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A review of different drying methods and their impact on physiochemical and functional properties of nutmeg and star anise

Gunaratnam Abhiram [1, 2 *]

[1] *Environmental Sciences, School of Agriculture & Environment, Massey University, Private Bag 11 222, Palmerston North 4442, New Zealand.*

[2] *Department of Export Agriculture, Faculty of Animal Science and Export Agriculture, Uva Wellassa University, Badulla, Sri Lanka.*

**Email: abhiram@uwu.ac.lk*

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Abstract

Drying is a simple method of preservation and value addition of spices. The moisture content of the spices curtails during the drying, which decreases the biological and enzymatic activity and prolongs the shelf life. The drying method significantly influenced the flavour, chemical composition, appearance, colour, and functional properties of the bioactive compounds. Several new drying technologies are being tested to improve the physiochemical properties of the nutmeg and star anise. This article reviews different solo-drying techniques, such as sun drying, solar drying, infrared and microwave drying as well as hybrid drying such as microwave and infrared-assisted drying applied to nutmeg and star anise. Further, it discusses the impact of drying methods on chemical composition and functional properties. The advantages of novel hybrid drying techniques over conventional methods are also discussed. Further, this review identifies the research gaps and future directions for drying nutmeg and star anise.

Keywords: Aroma, conventional drying, essential oil, novel hybrid drying, spices

Introduction

Spices are plant-derived substances such as fruits, seeds, bark, buds, and roots that can impart colour, aroma, taste, and flavour to food. Nutmeg (*Myristica fragrans* Houtt.) is a fleshy fruit which provides two different spices; nutmeg seed and mace (red colour aril) (Meetha *et al.,* 2016). Dried nutmeg seeds and mace have distinct and delicate flavours, thus they are used as spices in the food industry. Apart from this, it has been used in traditional medicine for stomach-related diseases (Anandu & Potluri, 2018). The nutmeg seed contains around 16% of secondary metabolites, mainly essential oil (Nikolic *et al.,* 2021). Approximately 80% of essential oils are composed of monoterpenes, while aromatic ethers make up around 8% of essential oils (Srinivas *et al.,* 2020). Myristicin is an aromatic ether, present in nutmeg that provides the characteristic flavour (Nikolic *et al.,* 2021). The fruit part of the star anise (*Illicium verum*) is used as a spice since it has a distinctive liquorice taste (Huang *et al.,* 2012). In traditional medicine, star anise has been used for colic and rheumatism, and as a digestion aid (Huang *et al.,* 2012). Besides the chemical compounds present in star anise such as aldehyde, alcohol, ketone, and ester, chemical compounds such as estragole, *cis*-anethole, anisaldehyde, and *trans*-anethole are responsible for the unique flavour (Wen *et al.,* 2021).

Chemical compounds in star anise and nutmeg exhibit several functional properties (Bhavaniramya *et al.,* 2019; Pan *et al.,* 2022). Nutmeg and star anise have around 16% and 10% of essential oil on a dry basis (Wong *et al.,* 2014). The functional properties of a few chemical compounds of star anise are; antifungal activity is shown by anethole (Huang *et al.,* 2010) and terpenoids (Caccioni & Guizzardi, 1994), antioxidant activity is possessed by monoterpenes (Yu *et al.,* 2021) and antiviral property is exhibited by shikimic acid, illiverin A and tashironin A (Patra *et al.,* 2020). Similarly, nutmeg essential oil also displays antioxidant, antibacterial, anti-inflammatory, anti-carcinogenic and hepatoprotective activities (Naeem *et al.,* 2016; Shi *et al.,* 2021). Therefore, essential oils from nutmeg and star anise are added as flavouring agents in many food items such as candies, confectioneries, liquors, and meat (Zhao *et al.,* 2019; Pateiro *et al.,* 2021; Moshrefi Zenoozi *et al.,* 2022).

Both nutmeg and star anise can't be stored for an extended period in a fresh form as they have a high moisture content that favours microbial growth and with storage time quality deteriorates. The moisture content of star anise in fresh form is around 75% (w.b) and dried form is around 12.5% (w.b) (Shi *et al,,* 2021) whereas the moisture of nutmeg in fresh form and dried form is 66% (w.b) and 6% (w.b), respectively (Srinivas *et al.,* 2020). Traditionally, both these spices have been preserved using the sun drying method as it is a low-cost and more convenient method (Srinivas *et al.,* 2020; Shi *et al.,* 2021). Nevertheless, several constraints such as nonuniform drying, low drying rate and variable solar radiation intensity are identified with this method which decreased the quality of the final product. As a result, high rejection rates were reported for the spices dried with the solar drying method in the global market (Dahlan *et al.,* 2018). Therefore, alternative methods are being adopted for drying these spices. They can be broadly categorized as solo and hybrid drying techniques. Hot-air drying (Ihsan *et al.,* 2021), solar drying (Sembiring, 2020), microwave drying (Nam *et al.,* 2017; Alfiya *et al.,* 2023), far infrared radiation (Shi *et al.,* 2021) and smoking with sulphur (Zhao *et al.,* 2019) are few solo drying methods used in nutmeg and star anise drying. The hybrid drying techniques including microwave-assisted hot air drying (Meetha *et al.,* 2016), microwave-assisted fluidised bed drying (Srinivas *et al.,* 2020), infrared-assisted hot air drying (Anandu & Potluri, 2018) and solar-biomass hybrid drying (Pavane *et al.,* 2018) are reported in drying of both these spices.

The drying method and conditions determine the final quality, nutritional value and essential oil content of nutmeg and star anise (Srinivas *et al.,* 2020; Shi *et al.,* 2021). With drying some flavour and nutritional compounds are lost due to thermal denaturing and/or loss through evaporation (Shi *et al.,* 2021). It is well documented that extended drying periods and high temperatures negatively influenced the appearance and essential oil content (Dahlan *et al.,* 2018; Srinivas *et al.,* 2020; Budiastra *et al.,* 2021; Punetha *et al.,* 2022). Therefore, maintaining the optimum drying conditions ensures better quality products (Abhiram & Amarathunga, 2024). The optimum drying temperature for nutmeg and star anise is 45-49 °C and 80-100 °C, respectively (Zhai *et al.,* 2009; Srinivas *et al.,* 2020). The drying time needs to be shortened to minimise the evaporation of oil from the nutmeg seed (Sembiring, 2020) and retain more redness of mace (Meetha *et al.,* 2016). Moreover, maintaining a constant temperature during drying is also reported to increase the oil yield (Budiastra *et al.,* 2021). Both these spices have a variety of uses and therefore, the expected properties of spices (colour, aroma, chemical content, oil yield, etc.) vary according to the use. A particular drying method and condition may not provide the best outcome for all attributes of a spice thus the best drying method and condition have to be chosen based on the requirement (Shi *et al.,* 2021). For example, Shi *et al.,* (2021) reported that microwave drying is superior for the retention of shikimic acid whereas heat pump drying is better for trans-anethole retention in star anise. A dedicated review for the drying of nutmeg and star anise and their impact on quality attributes is scarce. Therefore, the present review critically analyses the drying methods, and their influences on the physical, chemical and functional properties of nutmeg and star anise.

Different drying methods and their impacts on properties

The drying characteristics and changes in properties of nutmeg and star anise affected by solo drying methods are discussed below and salient outcomes are shown in Table 1.

Solo drying

The traditional way of drying spices is using a single-type method (solo drying method), especially sun or shade drying. In addition, microwave drying, hot-air drying, heat-pump drying and infrared drying are other solo drying methods used for drying nutmeg and star anise. This section covers the solo drying methods used for drying both these spices and their impact on physicochemical and functional properties.

a) Sun drying

Drying agricultural commodities under direct or indirect sunlight has been employed as a cost-effective method for centuries. Nutmeg and star anise are traditionally dried on racks under solar radiation (Aktaş *et al.,* 2016). This method is highly preferred by farmers since it has been practised for a long time, is low cost and needs only limited knowledge of operations. Despite the fact that it is a low-cost and convenient method, there are several shortcomings in this drying method such as long drying time, the uncertainty of the weather, uneven drying, bleaching of the products, high microbial contamination, unfavourable changes in physical and chemical properties, high aflatoxin content, high residual moisture, low storability, requires large space for drying, *etc* (Orphanides *et al.,* 2016; Srinivas *et al.,* 2020; Shi *et al.,* 2021).

A comparative study between combinations of drying methods; sun drying and smoke drying, and extraction methods; ultrasound and maceration on nutmeg was conducted by Budiastra *et al.,* (2021). The nutmeg samples were dried under solar radiation for 8-10 hours up to 7 days and 5-6 hours for 5 days under smoke drying until 10% moisture content was reached (Table 1). For both methods, the drying temperature was 35-40 °C and relative humidity was 65-75%. It was reported that smoke-dried nutmeg seeds assisted with the ultrasound extraction method gave the highest oil yield of 23.63% and the lowest non-volatile content of 35.54%. Further, the colour of nutmeg oleoresin dried under smoke drying was better than solar drying. However, it has to be very cautious with smoke drying since it is reported as a potential source of carcinogenic compounds such as polycyclic aromatic hydrocarbons (Adeyeye, 2019). Dahlan *et al.,* (2018) investigated continuous and intermittent (every other day) sun drying of nutmeg seeds for 18 days and measured the moisture content and aflatoxins in the dried seeds (Table 1). The average temperature and RH ranged between 29 – 41 °C and 38 – 70%, respectively. The intermittent drying decreased the moisture content from 33.3% to 10.7% while continuous drying to 13.5%. Although more fungal contamination was observed in continuous drying (28%) compared to intermittent drying (26%), more percentage of aflatoxins (14%) were found in intermittent drying. This could be ascribed to the low temperature and high relative humidity (RH) observed in intermittent drying that favour the fungal growth and increased aflatoxin content. Therefore, this study suggests continuous drying control fungal growth and eventually decrease aflatoxins in the dried nutmeg seeds. Another study reported that the aflatoxin content of nutmeg seeds dried under the sun drying method (on a bamboo shelf) was 389.97 g kg^{-1} which was far above the European standard level of 10 µg (Sembiring, 2020). Srinivas *et al.,* (2020) reported that sun drying took longer drying time and yielded a lower amount of essential oil than microwave-assisted

Table 1. Different drying methods of nutmeg

Drying method	Dried component	Measured parameters	Best drying condition/s	Main advantage/s	Reference
Microwave-assisted fluidized bed drying	Nutmeg mace	Colour, oil yield, and myristicin quantity	48.24 °C dry bulb temperature, 637 W microwave power for 1.3 hour	High essential oil yield	Srinivas *et al.*, (2020)
Microwave-assisted hot air drying	Nutmeg mace	Colour & myristicin	1.445 kW microwave with hot air at 45 °C	Retain the colour and myristicin content of the mace	Meetha *et al.*, (2016)
Hot air drying	Nutmeg seed and mace	Drying rate	45 °C for 4 hours	Low-cost dryer	Ihsan *et al.*, (2021)
Pyramid Shape Solar-Biomass Hybrid Drying	Nutmeg seed	Temperature, relative humidity and moisture content	Not available	Energy efficiency high	Pavane *et al.*, (2018)
Hot air drying	Nutmeg seed and mace	Temperature and moisture loss	Not available	Product became brittle and crispiness last long for many days	Roopaljith & Vignesh (2022)
Sun drying and smoke drying	Nutmeg seed	Colour, moisture content, specific gravity, oleoresin and chemical compounds in oleoresin	Smoke drying with ultrasound-assisted extraction	Smoke drying with ultrasound-assisted extraction provided the highest yield (23.63%) and lowest non-volatile content (35.54%)	Budiastra *et al.*, (2021)
Sun drying; continuous and	Nutmeg seed	Temperature, moisture content	Continuous sun drying	Low mold growth and aflatoxin in continuous	Dahlan *et al.*, (2018)

intermittent drying		and aflatoxins		sun drying	
Infrared-assisted hot air drying	Nutmeg seed	Physical properties	N/A	Quick and equal drying rate	Anandu & Potluri (2018)
Sun drying, oven drying, and mechanical drying	Nutmeg seed and mace	Microbial population, colour, drying rate, oleoresin and oil content	Mechanical drying method	Mechanical drying showed better performance in drying rate, colour, microbial content and sensory evaluation than other methods	Kumar e *et al.*, (2017)
Solar drying, hot air oven drying & sun drying on bamboo shelf	Nutmeg seed	Drying rate, oleoresin & oil content	Drying time, moisture content, temperature, RH, oil content and oleoresin.	Solar drying and hot air oven drying were better than open sun drying to decrease aflatoxin	Sembiring (2020)

fluidised bed drying (Table 1). Kumar *et al.,* (2017) investigated the impact of different washing methods (running water, lukewarm water, lukewarm water with 100 ppm chlorine and lukewarm water with 1000 ppm alum) with sun and bulb drying in nutmeg seed and mace quality (Table 1). They found that colour was bleached for mace samples dried under the sun and bulb drying due to high temperature and long drying time. In this study, the time taken for drying mace and nut was 16 and 56 hours, respectively. Further, the lowest grade nutmeg mace and nut in terms of colour, aroma and appearance was achieved in sun drying compared to oven drying and mechanical drying (Kumar *et al.*, 2017).

There are a few studies that reported the sun drying of star anise. In a study, fresh star anise fruits were dried using four different methods; sun drying (SD), hot water treatment followed by sun drying (HWSD), smoking with sulphur (SS) and oven drying (OD) (Table 2) (Zhao *et al.,* 2019). It was found that the SD method retained better colour and aroma and provided high essential oil content, but the final product had with high residual moisture content (14.6%). Wen *et al.,* (2021) reported that sun drying took 23 hours to decrease the moisture content of star anise to 12.5% on a dry basis (Table 2). Further, they reported that volatile oil content was higher and gave a stronger aroma compared to hot air and infrared-assisted hot air drying.

Table 2. Drying characteristics of star anise under different drying methods

Drying method	Measured parameters	Best drying method/ condition	Main advantage/s	Reference
Hot air drying (HAD), heat pump drying (HPD), far infrared radiation drying (FIRD), microwave drying (MD), and sun drying (SD)	Colour, volatile oil, shikimic acid (SA) content, and transanethole content	HPD with blanching; 55 °C, RH 30% and 14 hours	HPD with blanching gave the highest volatile oil content and dominant flavour	Shi *et al.*, (2021)
Microwave heating	Constituents in essential oil	325 W microwave power, 20 min irradiation time and 0.4 mm particle sizes yielded the highest essential oil	Fast and easy extraction of essential oil	Nam *et al.*, (2017)
Sun drying (SD), hot water treatment followed by sun drying (HWSD), smoking with sulphur (SS) & oven drying (OD)	Drying rate, essential oil and its components, and antimicrobial activity	SD and OD drying methods	High essential oil retention and antimicrobial activity	Zhao *et al.*, (2019)
Infrared radiation-hot air (IR-HA) drying, hot-air drying (HA) & sun drying (SD)	Drying characteristics, volatile oil yield and composition, and sensory parameters and	IR-HA drying at 70 °C	Higher aroma, higher trans-anethole content & better surface colour	Wen *et al.*, (2021)
Microwave heating	DPPH radical scavenging assay, ABTS assay, total antioxidant activity,	140 W for a 30-minute microwave treatment	Higher antioxidant activity	Rao *et al.*, (2012)

	hydroxyl radical assay, nitric oxide radical scavenging and total reducing power.			
Improved sol vent-free microwave extraction (ISFME), conventional sol vent-free microwave extraction (SFME) and conventional hydrodistillation (HD)	Essential oil yield and composition	85 W microwave irradiation power for 30 min at 100 °C	Simpler, quicker, and more economical	Wang *et al.*, (2006)
Microwave heating with ironic liquid extraction (MW-IL)	Essential oil yield and composition	Sample to IL ratio 20: 1.5	Quick recovery and doesn't need stirring the mixture	Zhai *et al.*, (2009)

However, *trans*-anethole and characteristic components were lower than other drying methods. Star anise is fumigated with sulphur in order to cut down processing time and cost. Moreover, this pre-treatment deactivates the enzyme activity, decreases moisture and acts as a fungicide and insecticide to increase the shelf life of star anise (Zhao *et al.*, 2019). This study reported that sulphur treatment decreased the components of essential oil which could be due to the decomposition or transformation of these specific components to others (Table 2). Although sulphur treatment is beneficial for star anise processing, this may cause health issues for the consumers and therefore, it is not recommended.

b) Hot air drying

Hot air drying is a conventional method of food preservation in which thermal energy produced from biomass or electricity is used to dry the substances (Abhiram *et al.*, 2023b). The underlying mechanism of this drying method is the simultaneous transport of mass and energy into the drying material that evaporates the moisture from it. This drying method is commonly used for drying different spices such as bell pepper (Vega *et al.*, 2007), saffron (Neri *et al.*, 2021), ginger (Juhari *et al.*, 2012), mint leaves (Therdthai & Zhou, 2009), *etc.* Ihsan *et al.*, (2021) developed a low-cost hot-air nutmeg dryer for local nutmeg farmers. This dryer is equipped with temperature and RH sensors to monitor and control the drying conditions. This study reported that drying nutmeg mace at 45 °C for nearly 4 hours decreased the moisture content by 50%. In a study, Roopaljith & Vignesh (2022) used a hot air dryer to reduce the moisture content of nutmeg seed and mace (Table 1). The samples were dried under 50, 55 and 60 °C until a constant weight was obtained. Nutmeg seed and mace took nearly 110 and 130 minutes to reach equilibrium moisture content, respectively. In another study, nutmeg seeds were dried using electric fan heaters (1500 W) at 42 - 43 °C temperature and 46% relative humidity (Table 1) (Sembiring, 2020). This method provided 11.9 % of oil content and 11.8% oleoresin content from the dried nutmeg seed. According to Kumar *et al.,* (2017), hot air-dried nutmeg maces were dark brown in colour due to smoke and therefore, air filters can be used to prevent it (Table 1).

c) Infrared heating

Infrared (IR) is an electromagnetic wave and the wavelength range is between 0.78 – 1000 μm (Delfiya *et al.,* 2022). IR became a popular and effective way of drying different food commodities (Abhiram, 2018). During the IR heating, thermal energy is absorbed and penetrates into the material which evaporates the water from the substance. High heating rate, not heating the medium, maintaining the quality of products and uniform heating are a few advantages of the IR drying method (Abhiram & Amaratunga, 2014; Delfiya *et al.,* 2022; Abhiram *et al.,* 2023a). Only one study employed IR for the drying of star anise. This study was conducted to dry the star anise using far infrared (FIR) with and without blanching at 55 °C (Shi *et al.,* 2021). It was reported that blanched and non-blanched samples took 10 and 12 hours for drying, respectively (Table 2). In FIR heating, the volatile oil was denatured and/or evaporated due to overheating and rapid temperature development (Shi *et al.,* 2021). Therefore, intermittent IR drying could be a viable option to overcome this issue.

d) Heat pump drying

Heat pump drying is a widely used technique for drying spices (Thamkaew *et al.,* 2021). Heat pump dryers can simultaneously increase the temperature and dehumidify the inlet air. Shi *et al.,* (2021) dried star anise using different drying methods; hot air drying (HAD), heat pump drying (HPD), far infrared radiation drying (FIRD), microwave drying (MD), and sun drying (SD) with and without bleaching (Table 2). For most of the heat treatments, blanching provided better quality star anise and shortened the drying time compared to unblanched one. Damage to the cell membrane in blanching treatment could be ascribed to shorter drying time and similar observations reported for white ginseng (Ning *et al.,* 2019). Out of all these drying methods, HPD with blanching was chosen as the best method since it showed the lowest volatile oil and trans-anethole loss and retained better colour and flavour. Therefore, this study suggests blanching as a pre-treatment method to get better-quality products. In this study, volatile oil content decreased with blanching for all the treatments and it is well-documented for other spices as well (Straumite *et al.,* 2012; Thamkaew *et al.,* 2021). Nevertheless, this study found that important flavour compounds such as limonene and trans-anethole were higher for samples blanched and dried with HAD and HPD (Shi *et al.,* 2021).

e) Solar drying

Solar dryers have a protected chamber which minimises contamination with foreign bodies and has higher efficiency than sun drying (Mustayen *et al.,* 2014). Sembiring (2020) dried shelled and unshelled nutmeg seeds in a solar dryer with 4 trays at a temperature of around 37 – 42.5 °C and relative humidity of 31% (Table 1). It was reported that the moisture content of the unshelled and shelled seeds decreased to 15 and 7% in 29 hours, respectively. The lower drying level of unshelled seed was possibly due to the harder outer cover that minimised the heat and moisture movement. Although the essential oil yield of unshelled seeds dried in the solar dryer was only comparable with the sun drying method, the essential oil yield of shelled seeds was higher than sun drying. This suggests that solar drying didn't have a detrimental effect on the essential yield and quality parameters and therefore, authors recommended this method for large-scale production.

f) Microwave heat application

Microwave heat application is a rapid and easy method for extracting essential oil from star anise (Table 2) (Nam *et al.,* 2017). Moreover, this method is the most economical method for extracting the compound from plants (Hemwimon *et al.,* 2007) and reduces the solvent required for extraction (Nam *et al.,* 2017). In a study, different microwave powers (100 – 400 W) were applied for 10 – 40 minutes on star anise and essential oil was extracted using the Soxhlet extraction method (Table 2) (Nam *et al.,* 2017). The drying combination of 325 W microwave power and 20 minutes of irradiation provided the highest essential oil yield of 8.3%. This study found that a few ingredients such as a-pinene, ß-myrcene, a-phelandrene were absent in the essential oil which could impact the quality of the essential oil. A similar study was conducted by applying different microwave powers (140 – 320 W) for 5 to 30 minutes to extract star anise and this method was compared with the conventional Soxhlet extraction method (Table 2) (Rao *et al.,* 2012). The antioxidant activity according to 2,2-diphenyl-1-picrylhydrazyl radical (DPPH) assay of microwave-assisted extraction was higher than the conventional method. The authors reported that flavonoid content decreased with increasing microwave power and increased with increasing microwave exposure time. Excess application of microwaves possibly degrades the flavonoid content due to high-temperature development (Rao *et al.,* 2012; Routray & Orsat, 2012).

Shi *et al.,* (2021) reported that microwave drying shortened the drying time of star anise (Table 2). However, the volatile oil content was low since microwaves damaged the cells and increased the internal temperature of the cells. Nevertheless, high shikimic acid (SA) was reported for microwave drying compared to other methods (Shi *et al.*, 2021). Therefore, microwave drying can be a choice for drying star anise if fast drying and high SA are required or it can be combined with other drying methods to neutralise the shortcomings of microwave heating.

Novel hybrid drying techniques

Hybrid drying technologies are becoming popular since the disadvantage of a drying technique can be masked or compensated by the advantage of other techniques. In this method, the product is dried by two or more methods simultaneously or successively (Majumder *et al.*, 2021). Many findings confirmed that hybrid drying showed a synergetic effect which improves the drying characteristics and quality of the products (Srinivas *et al.*, 2020; Wen *et al.*, 2021; Feng *et al.*, 2022). Microwave-assisted drying, infrared-assisted drying and solar-biomass hybrid drying are used in the drying of nutmeg and star anise and they are discussed here (Tables 1 & 2).

a) Microwave-assisted drying

Hot air drying takes a relatively longer time than other methods such as microwave and infrared drying. The combination of the microwave with hot air drying improves the drying rate, shortens the drying time and increases the product quality (Behera *et al.*, 2017; Palamanit *et al.*, 2019). Microwave penetrates into biological substances and increases the vibration of water molecules by changing their polarity. This increases the friction between water molecules and biological substances and eventually increases the temperature of the substance. Surface moisture can be easily removed by microwave thus surface burning can be minimised (Majumder *et al.*, 2021). However, several disadvantages of microwave heating are understood; charring of substance due to localised heating (Mohanta *et al.*, 2014), non-uniform heating (Srinivas *et al.*, 2020), soggy surface and firm texture (Sumnu & Sahin, 2005). Therefore, microwave heating is combined with other heating methods like hot air drying and infrared to get a synergetic effect of both heating methods. Microwave-assisted hot air drying has been used in spice or spice-related food commodities such as parboiled rice fortified with turmeric (Palamanit *et al.*, 2019), garlic (Cui *et al.*, 2003), turmeric (Behera *et al.*, 2017) and ginger (Mohanta *et al.*, 2014).

Microwave-assisted hot air drying method was investigated for drying nutmeg mace with a focus on retaining the colour of the mace (Table 1) (Meetha *et al.*, 2016). Fresh nutmeg mace dried under three different microwave power levels (0.5, 1 and 1.445 kW) with 30s pulsation at 45 °C hot air temperature. The samples were dried under a microwave-hot air system for the first 3s, followed by one-minute distinct drying under hot air. This cycle was repeated for a total drying time of 45 minutes. The authors found that increasing microwave power levels increased the drying rate of mace. The colourimetric analysis revealed that the redness and yellowness of the mace dried under high microwave power (1.445 kW) were higher than those dried under low microwave power (0.5 kW). In microwave-assisted hot air drying, the water molecules are loosened and brought to the surface of nutmeg mace and subsequently, this moisture is absorbed by hot air (Meetha *et al.*, 2016).

In another study, a microwave-assisted fluidised bed was used to dry the nutmeg mace at three drying temperatures (40, 45 and 50 °C) and microwave powers (480, 640 & 800 W) until the equilibrium moisture content of 5.9% was reached (Fig. 1) (Srinivas *et al.*, 2020). Colour, oil yield and myristicin quantity were measured and multiple linear regression (MLR) and artificial neural network (ANN) were used to optimise the processing conditions (Table 1). The authors reported that drying time decreased by 60 to 70% by microwave energy. Increasing the microwave power, significantly ($P<0.05$) decreased the drying time. The total colour changes (ΔE) showed a convex relationship with drying time and microwave power. The colour of mace produced by this hybrid drying was better than convective drying and sun drying. There are two possible reasons for this observation; the first reason is the mace exposed for a short time in fluidisation bed drying and the second is the acceleration of enzymatic and non-enzymatic browning by microwave heating (Srinivas *et al.*, 2020). Microwave-assisted fluidised bed yielded high essential oil compared to the sun and convective drying techniques used in this study. This is attributed to the ironic conduction and dipolar rotation in microwave heating disrupting the oil globules and expelling a large amount of oil. Further, shorter drying time in microwave heating minimised the volatilisation of essential oil. Therefore, myristicin content was high in microwave-assisted fluidised bed drying. It is an aromatic ether most sensitive to temperature and oxygen and therefore, microwave drying is more conducive for retaining myristicin.

b) Infrared (IR) assisted drying

Although IR can shorten the drying time, it can overheat the sample and potentially destroy the volatile oil in spices (Shi *et al.*, 2021). Therefore, it is used along with other drying methods for rapid moisture removal. IR assisted drying technique has been proven to increase the drying rate and quality of the product than drying alone with IR (Delfiya *et al.*, 2022). For instance, IR drying is used with other drying methods; IR-fluidised drying of tea dhool (Kumara *et al.*, 2022), IR-hot air drying of turmeric (Jeevarathinam *et al.*, 2022), IR-microwave drying of mushroom (Wang *et al.*, 2019) and IR-solar drying of melon (Aktaş *et al.*, 2016). Anandu & Potluri (2018) used infrared-assisted hot air drying to dry the nutmeg seeds using the combination of IR power between 225 – 1,125 W with the steps of 225 W and time between 50 – 250 seconds with 50-second steps. This hybrid drying method provides quick and uniform drying of the nutmeg seed. Also, the authors reported that myristicin content and flavour were preserved in this method since IR only penetrate to a shallow depth of the biological substance.

Wen *et al.*, (2021) studied three different drying methods: infrared radiation-hot air (IR-HA) drying, hot-air drying (HA) and sun drying (SD) on the physiochemical properties of star anise (Table 2). The samples were exposed to three different temperatures; 60, 70, and 80 °C under IR-HA and HA drying. IR-HA drying method outperformed since it has provided higher richness values of aroma, volatile oil contents, and trans-anethole contents. The volatile content increases with breathing intensity in the pores. In IR drying, the pores structure is destroyed which decreases the breathing intensity and oil diffusion (Mariani *et al.*, 1989; Wen *et al.*, 2021). This study suggested that the optimum drying temperature was 70 °C and a higher temperature than this could deprive the quality of the final product. The more suitable IR wavelength for drying was between 3 and 9 μm. IR-HA method decreased the drying time by 95, 87 and 83% at 60, 70, and 80 °C, respectively compared to the HA drying method.

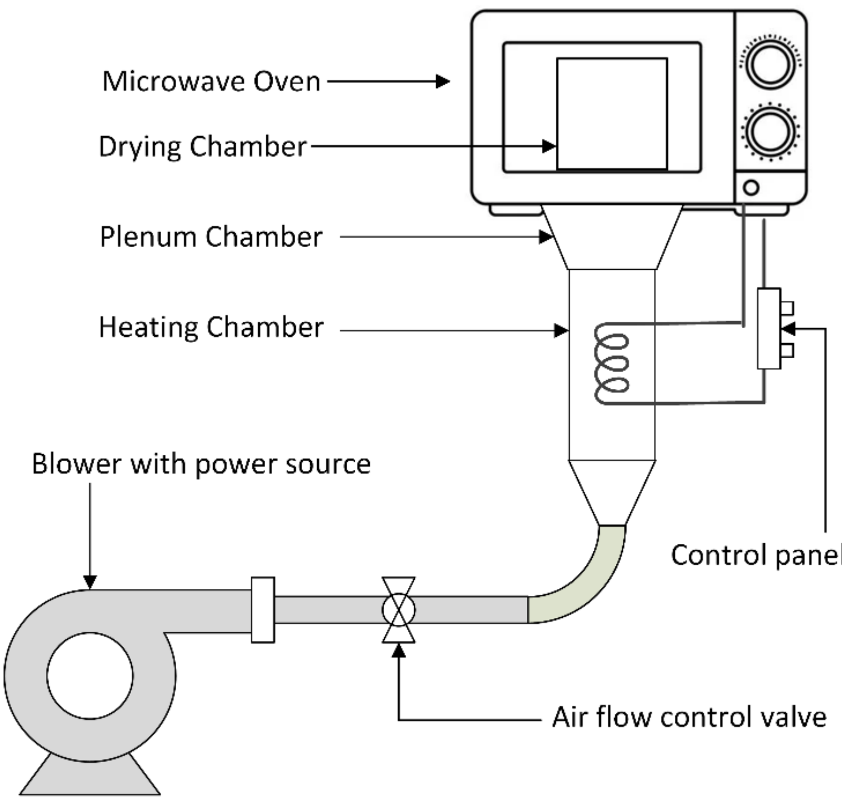

Fig. 1. Experimental setup of the microwave-assisted hot air dryer (adopted from Srinivas *et al.*, (2020)).

c) Solar-biomass hybrid drying

One of the main constraints of solar drying is lower efficiency during the wet season and days having low solar radiation. Therefore, solar-biomass hybrid dryers are used to overcome this issue. The biomass dryer coupled with the solar dryer provides additional heat energy by combusting the biomass when solar energy is not sufficient. A study was conducted with a pyramid-shaped solar-biomass hybrid dryer for drying the nutmeg seeds (Pavane *et al.*,, 2018). Solar energy is used as the primary source of energy and biomass combustor is used as a secondary source of energy. The main components of the dryer are shown in Fig. 2. The capacity of this dryer is 25 kg per batch. The average temperature developed in the dryer at no load was nearly 60 °C. The average moisture loss of nutmeg seeds was reported as 54% in 19 hours. This study didn't detail the physicochemical and functional property change during solar-biomass hybrid drying.

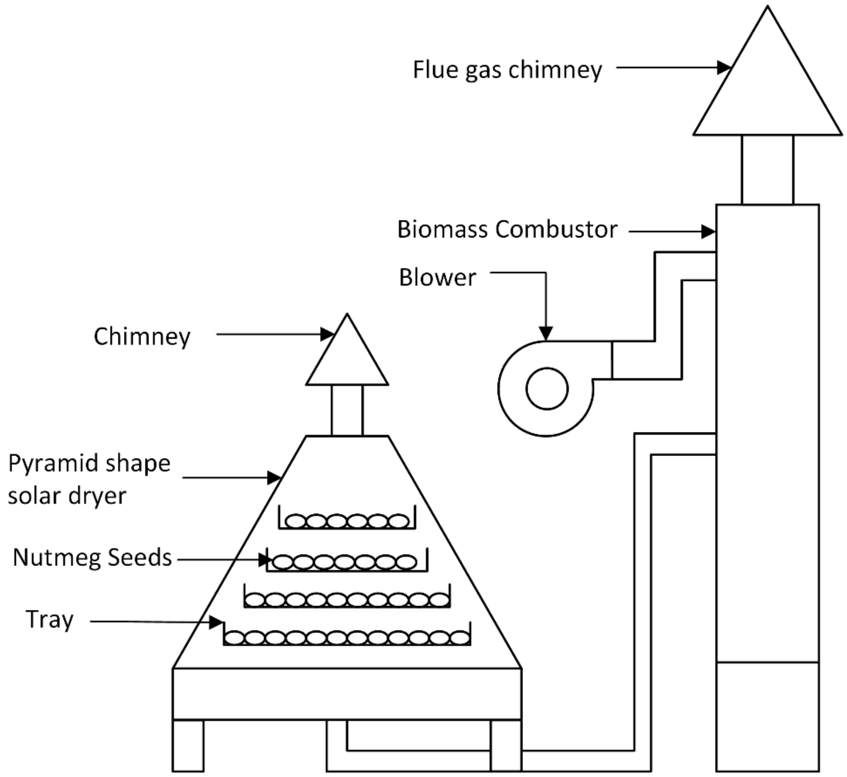

Fig. 2. The schematic diagram of the pyramid shape solar dryer and biomass combustor (adopted from Pavane *et al.,* (2018)).

Research gaps and future scope

The drying methods of nutmeg and star anise are targeted to increase the shelf life while retaining a high yield of bioactive ingredients such as essential oil and sustaining their functional properties. Additionally, colour, flavour, fast drying rate, and chemical composition of essential oil are other targeted attributes in drying. Various solo and hybrid drying methods have been employed to achieve these purposes. The common industrial-scale drying methods of these spices are sun drying, hot air drying, heat pump drying, microwave drying, and infrared drying. The results of these studies revealed that all drying methods have their own advantages and disadvantages. Therefore, the selection of a drying method is crucial to get a high-quality product. Several studies acknowledged that hybrid drying methods outperformed solo drying methods due to the synergetic effect. Only a few hybrid drying methods were tested in the drying of these spices. Newly emerging drying technologies such as freeze-drying assisted methods, cold plasma assisted drying, pulse electric field assisted drying, ultraviolet assisted drying, radio frequency assisted drying and reflectance window drying could be also potential methods for drying these spices. Only a few studies are available on the comparison of drying methods on star anise and therefore, more comprehensive studies are merited.

Optimisation of drying condition is an important step for enhancing the quality of the product, decreasing the drying time and increasing the energy efficiency. A few studies only detailed the optimisation of drying parameters and reported the optimum drying conditions. Several techniques are used for optimisation including response surface methodology (Abhiram *et al.,* 2023a), desirability function analysis (DFA), technique for order preference by similarity to ideal solution (TOPSIS) (Deng *et al.,* 2024), machine learning and deep learning methods (Martynenko & Misra, 2020). These methods could be used to improve the drying parameters and to get better characteristics of the final product. Pretreatments are a common method in spice drying aimed to reduce drying time and energy consumption and increase the quality of the product. The common pretreatment methods are blanching, pulsed electric field, and ultrasonic treatment. Of these methods, blanching pretreatment was employed in the drying of nutmeg. However, other pretreatment methods have not been tested for drying nutmeg and star anise.

Future studies need to be focused on adopting emerging drying technologies for both spices. In drying studies, high priority should be given to the optimisation of processing parameters of pre-drying and drying methods. Further, the intervention of machine learning and deep learning techniques are merited for more precise determination of quality attributes, drying modelling, characterisation, and process optimisation. Studies on changes in physiochemical and functional properties of dried spices with storage time are also beneficial to understanding how long these spices hold their beneficial characteristics.

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