Pertanika J. Sci. & Technol. 31 (5): 2621 - 2644 (2023)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

Progress, Trends and Development of Drying Studies on Coconut Kernel Products: A Review

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ABSTRACT

There are several different forms of coconut kernel products, such as copra, desiccated coconut, coconut chips, strips, and flakes, each with its identity, industrial standard, and use in the food sector. In view of this, many studies concentrate on drying kinetics and the quality of the final dried product and extend from laboratory-scale research to industrial operations. This article discusses the application of various drying processes for various types of coconut kernel products, the pre-treatment involved prior to drying and some qualitative aspects associated with the final product. The use of mathematical modelling in various drying techniques was also examined and compared in this article. The effects of drying parameters such as air temperature, velocity, and pre-treatment on drying rate, time, colour quality, energy consumption, and yield are particularly interesting. Future suggestions and directions are emphasised and featured to fill the research gap in this product and sector.

Keywords: Coconut kernel, dried quality product, drying kinetics, drying methods, drying model

ARTICLE INFO

Article history:
Received: 24 September 2022
Accepted: 25 January 2023
Published: 27 July 2023

DOI: https://doi.org/10.47836/pjst.31.5.30

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INTRODUCTION

In post-harvesting processes, drying or dehydration is crucial to preserve food materials before further processing. Due to the high moisture and nutritional content in most agricultural products, they are

ISSN: 0128-7680
e-ISSN: 2231-8526

susceptible to spoilage, which could end up lowering the shelf life and quality of the product (These, 2016). The degradation of product quality is mainly due to microbial, chemical, and physical actions that occur within the product and its surroundings (Lamidi et al., 2019). Therefore, food materials must be dried or dehydrated to retain their quality for longer periods. In principle, drying depends on two fundamental factors (heat and mass transfer). When heat is applied to the product, water vapour is eliminated from its surface and released into the surrounding environment, resulting in a dried material with a longer shelf life and reduced water activity in food products (Erkmen & Bozoglu, 2016).

In drying food products, heat can be applied via conduction, convection, radiation, or a combination of these methods. In principle, sun drying and solar drying are considered natural drying, whereas convective drying, fluidised bed drying, microwave drying, infrared drying, heat pump drying, and freeze drying are categorised as artificial drying. Recently, there have been remarkable developments in the use of novel drying techniques such as microwave, infrared, pulsed electric field, ultraviolet, and ohmic, which improve drying efficiency and product quality (Guiné, 2018). Apart from that, most agricultural products also undergo pre-treatment prior to drying to retain the nutrients better and enhance the appearance of the dried product (Hii & Ogugo, 2014).

It is also true for coconut kernel-based products such as desiccated coconut, copra, coconut chips and flakes, and coconut strips and slices (Figure 1), whereby drying is needed in the production of each product. At complete development and full maturity, the coconut comprises an average of 33% husk, 16% shell, 33% kernel, and 18% coconut water (Konan et al., 2009). Generally, the coconut fruit is spherical to oval with a rough outer husk, and the size varies depending on the source and breed (Arulandoo et al., 2017). The kernel of a mature coconut is rich in oil and, in fact, the most valuable part of the fruit, as it provides an important ingredient in the food. The details of fresh coconut kernel composition can be referred to in Table 1. Coconuts play a significant part in human eating because of the presence of physiologically vital components such as fatty acids. Natural coconut fat in the diet helps improve the immune system's anti-inflammatory response (Joshi et al., 2020).

(a) (b) (c) (d)

Figure 1. Common coconut kernel products: (a) coconut slices; (b) copra; (c) desiccated/grated coconut; (d) sweetened coconut flakes

Fresh coconut meat is high in protein, lipids, and carbohydrates, making it an excellent supplement for the growth of microorganisms (Gupta et al., 2010). Subsequently, they have a very short shelf life, and during processing and storage, coconut meats go through physico-chemical and biological changes like browning, drying out or hardening, changes in texture, mould growth, and others (Gupta et al., 2010). In the coconut industry, the drying process is vital in downstream unit operations. While there are numerous post-harvest losses, the efficacy of the drying process is the most critical stage since it can determine subsequent losses in product quality and market prices (Mithra et al., 2013). It is true, as Nor et al. (2021) mentioned, that traditional and conventional drying of coconut kernels could potentially degrade the quality of final and subsequent products with oxidative rancidity, aflatoxin contamination, unpleasant colour, and aroma.

Table 1
Fresh coconut kernel composition per 100 g (Lal et al., 2003)

Water	**36.3 ml**
Protein	4.5 g
Fat	41.6 g
Carbohydrates	13 g
Fibre	3.6 g
Minerals	1.0 g
Among the minerals present:	
Ca	10 mg
P	24 mg
Fe	1.7 mg

Therefore, by determining through experiments what proper drying methods and strategies are, they can contribute to the quality of the coconut kernel-based products being produced. A harmful loss can occur during post-harvest processing if there is a lack of knowledge about correct drying techniques. As with many other agricultural products, a thorough understanding of the physical and chemical changes during drying is essential. The physico-chemical properties and related parameters of air as a medium (temperature, thermal conductivity, specific heat capacity, air velocity, relative humidity, and density) are required to analyse the drying mechanism. Size, shape, dimension, structure, porosity, and specific types of product interest are also highlighted in terms of the product's physical properties. These factors play a significant role in drying kinetics and mechanisms (Mühlbauer & Müller, 2020a). Furthermore, adequate drying kinetics models must be introduced and established to describe the quantitative monitoring of physico-chemical changes during the process. On top of that, the mathematical considerations related to proper assumptions and parametric considerations in the design of the dryers would lead to an optimum process design, less energy consumption, and increased profitability (Inyang et al., 2018).

Therefore, this paper aims to let the reader understand the effect and impact of drying methods and strategies on the quality of coconut kernel-based products. This paper will also focus on the selected types of coconut kernel-based products, pre-treatment, drying strategies, energy requirements, drying kinetics and modelling, and final product quality.

COCONUT KERNEL PRODUCTS

Copra

Copra is the main traditional product processed from coconut and is always perceived as a low-value product. As such, more than half of the world's coconut production is converted into copra. Copra is a dried endosperm and a source of coconut oil. It is an intermediate product and can be classified into edible copra and milling copra (Mithra et al., 2013). Sun drying, solar drying, conventional smoke kiln drying, indirect drying, and cabinet drying are some methods used to make copra. Copra is always referred to as an inferior-quality product, where the oil extracted from it is of poor quality and further refinement is expected to fulfil global standards.

The important factors in copra processing are to quickly reduce the moisture level of the coconut to 6% w.b. after splitting the coconut to avoid microbiological deterioration and to preserve the oil composition and quality (Thanaraj et al., 2007). Indonesia boasts the world's largest coconut plantation and produces most world's copra. Nevertheless, the quality of copra produced in rural regions is somewhat low and is complained about by the international market as it contains aflatoxin (Santosa et al., 2019). Small farmers and smallholders in India also face problems related to copra quality. Coconut products are mostly traded internationally because of their major processing product, copra. These days, as significant coconut-creating nations are capable and outfitted with modern crushing units that allow them to export crude oil, almost no more traded copra is traded on the international market (Prades et al., 2016).

Desiccated Coconut

Desiccated coconut is a significant commercial product with global demand and is used in various food industries, particularly confectionery and bakery (Mithra et al., 2013). In another study reported by (Nelsonekanem et al., 2020), dried shredded coconut or desiccated coconut could also be used to produce coconut oil by extracting the oil using a mechanical press. Generally, desiccated coconut is produced from fully developed and matured coconut kernels under strict hygienic conditions. According to Marikkar & Madurapperuma (2012), a fresh mature coconut kernel's granulated or shredded white meat is dried to make desiccated coconut. It should contain less than 3% moisture content and no less than 60% oil. Oil contents of less than 60% can be considered low-fat desiccated coconut. After the coconut milk is removed from the coconut meat, low-fat desiccated coconut is sometimes called "coconut residue." Desiccated coconut is considered a contemporary, non-traditional coconut product traded in the world market. The Philippines and Indonesia, as members of the Asian and Pacific Coconut Community (APCC), are the leading exporters of desiccated coconut, accounting for 44% of total exports (Jayasekhar et al., 2017).

Coconut Flakes/Chips

In principle, coconut flakes are made from coconut residue, a by-product of coconut milk production. Like any other snack item, coconut chips or flakes are available in salted or sweetened varieties. It also has distinct characteristics such as no preservatives, no frying in oil, no loss of flavour in the kernel, and is sometimes treated with osmotic dehydration or agents prior to drying (Pravitha et al., 2022). Manikantan et al. (2015) suggested that coconut kernels must be parred, blanched, osmotically dehydrated, and dried before being made into ready-to-eat coconut chips.

PRE-TREATMENT EFFECTS ON DRYING RATE AND QUALITY OF COCONUT KERNEL PRODUCT

In most situations, fresh agricultural products are perishable, decaying quickly due to their high moisture content and physical tender texture. While drying is one of the most frequent preservation procedures, pre-treatment prior to drying is equally essential for producing a high-quality end product. According to Yu et al. (2017), prior to drying, physical and chemical pre-treatments can be given to fruits and vegetables to reduce drying time, reduce energy consumption and protect product quality.

Pre-treatment is a substantial operation that aims to increase the drying rate, maintain quality, and decrease the microbial load of products (Deng et al., 2019). It is also true when pre-treatments are applied to coconut kernel products to achieve certain product qualities and optimum processing parameters. The coconut meat was immersed in a 50-ppm chlorine solution for 5 minutes to inactivate microorganisms, according to (Madhiyanon et al., 2009; Niamnuy & Devahastin, 2005). In another attempt, Chantaro et al. (2016) compared three different pre-treatments ($K_2 S_2 O_5$, $CaCl_2$, and hot water blanching) on coconut kernel cubes. The coconut cubes were then subjected to a sucrose solution for 24 hours prior to drying. The authors discovered that hot water blanching at 95°C for 5 minutes increased the total sugar and lightness (L*) of dried osmotic dehydrated coconut cubes, improving the colour and making the product more consumer-acceptable. Furthermore, Waisundara et al. (2007) revealed that the pre-treatment used (blanching and freezing) had suppressed the chemical and enzymatic deterioration of coconut kernels, whereas the untreated coconut kernels are likely to result in the loss of quality of the coconut milk when extracted.

Meanwhile, after blanching in hot water at 90–95°C for 2 minutes, coconut slices are dipped in an osmotic medium known as a syrup for one hour to create coconut chips (Manikantan et al., 2015). Kamalanathan & Meyyappan (2014) also reported a similar method, as the authors applied to blanching and immersing the coconut in a citric solution followed by osmotic dehydration. According to Manikantan et al. (2015), the osmotic medium differs based on the type of coconut chips. The rule of thumb is that the coconut slices after osmotic dehydration need to be dried immediately. Sarkar et al. (2020)

discovered that osmotic dehydration reduces the drying time of coconut samples since the initial water content is lost. In contrast, no special pre-treatment has been reported with regard to copra production. As such, using chemical dip can only add to the cost of processing, and health authorities also raise the concern about chemical residues. Very often, coconut kernel products such as dried grated coconut or desiccated coconut must go through some kind of pre-treatment prior to drying, as this will ensure that the colour and quality of the product meet industrial standards. However, several laboratory studies that focused primarily on drying kinetics did not apply pre-treatment prior to hot air drying (Wutthigarn et al., 2018; Yahya et al., 2020). Kurniawan et al. (2021) revealed the necessity of having a steam-blanching process during the production of desiccated coconut. Devi and Ghatani (2022) also recommended a similar approach to reduce the microbial load of coconut flakes before the drying process.

Hot water blanching, which involves immersing fresh products at a steady temperature of 70–100°C for several minutes before drying, is still a popular pre-treatment (Guida et al., 2013). On the other hand, oxidase inactivation is also linked to the significant decline in food quality during the hot water blanching process, particularly with the emergence of cooked-off tastes, colour changes, and the loss of thermosensitive components (Deng et al., 2019). Since hot water blanching produces much wastewater, which raises the pollution level, steam blanching, high humidity hot air impingement blanching, ohmic blanching, ultrasound, infrared and microwave blanching are all alternate thermal blanching methods that are quite appealing for the food sector to adopt them.

EFFECTS OF DRYING METHODS AND STRATEGIES ON THE QUALITY OF COCONUT KERNEL PRODUCTS

Sun Drying and Kiln Drying

Copra is typically dried using one of two methods: kiln drying or sun drying. Sun drying copra takes roughly 5 to 6 days during the dry season, as illustrated in Figure 2. Due to unpredictable weather, copra becomes dark, rancid, and mouldy as the drying rate is interrupted during sun drying. A similar finding by Mohanraj & Chandrasekar (2008a) reported that sun drying was very slow compared to solar drying due to lower heat and mass transfer coefficients. The authors also revealed that the moisture content of copra was increased by 0.11.0% due to desorption during cloudy hours; hence, nearly 25% of the copra was affected

Figure 2. Sun drying of copra (Arun et al., 2014)

by bacterial infection due to the extended drying period. Consequently, poor quality copra would not only reduce the market prices but, to some extent, increase health hazards due to contamination of polycyclic aromatic hydrocarbons (PAH) and also aflatoxin. The quality of extracted coconut oil from low-quality copra could also be affected; hence, additional extraction oil refinement is required to meet international requirements.

Direct kiln drying, on the other hand, uses smoke as a media and directly contacts the copra, and this method is likely to form PAH in copra. It is supported by Thanaraj et al. (2007), who revealed that the thermal efficiency of the kiln dryer was better than the solar dryer. Nonetheless, direct contact with smoke and kiln dryer burnt gases may result in the formation of carcinogenic substances. There was no chance to make white copra with a direct kiln drier. A semi-direct kiln dryer was also available, which appeared adaptable and economical for small farmers. Indirect kiln dryers of a different type, in which smoke does not contact the coconut kernel, were studied by Dippon and Villaruep (1996). The authors also noted that the indirect kiln dryer outperformed the direct kin dryer in terms of copra quality. However, maintenance and repair costs must be considered because the dryer component is exposed to high temperatures and strong gases, which would cause corrosion. There is also a concern about considerable heat loss unless the heat exchanger is designed efficiently.

Convective/Cabinet Drying

Unlike a kiln or a smoke dryer, a convective dryer or so-called cabinet dryer is used to dry coconut kernels by passing uncontaminated hot air through the product. In this case, the product can be guaranteed to be clean and white. Figure 3 shows the laboratory scale of a cabinet dryer for drying coconut kernels. Samson (1971) study's suggested that fresh coconut meat may withstand temperatures up to 100°C without considerable protein solubility loss. It also indicated that protein solubility would be low when the coconut meat turned brown and had a toasted odour. There was an attempt by Deepa et al. (2015) to use cabinet drying to dry copra at different air temperatures (60, 70, 80, and 90 °C). It was found that the drying temperature of 90 °C had the least drying time and took only 12 hours to reach the desired moisture content, whereas 60 °C had the longest drying period of 42 hours. On top of that, Deepa et al. (2015) also noticed that the mouldy cups of the kernel were higher (5%) at 60 °C compared to 90 °C with only 2%. Other than that, the higher temperature also contributed to the higher percentage of chips due to the case hardening of copra, hence the small broken pieces.

Figure 3. Hot air drying of copra (Pestaño & Jose, 2016)

Interestingly, the recovery of oil extracted from samples dried at 60, 70, 80, and 90 °C was 65.27%, 67.10%, 42.70%, and 40.1%, respectively.

Another attempt was made by Guarte et al. (1996), where the study focused on the single layer of halved nuts, consisting of the meat and the shell. The divided nuts were dried at temperatures ranging from 40 to 100 °C and oriented upwards and downwards with respect to the direction of the air stream, and drying times decreased exponentially as the drying temperature increased. For producing high-quality copra and coconut oil in the shortest amount of time, a drying temperature of 90 °C is recommended. Guarte et al. (1996) also concluded that there was no significant influence on the position of halved nuts during drying. The findings from Deepa et al. (2015) and Guarte et al. (1996) are consistent with the research done by Satter (2001), where moisture removal from wet copra increases with temperature. Nevertheless, the study also mentioned a limitation to the temperature used without compromising copra quality. Moreover, prolonged exposure of copra to temperatures beyond 90 °C may cause the copra surface to become hard and scorched as a result of further moisture and oil removal.

A recent attempt also declared that a handy electrical heat dryer, designed, fabricated, and tested by Thiyagarajan et al. (2020), can considerably reduce the drying period of copra. The results also revealed that the copra could reach its final moisture content of 6% in just 11 hours with better quality in colour and aroma. In a different approach to drying desiccated coconut, Yahya et al. (2020) reported that a specially designed cabinet dryer using the tumbling effect had proven that temperature, air velocity, and rotational speed of the tumbler played a significant role in the drying time of desiccated coconut. Unlike desiccated coconut, coconut residue, also called low-fat desiccated coconut, is a by-product of coconut milk extraction. At a 50–110 °C drying temperature, the drying time and drying rate (DR) were 540–100 minutes and 0.0048–0.0182 g water/g minutes, respectively (Wutthigarn et al., 2018). A research study by Jongyingcharoen et al. (2019) also likewise tracked down those drying temperatures (50–80 °C) and layer thickness (5–10 mm), which contributed altogether to the drying time, whiteness, and oil content of coconut residue.

On the other hand, there was a study done by Prieto et al. (2011) with regard to drying green coconut pulp. It was reported that drying in a cabinet dryer at 70 °C led to a better and more snack-like product after 8 hours of drying. However, it largely depends on the degree of maturity and fat content of the coconut. In an attempt to use a laboratory cabinet dryer, many authors (Abidin et al., 2014; Pestano & Jose, 2016; Sarkar et al., 2020) have discovered interesting findings with regard to coconut slices, copra, coconut cut, and desiccated coconut, respectively.

Fluidised Bed Drying

Fluidised bed drying is one of the most successful due to its extensive mixing behaviour, which speeds up heat and mass product transfer. Due to the amount of free water on the product surface, the moisture content reduced significantly in the early drying stage, as expected, before it became more difficult to expel water. The chopped coconut was dried at drying temperatures of 60–120°C at a constant velocity of 2.5 m/s to dry from around 105% d.b. to roughly 3% d.b., according to Madhiyanon et al. (2009). In another study, Niamnuy and Devahastin (2005) discovered that air velocity and temperature influence the drying kinetics and qualitative features of dried coconut, such as colour and surface oil content.

Interestingly, air velocity has played a more important role in determining the quantity of oil on the surface of dried coconut than the inlet temperature. For green coconut pulp, drying at 70°C using a pulsed fluidised bed dryer was reported to be advantageous due to its high productivity and ability to produce a snack-like product (Prieto et al., 2011). A schematic diagram of a fluidised bed dryer can be seen in Figure 4.

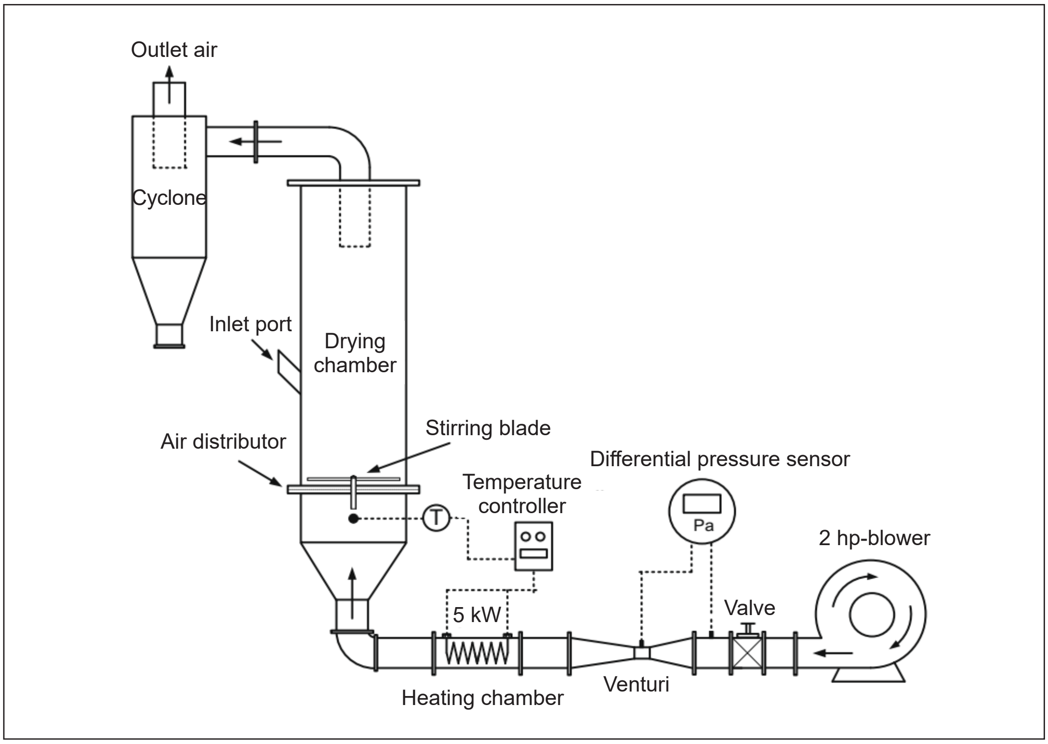

Figure 4. Schematic diagram of fluidised bed dryer for drying coconut kernel product (Madhiyanon et al., 2009)

Solar Drying

Solar dryers are becoming more popular as a drying method because they are cost-effective and energy-efficient. Nevertheless, the efficiency of solar dryers depends on the type, design, and material used. Figure 5 shows the schematic diagram of a solar dryer used to dry copra. A solar dryer with an evacuated tube collector achieved 70°C of drying air and could dry 20 kg of copra in 28 hours from an initial moisture content of 52.5% to a final moisture content of 7%, according to Krishna and Mathew (2018). Apart from that, the efficiency of the evacuated solar collector, which is incorporated with 30 tubes, was claimed to reach 44%, producing a better quality of copra with a minimum drying time. In another approach by Mohanraj and Chandrasekar (2008b), it was suggested that applying forced air convection in a solar dryer could produce more than 75% of high-quality milling copra grade 1 (MCG1) with 24% thermal efficiency. The authors also mentioned that the copra obtained was free of smoke, dust, and rodent damage.

Research findings by Thanaraj et al. (2007) also point to the advantages of solar dryers. It was found that the solar dryer was superior to the kiln dryer when it came to the high quality and yield of the white copra. Similarly, Arun et al. (2014) discovered that combining a solar tunnel greenhouse dryer with a biomass backup heater shortened the drying time of copra by allowing the biomass heater to deliver heat to the dryer during periods of low sunlight intensity. As a result, copra dried in a solar tunnel greenhouse dryer will be of higher quality than copra dried in the open sun.

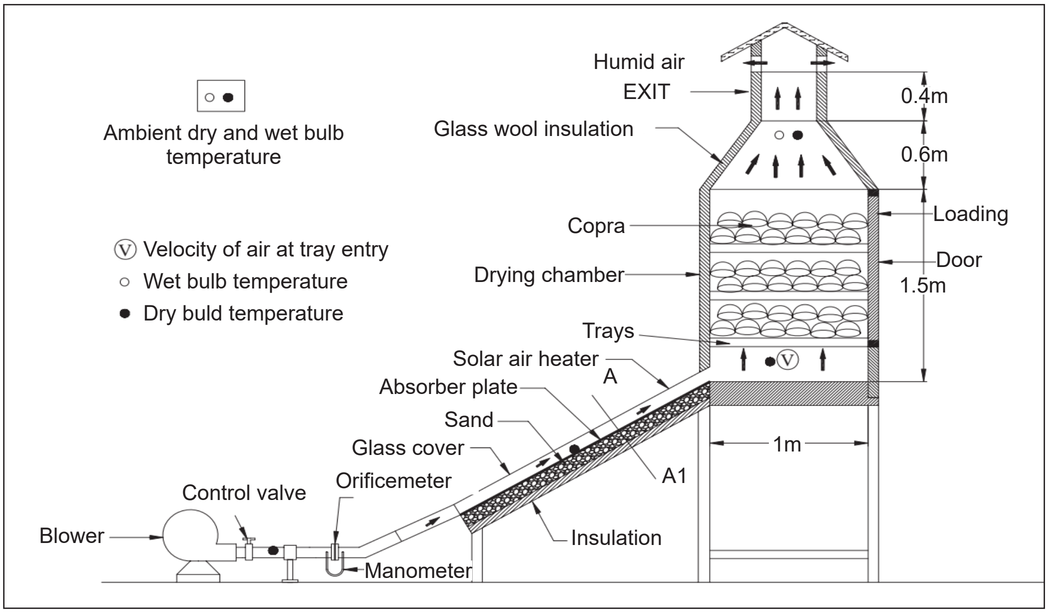

Figure 5. Schematic diagram of the solar dryer for drying copra (Mohanraj & Chandrasekar, 2008b)

Heat Pump Drying

A heat pump dryer is a promising technology for preserving product quality while reducing drying energy usage, especially for high-value products such as fruits and vegetables. To preserve the quality of the product, Mohanraj et al. (2008) found a potential method to dry copra using a heat pump. The experiments were conducted at a significantly lower temperature (40 °C) with a 1.5 m/s air velocity. According to the findings, the moisture content of the copra was reduced from 52.6% (wet basis) to 8.5% in 48 hours. Because 92.7% of the dried copra was classified as milling copra grade 1 (MCG1), heat pump drying is better suited for large-scale copra processing and generating high-quality oil (MCG1). Even though the drying period is longer than fluidised bed drying, heat pump drying retains colour, has better physical properties, and is suitable for heat-sensitive products (Salehi, 2021).

Furthermore, with the ability to recover latent and sensible heat, energy efficiency in heat pump drying can be significantly improved, which would otherwise be wasted in the environment in conventional dryers (Fayose & Huan, 2016). A schematic diagram of heat pump drying is shown in Figure 6.

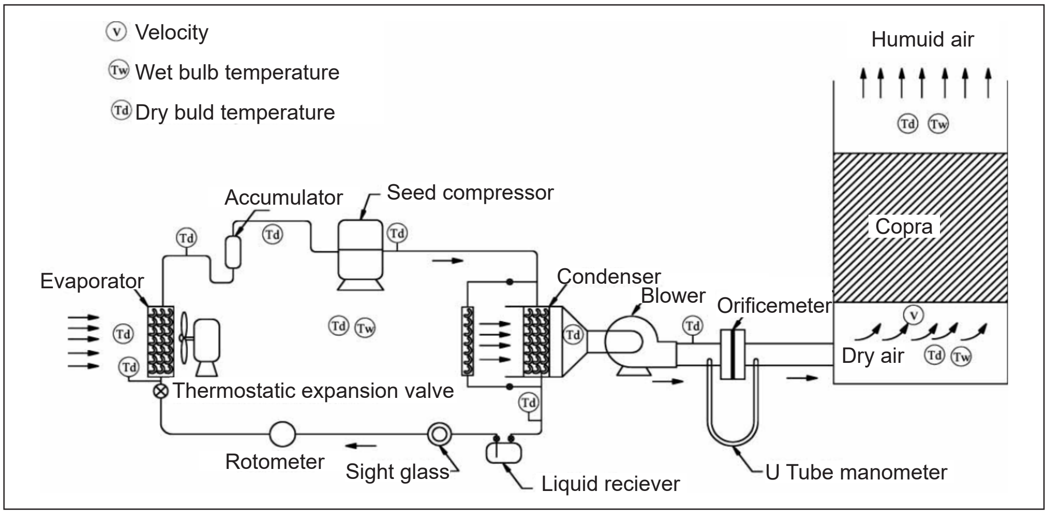

Figure 6. Schematic diagram of heat pump drying (Mohanraj et al., 2008)

Microwave Drying

One modern technique is microwave drying, which employs radiation as a heat source to dry food products. Microwave drying is a potential food dehydration method since it frequently results in a significant decrease in drying time and improved product quality (Feng et al., 2012). Using microwave energy to dry food products is a good solution to some of the problems with traditional drying. Domestic microwave ovens expose food to microwave radiation, typically at 2450 MHz (Sutar & Prasad, 2008).

Various food products have been investigated using microwave dryings, such as corn (Liu et al., 2021), radish (Lee et al., 2018), and bamboo shoots (Bal et al., 2010). With regard to coconut, there was also a study done by Moses et al. (2013). The study found that microwave drying at 180 and 360 W improved the desiccated coconut's colour, indicating that the microwave technique could potentially be used to produce a better-quality product.

However, desiccated coconut had a higher rehydration capacity at much higher microwave powers (720 and 900 W) as a result of the structural damage caused by overheating and rapid drying (Moses et al., 2013). Similar findings were also reported by Tepe and Tepe (2020), whereby the rehydration ratio of dried apple slices using the microwave was greater than hot air drying. The details of the drying parameters and the effect of drying methods on coconut kernel products for the past ten years are summarised in Table 2.

Table 2
Summary of drying methods, parameters, and significant findings of coconut kernel products for the past ten years

Drying method	Coconut kernel product	Drying parameters	Significant finding(s)	References
Solar dryer	Copra	The drying chamber was at 70°C. The collector efficiency was 44%.	Required 28 hours to complete drying of copra.	(Krishna & Mathew, 2018)
		Solar tunnel greenhouse dryer type. Combine polyethene film with biomass backup heater.	It required about 44 hours to complete the drying of the copra. Biomass heater provides backup heating. Copra produced was better than sun drying.	(Arun et al., 2014)
Fluidised bed dryer	Chopped coconut	Comparing parameters: First part: inlet air temperature of 65°C and air velocity of 3.82 m/s. Second part: stepwise change in inlet air temperature of 65, 80, and 120°C, and air velocity of 5.94, 4.98, and 3.82 m/s.	Drying from 60% d.b to 2% d.b. The colour of the dried product was most affected by inlet air temperature, while the quantity of surface oil was more affected by air velocity	(Deng et al., 2019)
	Coconut residue	Drying air temperature of 70–100°C and air velocity of 1.07 m/s	The drying behaviour of coconut residue was significantly affected by the air temperatures	(Kalayanamitra & Assawarachan, 2022)
Microwave dryer	Desiccated coconut	Samples with uniform size (~ 1 cm) were dried at power levels ranging from 180–900 W.	Colour changes were minimum at 180 and 360 W compared to conventional drying. Higher power levels caused higher rehydration capacity	(Moses et al., 2013)
Convective and cabinet dryer	Copra	Cabinet dryer with different drying air temperatures (60, 70, 80, and 90°C).	Required 24 hours of drying copra from 52% (w.b) to 6.1% (w.b) at 70°C. The fastest drying period (12 hours) was at 90°C. Based on the BIS standard, the best quality copra was obtained at a drying temperature of 70°C.	(Deepa et al., 2015)

Table 2 *(continue)*

Drying method	Coconut kernel product	Drying parameters	Significant finding(s)	References
		The handy electrical convective heat dryer with SMER was about 0.12 kg/kWh. It has a drying rate of 0.0001 kg/s with 0.2265 m^3/s of mass air flow rate.	Managed to dry copra in 11 hours, with 92.7% of the copra graded as MCG1.	(Thiyagarajan et al., 2020)
	Desiccated coconut	Three factors of drying parameters (air temperature, air velocity, and rotational speed of the tumbler) were studied using a convective dryer with a tumbler.	A combination of 60°C, 6 RPM, and 4.31 ms^{-1} had the shortest drying time and the highest drying rate. The drying rate rose as the air temperature, rotating speed, and air velocity increased.	(Yahya et al., 2020)
	Coconut residue/ low-fat desiccated coconut	Air drying temperatures of 50–80°C and 5–15 mm layer thickness.	Air drying temperatures and layer thickness essentially impacted drying time, whiteness, and oil content buildup. In the shortest drying period, the highest temperature and thinnest layer were achieved (70 minutes).	(Jongying-charoen et al., 2019)
		A thickness of 1 cm of coconut residue and drying at 50, 60, 70, 90, and 110°C. The air velocity was fixed at 1 m/s. The targeted final moisture content was 0.03 g water/g dry matter.	An increase in drying temperature by 20°C reduced drying time by 50 minutes or higher.	(Wutthigarn et al., 2018)
	Coconut chips	Immediately after osmotic dehydration, the samples were dried using a forced hot air electric tray dryer at 70–80°C.	The drying time was about (5–6 hours)	(Manikantan et al., 2015)
	Coconut slices	Hot air batch dryer with about 30–40% relative humidity. Drying air temperatures (60–80°C) and a constant air velocity of 0.80 ms^{-1} were used.	At 80°C, it produced the shortest drying time of 181.05 minutes.	(Pestaño, 2015)
		Hot air batch dryer with a single layer of thinly sliced coconut meat.	Produced white copra with high-quality coconut oil and clean white pressed cake. High-quality copra with aflatoxin and PAH-free.	(Pestaño & Jose, 2016)

Table 2 *(continue)*

Drying method	Coconut kernel product	Drying parameters	Significant finding(s)	References
	Coconut strips	The pre-treated coconut strips (three different sucrose solution concentrations and immersed in three different water bath temperatures) were dried in an oven at a drying temperature of 60 °C.	As the pre-treatment temperature increased, the initial drying rates were reduced.	(Agarry & Aworanti, 2012)
	Coconut cuts	Pre-treated with different concentrations of sugar solutions (40, 50, and 60° Brix), and the temperature of the solution was maintained at 35, 45, and 55°C. The drying process was then done at 60°C and 60% relative humidity.	Osmotic dehydration reduces the drying time considerably. It also had a considerable impact on coconut thermal air drying.	(Sarkar et al., 2020)

MATHEMATICAL MODELLING OF COCONUT KERNEL PRODUCT

A proper understanding and research of physical phenomena during the drying process are crucial to identify the behaviour of the product being dried. For this reason, drying kinetics or mathematical modelling of drying is a necessary tool for quantitatively describing the physico-chemical changes of a product. Thin layer drying equations are one of the most frequently used by researchers and can be categorised into three different types of models, such as theoretical, semi-empirical, and empirical (Mühlbauer & Müller, 2020).

These models have been used in identifying and verifying appropriate drying methods and parameters by obtaining the best-fit kinetic model for certain drying conditions and products. There are many types of products whose drying behaviour can be explained through drying kinetic models. Table 3 shows the drying kinetics models, effective moisture diffusivity and activation energy for coconut kernel products using different drying methods. Theoretical models are based on Fick's second law of diffusion, where D represents the diffusion coefficient as shown in Equation 1:

$$\partial MC/\partial t = \nabla^2 . D . MC \quad (1)$$

where MC is the moisture content on a dry basis (d.b), t is the time (s), and D is the moisture diffusivity (m^2/s). Like many agricultural and food products, they can be prepared and processed into several types of geometries to suit the final product requirement and the unit operation involved. However, to solve the equation, geometry has to be idealised as a sphere, cylindrical or cuboid with assumptions such as homogeneity, uniform temperature distribution, neglect of volume shrinkage or constant moisture diffusivity, which can lead to substantial differences between experimental data and calculated drying curves. On the other hand, Semi-empirical models are based on diffusion theory and are thus valid within the experimental range of temperature, relative humidity, air velocity and moisture content. It can also be described by Newton's Law of Cooling (Equation 2):

$$MR = \frac{MC\ (t) - MC_{eq}}{MC_1 - MC_{eq}} = exp(-k_o . t) \qquad (2)$$

where MR is the moisture ratio, $MC(t)$ is the moisture content of a product measured or determined during drying, MC_1 is the moisture content of a product prior to the start of drying, MC_{eq} is the moisture content of a product in equilibrium with mean dry bulb temperature and relative humidity of the drying air, t is the time (s) and k_o represents the drying coefficient. Therefore, semi-empirical models provide some understanding of the transport processes during the drying operation. Nevertheless, due to some simplifications required, accuracy is still lacking. Researchers have used and applied many semi-empirical models, such as Lewis/Newton, Page, Henderson/Pabis and Two-term, Logarithmic.

Unlike the semi-empirical model, the empirical model strongly relies upon experimental conditions without thought of the transport processes and fundamentals of drying. Some empirical models observed that the Page model adequately captured the drying characteristics of sliced coconut meat at 80°C in their kinetic modelling of coconut kernel products Kalayanamitra and Assawarachan (2022). Research findings by Madamba (2003) and Pestaño (2015) also point towards drying kinetic modelling on osmotic coconut strips and found that the Page model better fit the experimental data. Interestingly, the Page model successfully fits the coconut kernel product and other commodities, such as tubers (Vera et al., 2021). The success of Page's equation is connected to incorporating the term *n* in the equation and to a phenomenological justification for its consideration tracked down through the solution of diffusion phenomena (Simpson et al., 2017).

In another experiment with grated coconut, Abidin et al. (2014) reported that the Logarithmic model at 60°C is the most accurate prediction for the drying kinetics of grated coconut via oven drying. Nonetheless, the author only compared a few models in the trials. Wutthigarn et al. (2018) also examined a similar drying method, whereby a Linear plus-exponential model provided the best fit for drying coconut residue or so-called low-fat desiccated coconut. The only thing lacking in the studies made by Abidin et al. (2014), Pestaño (2015) and Wutthigarn et al. (2018) was no further investigation on the effective moisture diffusivity and activation energy. In a different study using the fluidised bed drying method, Madhiyanon et al. (2009) found that the Modified Henderson and Pabis model was the most precise model to describe the drying behaviour of chopped coconut, as reflected by the highest value of R^2 and the lowest value of root mean square error (RMSE). In contrast, Kalayanamitra and Assawarachan (2022) reported that the Midilli model had satisfactorily predicted the drying behaviour of coconut residue under the same fluidised bed drying method. It could be due to the different types of coconut kernel products, which behave differently when it comes to drying.

Interestingly, some researchers that worked on coconut residue products had suggested different drying models: linear plus exponential and Midilli using hot air and fluidised bed drying, respectively (Kalayanamitra & Assawarachan, 2022; Wutthigarn et al., 2018). Another attempt by Moses et al. (2013) claimed that the Midilli model better predicted desiccated coconut's drying behaviour during microwave drying.

According to Mohanraj and Chandrasekar (2008b), effective moisture diffusivity is determined using Fick's diffusion equation for objects having spherical geometry, such as chopped coconut and using Equation 3 as follows:

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \left(- \frac{n^2 \pi^2 D_{eff}\, t}{r^2} \right) \tag{3}$$

where D_{eff} is the effective diffusivity (m^2/s, r is the radius of the sphere (m), and n is the positive integer. Taking into consideration the first term in the series Equation 4 and the natural logarithmic form as follows:

$$ln\, MR = ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2\, D_{eff}\;\, t}{r^2}\right) \tag{4}$$

Other than the assumption of sphere geometry, there was also a study done by (Agarry & Aworanti, 2012), where the assumption of the slab was used for coconut strips. Equation 5 is as follows:

$$ln\, MR = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2\, D_{eff}\;\, t}{4l^2}\right) \tag{5}$$

where l is the thickness (m) to determine the effective diffusivity coefficient (D_{eff}). First, the slope of the relationships between ln MR and time (Equation 4) is computed, and D_{eff} is then calculated by the following Equation 6:

$$Slope = \frac{\pi^2\, D_{eff}}{r^2} \tag{6}$$

In the case of the effective moisture diffusivity value of coconut kernel product, it can be seen that Madhiyanon et al. (2009) reported that the value was higher than the one produced by Agarry and Aworanti (2012). The different drying methods and parameters predominantly cause the difference in value. Compared to a fixed bed or tray dryer, fluidised bed drying produces a more consistent temperature, which speeds up the moisture removal of the product. It is proven as the moisture diffusivity of chopped coconut using a fluidised bed dryer (Madhiyanon et al., 2009) was much higher as compared to coconut strips using hot air drying (Agarry & Aworanti, 2012; Madamba, 2003). Similar findings were published by Motevali et al. (2016) and Sharabiani et al. (2021), who found that increasing hot air temperature and air velocity improved moisture diffusivity for certain agricultural products (leaves and apples, respectively). As far as pre-treatment is concerned, osmotic pre-treatment increases the effective moisture diffusivity of the coconut kernel product. Similar trends were also noticed by Ramaswamy and Nsonzi (2007) and Revaskar et al. (2014) on the effect of pre-treatment on moisture diffusivity.

For further analysis, activation energy could also be obtained from the Arrhenius correlation, which demonstrates the effective diffusivity's reliance on temperature as shown in the following Equation 7:

$$D_{eff} = D_o \exp\left(\frac{E_a}{RT_{abs}}\right) \quad (7)$$

where D_o is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (kJ/mol K), and T_{abs} is the absolute temperature (K). By taking the natural logarithm of both sides, the above exponential form of Arrhenius can be transformed into a linear, logarithmic form, and the E_a can be computed from the slope of Equation 8:

$$\ln D_{eff} = \ln D_o - \frac{E_a}{RT_{abs}} \quad (8)$$

While many research findings investigated the activation energy of rice products using various drying methods (Ahou et al., 2014; Anuththara et al., 2019; Khanali et al., 2016) and apples (Cruz et al., 2015; Meisami-asl et al., 2010; Sharabiani et al., 2021), very few studies have been done on coconut kernel products except the one that was reported by Kalayanamitra and Assawarachan (2022) and Madhiyanon et al. (2009). Table 3 shows that the result of the activation energy of chopped coconut was 25.92 kJ/mol, which was close to the other findings of coconut residue at 26.09 kJ/mol using the same fluidised bed drying method. Only two drying methods, fluidised bed drying and hot air drying, were used in the previous studies on drying kinetics. It demonstrates that work on coconut kernel products, particularly in drying kinetics, is still lacking. Research in finding the activation energy of coconut kernel products with different drying methods is necessary for designing alternative and better drying systems.

Table 3
List of drying kinetic models, moisture diffusivity and activation energy for coconut kernel product

Coconut kernel product	Best fit model	Moisture diffusivity (D_{eff}) and Activation energy (E_a)	Drying method	eferences
Chopped coconut	Modified Henderson and Pabis	D_{eff} = 5. 9902 × 10^{-8} to 2.6616 × 10^{-7} m^2/s E_a = 25.92 kJ/mol	Fluidised bed drying	(Madhiyanon et al., 2009)
Osmotic Coconut strips	Page	D_{eff} (osmosised)= 5.74 to 7.88 × 10^{-10} m^2/s D_{eff} (non-osmosised) = 5.44 × 10^{-10} m^2/s	Hot air drying	(Agarry & Aworanti, 2012)
Osmotic pre-dried young coconut strips	Page	D_{eff} = 1.71 to 5.51 × 10^{10} m^2/s	Oven drying	(Madamba, 2003)
Grated coconut	Logarithmic	-	Convective oven	(Abidin et al., 2014)
Coconut residue	Linear plus-exponential	-	Hot air drying	(Wutthigarn et al., 2018)
	Midilli	E_a = 26.09 kJ/mol	Fluidised bed drying	(Kalayanamitra & Assawarachan, 2022)
Coconut slices	Page	-	Hot air drying	(Pestaño, 2015)

CONCLUSION

The drying methods, parameters, and types of final products predominantly influence the drying behaviour and characteristics of coconut kernel products. For drying parameters, it is deliberately mentioned that air temperature, velocity, and pre-treatments contributed to the increment of the drying rate and the quality of the final coconut kernel product. Apart from that, it is well understood that certain traditional products, such as copra, do not need pre-treatment prior to drying, while some recent developments in new products, such as desiccated coconut and osmosised coconut strips, do need pre-treatment beforehand to retain some quality standards set by the industry. However, there has been no research into optimising coconut kernel products' drying process. In terms of the drying method, it is clearly stated that physico-chemical properties and the coconut kernel product market determine the drying method being applied. It is true as most copra products go through the traditional way of drying and serve as second-grade products, whereas products like desiccated coconut and coconut flakes use a more advanced drying technique, such as fluidised bed drying. Convective drying, such as cabinet drying, remains the most popular method for coconut kernel products. Nevertheless, as technology advances, there is still room for research in drying coconut kernel products, particularly using other recent drying techniques such as hybrid and non-thermal pre-treatments. Also, very few studies have been carried out on the drying kinetics model of coconut kernel products, and among the models presented, it was found that most of the well-suited models were semi-empirical type models. The Page model performed the best in fitting the drying of coconut kernel products. Also, very few studies were reported on the effective moisture diffusivity and activation energy of coconut kernel products compared to other agricultural products.

Finally, more comprehensive studies regarding drying parameters, pre-treatment methods, appropriate kinetic models, and optimisation of drying could provide a better understanding of the drying of coconut kernel products, thereby contributing to an efficient drying method and high quality of the final product. In the future, other recent drying methods, such as radiation-type and hybrid drying, could also be considered with more systematic design protocols. Moreover, attempts should also be made to scale up certain laboratory drying methods to an industrial scale.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Universiti Putra Malaysia (UPM) and the Malaysian Agricultural Research and Development Institute (MARDI) for their PhD scholarships, technical support, and guidance towards the success of this research work. On top of that, the authors also express gratitude for the financial support for this research provided by the Universiti Putra Malaysia under the *Inisiatif Putra Siswazah* Research Grant (GP-IPS/2022/9722300) with VOT number: 972230.

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