	-1.86	-0.22	10.85	0.69
		3	204.04	53.93	60.32	318.30	202.61	53.80	66.57	322.98	-0.70	-0.25	10.35	1.47
70	Polycarbonate	1	210.42	54.61	63.54	328.57	215.73	56.09	69.15	340.97	2.52	2.71	8.83	3.77
		2	190.03	49.57	55.33	294.93	211.71	57.50	72.22	341.43	11.41	16.00	30.52	15.77
	PMMA	1	212.65	54.51	63.09	330.25	201.29	51.97	63.11	316.36	-5.35	-4.66	0.04	-4.20
		2	221.07	57.14	63.47	341.68	203.95	55.14	68.01	327.10	-7.74	-3.51	7.15	-4.27

Table A27 *AIC* output for the selection of thin-layer model.

Drying temperature (°C)	Cover materials	Model	Number of parameter (K)	AICc	Delta_AICc (compared to best model)	AICc Weight	likelihood
40	Polycarbonate	Midilli and Kucuk	5	-132.32	0.00	0.99	73.16
		Modified Page	3	-122.40	9.92	0.01	64.91
		Page	3	-122.40	9.92	0.01	64.91
		Henderson and Pabis	3	-88.72	43.60	0.00	48.07
		Newton	2	-83.66	48.65	0.00	44.17
	Plexiglass	Midilli and Kucuk	5	-141.81	0.00	1.00	78.05
		Page	3	-129.12	12.69	0.00	68.31
		Modified Page	3	-129.12	12.69	0.00	68.31
		Henderson and Pabis	3	-82.39	59.42	0.00	44.95
		Newton	2	-78.04	63.78	0.00	41.37
50	Polycarbonate	Midilli and Kucuk	5	-110.40	0.00	1.00	63.93
		Page	3	-98.00	12.41	0.00	53.92
		Modified Page	3	-98.00	12.41	0.00	53.92
		Henderson and Pabis	3	-66.64	43.76	0.00	37.24
		Newton	2	-63.95	46.45	0.00	34.40
	Plexiglass	Midilli and Kucuk	5	-111.39	0.00	1.00	63.69
		Page	3	-98.88	12.51	0.00	53.44
		Modified Page	3	-98.88	12.51	0.00	53.44
		Henderson and Pabis	3	-60.60	50.79	0.00	34.30
		Newton	2	-58.77	52.62	0.00	31.85
60	Polycarbonate	Page	3	-77.89	0.00	0.50	43.44
		Modified Page	3	-77.89	0.00	0.50	43.44
		Midilli and Kucuk	5	-69.90	7.98	0.01	44.95
		Henderson and Pabis	2	-41.77	36.11	0.00	23.55
		Newton	3	-40.49	37.39	0.00	24.75
	Plexiglass	Page	3	-60.02	0.00	0.49	34.73
		Modified Page	3	-60.02	0.00	0.49	34.73
		Midilli and Kucuk	5	-52.79	7.23	0.01	37.40
		Henderson and Pabis	2	-37.46	22.57	0.00	21.48
		Newton	3	-35.16	24.87	0.00	22.29
70	Polycarbonate	Modified Page	3	-97.86	0.00	0.49	53.13
		Page	3	-97.86	0.00	0.49	53.13
		Midilli and Kucuk	5	-91.03	6.83	0.02	54.27
		Henderson and Pabis	3	-41.63	56.22	0.00	25.02
		Newton	2	-40.88	56.97	0.00	22.99
	Plexiglass	Modified Page	3	-78.78	0.00	0.50	43.59
		Page	3	-78.78	0.00	0.50	43.59
		Midilli and Kucuk	5	-70.95	7.83	0.01	44.23
		Henderson and Pabis	3	-44.40	34.39	0.00	24.74
		Newton	2	-44.05	34.73	0.00	26.22

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AWARD RECEIVED

Best poster presentation award, 1st International Conference on Innovations in Food Ingredients & Food Safety (IFIFS 2018), Bangkok, Thailand

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