# DEVELOPMENT OF MICROWAVE ASSISTED FLUIDISED BED DRYER FOR NUTMEG MACE

*by*

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## DECLARATION

I hereby declare that this thesis entitled **"Development of microwave assisted fluidised bed dryer for nutmeg mace"** is a *bonafide* record of research work done by me during the course of research and the thesis has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

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*Dedicated to*

*My beloved parents*

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*Yarrakula Srinivas*

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## SYMBOLS AND ABBREVATIONS

| | |
|---|---|
| > | Greater than |
| ≤ | Less than or equal to |
| % | Per cent |
| °C | Degree centigrade |
| Cm | Centimeter |
| d.b | dry basis |
| et al. | and others |
| FBD | Fluidized bed dryer |
| G | Grams |
| GHz | Giga Hertz |
| ha | Hectares |
| i.e. | that is |
| ID | Inner diameter |
| Kg | Kilogram |
| K.C.A.E.T | Kelappaji College of Agricultural Engineering and Technology |
| $kg/m^3$ | Kilogram per cubic meter |
| KJ/mol. | Kilo joule per mole |
| KWh | Kilowatthour |
| MJ/kg | Mega joule per kilogram |
| Ml | Milliliter |
| Mm | Millimeters |
| MT | Metric tonne |
| $m^2/min$ | Meter square per minute |
| MHz | Mega Hertz |
| OD | Outer diameter |

| | |
|---|---|
| RDA | Recommended Dietary Allowance |
| Rpm | Revolutions per minute |
| S | Second |
| W | Watts |
| w/g | watt per gram |
| $W/m^2$ | Watt per square meter |

# CHAPTER I

# INTRODUCTION

Spices are used for flavour, colour and aroma in food for more than 2000 years and also used in medicine because of their carminative properties. It is used for preservation of food and beverages primarily due to their phytochemicals (Embuscado, 2015). India is the Home of Spices. India produces almost all the known spices and is the largest exporter of its commodity. India exports nine per cent of its total spice production to more than 100 countries and the remaining are consumed internally. India commands a formidable position in the world spice trade with 45 per cent share in volume and 30 per cent in value.

Nutmeg (*Myristicafragrans*Houtt.) belongs to the family Myristicaceae a unique tree spice plant gives two commercial spice products namely, nutmeg and mace. Nutmeg is the black seed and mace is the aril covering the outer surface of the seed. The yield of mace is about 15 per cent that of nutmeg percent which is more expensive. The spice is widely used as a condiment and also in medicine. In India, nutmeg and mace are used more as drugs than as condiments because of their valuable medicinal properties (Pruthi, 1970). Nutmeg is native of Moluccas Island and in India it is cultivated throughout Kerala, parts of Tamil Nadu, Karnataka, Goa, Assam and Andaman and Nicobar Islands. According to Spices Board, the total estimated nutmeg production in India in 2015-16 is 14400 tons in an area of 21110 ha in that the major contribution from Kerala, Karnataka and Andaman and Nicobar (Anon., 2015).

Drying is one of the most important unit operation adopted for agricultural commodities for enhancing the shelf life. Drying is the process which converts a solid, semi-solid or liquid feedstock into a solid product by evaporation of the liquid into a vapor phase via application of heat. The essential features of the drying process include phase change and production of a solid phase. The most important parameters in drying are the temperature and time of exposure and may vary with the end use of

the product (Gopalakrishnan, 1992).Traditionally, sun drying method is applied in the drying of agricultural products. The main drawbacks are large space requirement, low drying rates, prolonged drying and exposing of the drying material to contaminating agents such as microbes, and spores in the ambient air (Law *et al.*,2014). The drying process is broadly classified into three categories including hot air drying, freeze drying and vaccum drying based on the operating pressure. The hot air drying technique is the most economical drying method which has been adopted from ancient days. Over 85 per cent of industrial dryers are of the convective type with hot air or direct combustion gases as the drying medium (Mujumdar and Devahastin., 2011). Among various hot air drying methods, the more efficient method is fluidized bed drying for drying of foods, fruits and vegetables (Kassem *et al.,* 2011). It offers significant advantages like high heat and mass transfer, mixing solid materials efficiently with the drying air, high drying rate and uniform moisture reduction with less drying time. It provides uniform bed temperature throughout the drying period and lengthened constant drying rate period (Emam-Djomeh *et al.,* 2013).

Microwave drying, an alternative method which gained popularity for the drying of food products has gained popularity is adopted. In microwave heating, heat generation takes place from inside to outside of the material due to the absorption of microwave energy by the regions with higher moisture levels (Zare and Ranjabharan, 2013). Advantages of microwave drying over conventional hot air drying include higher drying rate, minimal heating at locations with less water, thus reducing overheating the atmosphere and less drying time. Other advantages are less space and energy requirements since most of the electromagnetic energy is transformed into heat. However, the application of microwaves solely result in uneven heating of certain products, depending on their dielectric and thermo physical properties. This is a more significant problem when processing at low frequencies because the dielectric properties of microwaves are considerably dependent on temperature variations. Thus, combining microwave radiation with hot air fluidization also provides an

effective means of overcoming the non-uniform heating problems in conventional microwave heating (Zare and Ranjabharan, 2013).This novel technology has several advantages which include temperature uniformity of the particles in the bed provided by good mixing due to fluidization and reduction in drying time and product shrinkage, improvement in color and rehydration capacity produced by the use of microwave energy (Reyes *et al.*, 2007).

The harvesting period of nutmeg in kerala is from june to August. The availability of this fruit in rainy season is more than the other months of the year. Dried nutmeg and mace possess great importance in international trade and are used in the preparation of extractives and volatile oils. Drying to optimum moisture level without losing the inherent qualities especially the colour yields better price and is a prerequisite for long storage (Gopalakrishnan *et al.,* 1980). The traditional drying method of this fruit is sun drying which is cumbersome, un hygienic and laborious method. Also, apart from the contamination with dirt and dust, uncontrolled temperature during drying deteriorates the final quality of the product. Keeping quality of spices depends much on drying and the storage moisture content and it should be kept between 8 to 10 per cent. If the moisture level of mace exceeds by even one percent than critical moisture level, the quality may be affected (Naveen Kumar *et al.,* 2017).

In view of the above points, the present study is undertaken on **"Development of microwave assisted fluidized bed dryer for nutmeg mace''** with the following objectives:

1. Studies on engineering properties of nutmeg mace relevant to the design of microwave assisted fluidized dryer.
2. Development of drying unit using microwave assisted fluidised bed drying method for nutmeg mace.

3. Optimization of drying parameters and comparison of the drying performance of microwave assisted fluidised bed dryer with conventional fluidised bed dryer and with sun drying.

## CHAPTER II

# REVIEW OF LITERATURE

This chapter deals with the review of research work reported on the scenario of nutmeg and benefits of nutmeg usage as a food ingredient, physico-chemical parameters of nutmeg. Details of various earlier research findings of scientists on various drying methods such as sun drying, smoke drying, fluidized bed drying and dielectric properties of microwaves and their application in drying on different food products and their characteristics has been elaborately presented.

### 2.1 Nutmeg

Nutmeg (Myristicafragrans) is a nut like fruit which is cultivated for its spice belongs to*Myristicaceae* family. This evergreen tree should be grown in the shade for the first two to three years. In a deep, well drained loamy sandy soil, it grows to about 18 meters tall. The optimal growing temperature is between 20-30°C and the annual rainfall is between 1500-2500mm. The tree starts to fruit about five to eight years after planting and will continue to yield for about thirty years. When the fruit is ripe, it turns yellow and splits into two halves. Centrally situated oval shaped dark brown hard seed (kernel) known commercially as the "nutmeg." Adhering closely to this nutmeg kernel is a thread like aril known as "mace". At the time of harvesting it is bright red to purple but after drying this colour changes red to amber. Mace is generally said to have a finer aroma than nutmeg, but the difference is small (Azam Ali, 2007).

#### 2.1.1 Global scenario

Indonesia, a country popularly known because of its various spices. Nutmeg is one of Indonesian popular spices. Average world nutmeg production of nutmeg is 10,000-12,000 ton/year. Indonesia and Granada dominate the production for 75% and 20% respectively. Other countries that supply nutmeg to the world market include

India, Malaysia, Papua New Guinea and Sri Lanka, and other Caribbean countries. Today, India is a main nutmeg producer but comes nowhere near the volume of with Indonesia and Grenada. The total estimated exports of nutmeg and mace from India in 2014-15 is 4475 MT whose value is 26797.5 lakhs. The main importers are the European Community, the United States, Japan and India (Abdullah *et al.*, 2010).

### 2.1.2 National scenario

In India it is mainly cultivated in South India particularly in certain pockets of Kerala, Tamil Nadu and Karnataka. The total estimated nutmeg production in India in 2015-16 is 14400 tons in an area of 21110 ha in that the major contribution from Kerala, Karnataka and Andaman and Nicobar. According to Spices Board, the estimated nutmeg production from Kerala, Karnataka and Andaman and Nicobar are 14190 tons, 150 tons and 50 tons respectively and the estimated nutmeg growing areas of land are 20630 ha, 150 ha and 70 ha respectively (Anon., 2015).

### 2.1.3Nutritional Benefits of Nutmeg

Nutritionally, nutmeg is rich in carbohydrates, proteins and dietary fibre and also rich in vitamins A, C and E. It contains minerals (calcium, copper, iron, magnesium, manganese, zinc and Phosphorus) electrolytes (Sodium and Potassium), and phyto nutrients including β carotene and crypo-xanthin B. The nutmeg oil is a mobile, pale yellow liquid, with a characteristic odour and the major constituents of the oil are d-camphene and d-prinene (Gordon, 2005).

#### 2.1.3.1 Fixed oil

Chemically, about 20% to 40% of fixed oil (commonly called nutmeg butter) is presented in nutmeg seeds. It contains mysristica acid, mymiristin, and glyecrides of lauric, trrdecanoic, stearie and palmitic acids. Mace contains 20 to 35% of fixed oil. The volatile oils contain small amounts of myristicin and elemicin (Gopalakrishnan, 1992) Myristicin is a potential cancer chemopreventive agent.

Table 2.1. Nutritional value per 100 g of nutmeg spice (Agbogidi and Azagbaekwe, 2013).

| **Principle** | **Nutrient Value** | **Percentage of RDA** |
|---|---|---|
| Energy | 525 Kcal | 26 |
| Carbohydrates | 49.29 g | 38 |
| Protein | 5.84 g | 10 |
| Total Fat | 36.31 g | 180 |
| Cholesterol | 0 mg | 0 |
| Dietary Fiber | 20.8 g | 55 |
| Vitamins | | |
| Folates | 76 µg | 19 |
| Niacin | 1.299 mg | 8 |
| Pyridoxine | 0.160 mg | 12 |
| Riboflavin | 0.057 mg | 4 |
| Thiamin | 0.346 mg | 29 |
| Vitamin-A | 102 IU | 3.5 |
| Vitamin C | 3 mg | 5 |
| Electrolytes | | |
| Sodium | 16 mg | 1 |
| Potassium | 350 mg | 7.5 |
| Minerals | | |
| Calcium | 184 mg | 18 |
| Copper | 1.027 mg | 114 |
| Iron | 3.04 mg | 38 |
| Magnesium | 183 mg | 46 |
| Manganese | 2.900 mg | 126 |
| Phosphorus | 213 mg | 30 |
| Zinc | 2.15 mg | 20 |

The major components of essential oil and their relative percentages are as follows:

Table 2.2. Major components of essential oil of nutmeg mace. (Dilon Daniel, 1994).

| Sl.No | Component | Percentage (per cent) |
|---|---|---|
| 1. | Sabinene or Camphene | 50 |
| 2. | d-Pinene | 20 |
| 3. | Dipentene | 8 |
| 4. | d-Linalool, d-Borneol, i-Terpineol & Geraniol | 6 |
| 5. | Myristicin | 4 |
| 6. | Safrole | 0.6 |
| 7. | Eugenol & isoEugenol | 2 |

**2.1.3.2 Essential oil**

About 8- 15% of essential oil is yielded from nutmeg and partially responsible for the effects associated with nutmeg intoxication. The chemical composition and aroma of essential oils of nutmeg and mace are almost similar but in the case of colour the difference is more (brilliant orange to pale yellow). These oils are also used for flavouring food product.

Table 2.3 Chemical composition of nutmeg and mace (Gopalakrishnan, 1992)

| Composition (%) | Nutmeg | Mace |
|---|---|---|
| Moisture | 40.00 | 40.00 |
| Volatile oil (V/W) | 11.00 | 15.30 |

| | | |
|---|---|---|
| Non-volatile ether extract | 33.60 | 21.98 |
| Starch | 30.20 | 44.05 |
| Sugars | | |
| Glucose | 0.1 | 0.17 |
| Fructose | 0.07 | 0.10 |
| Total reducing sugars | 0.17 | 0.27 |
| Sucrose | 0.72 | 0.39 |
| Total sugars | 0.89 | 0.65 |
| Protein | 7.16 | 9.91 |
| Crude fibre | 11.7 | 3.93 |
| Total ash | 2.57 | 1.56 |
| Ash insoluble in HCl | 0.20 | 0.15 |
| Polyphenols | | |
| Total tannins | 2.50 | - |
| True tannins | 1.00 | - |

### 2.1.4 Health Benefits of Nutmeg

It helps in stimulating the brain, relief from stress and fuels mental activities as well. It can even boost concentration and assimilation rate as it is supposed to improve blood circulation to brain (Hallstrom and Thuvander, 1997). Nutmeg as a tonic recommended best for the cardiovascular framework. It builds the blood course and empowers the heart capacities (Balick and Paul, 2000). Nutmeg oil is an extraordinary liver tonic, as it can expel the poisons in that. It is useful in treating kidney diseases and disintegrates kidney stones additionally (Kasahara *et al*., 2005). Nutmeg oil is useful in treating terrible breath (Barceloux, 2009). It is likewise disinfectant in nature and helps cure toothaches also gum issues (Duke, 1994;Osemene*et al*., 2013). Nutmeg oil treats rheumatic fever, reduces the joint

swelling and acts as pain reliever (Ernest, 2002). Nutmeg is widely used in cough syrups to help in clearing up the congestion which results from cold (Gill, 1992; Iwu, 1993).

## 2.2 Methods of drying of spices

### 2.2.1 Sun drying

When the fruits ripe, they split open. The split fruits are either plucked from the tree with a hook bill or are collected soon after they fall onto the ground. Nutmeg is dried in large trays by various procedures. The unshelled nutmegs undergone the sun drying operation until the seeds inside rattle on shaking. Normally nutmegs take 7 days time to dry. The seed cover is removed by breaking the hard seed coat mechanically (Rema and Krishnamoorthy, 2012).

The findings of Gopalakrishnan*et al.*1980 reported that sun drying of mace takes about 12 to 16 hours under open sun.

John *et al.* 2004 reported that mace is usually dried in the sun on large trays or mats which can quickly be removed to shelter if it rains and at night, as increased humidity will spoil its quality. As the harvesting season comes under monsoon season, it is very difficult to dry the mace in sun drying. Also it is difficult to control the temperature if drying, which has profound influence on the colour of the dried mace. The dried mace so obtained does not possess uniform red colour. Also about 2-3% of the mace gets charred in the process. Sun drying bleaches the colour and contaminates mace with mold growth ending in poor appearance.

### 2.2.2 Smoke drying

Pruthi, 1970 stated that farmers dry the mace by smoke or in kitchen fire place utilizing the heat from the stove. The dried mace obtained by these methods does not possess good appearance and there is loss of volatile oil.

### 2.2.4 Fluidized bed drying

Fluidized bed dryer (FBD) is a drying system where high velocity of heated air is forced through a bed of wet granular product to come under fluidization condition by overcoming the gravitational effects. FBD can be found in many applications for drying of granular solids in the food, pharmaceutical and agricultural industries.

Chen and Wang (2000) analyzed the heat and mass transfer mechanisms in the batch fluidized-bed drying of porous particles. The results showed that moisture transfer in the particle is due to capillary flow and vapor diffusion during different drying periods. As the effect of gas pressure distribution is insignificant, the internal heat transfer can greatly affect the drying process. Due to the coupled effects between gas and particles, the state of gas in the fluidized-bed changes substantially along the bed height and affects the heat and mass transfer in the particle significantly.

Kamarudin *et al.* (2007) investigated the he drying kinetics of bird's eye chilli in fluidized bed dryer at air velocities of 0.85 m/s, 0.97 m/s and 1.09 m/s, and operating temperatures of 50 C, 60 C and 70°C and found that at a low temperature of 50°C the reduction of moisture content was slow and the rate of heat transfer was low when compared to other temperatures and air velocities and the drying time was reduced with the increased operation temperatures. Chillies dried under fluidized bed drying had a dark greenish colour whereas chillies dried by direct sunlight appeared yellowish-brown. Aroma wise, fluidized bed chillies produced a pungent and intense smell whereas the sun dried chillies produced a 'sour' smell and lack pungency.

Parlak (2014) conducted a study on ginger slices under fluidized bed drying at 40,50,60 and 70°C temperature and at 3, 4 and 5m/s air velocity and found that drying at higher temperature provided a larger driving force for heat transfer. Also, air velocity dominantly affects evacuating water moisture content and increment in the gas velocity enhances the drying rate. Drying was quickest at 5 m/s air velocity.

At the initial stages most of the drying of product was completed though the external resistances to heat and mass transfer dominated the drying process. Also the reduction in drying time was occurred with the increasing drying air temperature or decreasing the drying humidity. On the other hand, the air velocity effect was less at higher temperature.

### 2.3 Principles of Microwave heating

Conventional drying techniques viz., hot air, freeze and vaccum drying result into low drying rates, particularly in the falling rate period of drying. Prolonged drying at moderately high temperatures increases during the falling rate period which lead to undesirable thermal degradation of the dried products. In order to address the limitations of conventional drying methods, new drying methods and dryers with new heating source have been investigated and developed in last few decades. Microwave is more efficient and more broadly applied among the novel technologies. Microwave heating has considerable advantages over conventional heating methods, especially with regard to energy efficiency (Ramya *et al.,* 2015).

Microwaves are the electromagnetic waves with frequencies ranging between 0.3 to 300 GHz corresponding to wavelength from 0.1 to 100 cm. Two major mechanisms such as ionic conduction and dipolar rotation are involved in the microwave heating. In ionic conduction, ions are accelerated by electric fields causing them to move towards the direction opposite to their own polarity. The movement of the ions provokes collisions with the molecules of the material. A disordered kinetic energy is created and, as a result, heat is generated. The energy level of microwaves corresponds to the rotational energy level of polar molecules. Therefore, the interaction of microwave energy with matter is through the dielectric rotation of the molecules. Polar molecules subjected to microwave radiation at 2,450 MHz will rotate $2.45 \times 10^9$ time every second. The friction between the fast rotating

molecules generates heat throughout the material instead of being transferred from the surface to the inner part as it is the case in conventional hot air drying

At the point when the microwave control is turned off, these activities all stop and the temperature decreases quickly. These attributes distinguish microwave drying itself from all other conventional drying techniques, where heat is usually transported from the surface to centre and temperature increments and reductions gradually. Therefore, a quick temperature control is conceivable just in microwave drying if the power can be right away and legitimately controlled during drying process (Orsat *et al*., 2006).

### 2.3.1. Microwaves

Microwave frequencies of 915 MHz and 2450 MHz can be utilized for industrial, scientific & medical applications. Microwaves have been applied in a broad range of food processing such as drying, tempering, blanching, cooking, pasteurization, sterilization, and baking (Fellows, P. 2000). Microwaves are reflected by metals, transmitted by electrically neutral materials, such as glass, plastics, paper and ceramics and absorbed by electrically charged materials (Vadivambal and Jayas, 2010).

### 2.3.2 Dielectric properties

Food materials belong to the group of dielectric materials are neither conductors nor insulators. Electromagnetic waves propagate into dielectric materials and the energy of that waves is converted into heat inside the material. As microwave heating is a form of dielectric heating, dielectric properties are thus the most important factors among all. Dielectric properties directly influence microwave drying characteristics of food products. Interaction between a food product and microwave energy is governed by the relative complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) of the product. The real component of the complex permittivity is the dielectric constant

(ε′) which is related to energy storage and the imaginary component is the loss factor (ε″) which is related to energy dissipation. Both these properties are influenced by product composition, temperature, and moisture (Feng *et al*., 2002).

The equation which is used to calculate the energy absorption is $P = 2\pi f \varepsilon o \varepsilon'' |E|^2$. Where *P* is the energy developed per unit volume (W/m3); *f* is the frequency (Hz); $\varepsilon_o$ is the absolute permittivity of vacuum (8.854188 × 10-12 F/m); ε" is the loss factor; and |E| is the electric field strength (V/m) (Orsat *et al*., 2006).

Feng *et al*. (2002) designed a method for dielectric constant and loss factor for red delicious apples (Malusdomestica Borkh.) and measured over a moisture content range of 4% to 87.5% at 22 °C and 60°C. At high moisture content (>70%), free water scattering and ionic conduction demonstrated the dielectric behavior. At medium moisture content (23%), ionic conduction played a major role. At low moisture content (4%), bound water accounted for the major dispersion mechanism. A decrease in moisture content resulted in a decrease in ε′ and ε″. Microwave drying process can be divided into three periods according to temperature variations: 1. Warming-up period in which sample temperature increases with little moisture removal, 2. Constant temperature period in which most of the drying takes place and 3. Heating-up period when the drying rate decreases and sample temperature increases rapidly.

**2.4 Microwave drying**

Maskan (2000) conducted a comparatative study on banana slices between convection drying, microwave drying and convection followed by microwave finish drying. It was observed that hot air followed by microwave finish drying increased the drying rate and reduced the drying time. At higher power levels, higher drying rates were achieved. About 64.3%of convection drying time reduced by microwave

finish drying. Microwave finish dried banana was lighter in colour and had the highest rehydration value.

Soysal *et al*. (2006) performed the microwave drying experiments on Parsley (Petroslinumcrispum Mill.) leaves of different loads ranging from 64.30 to 128.57 g at a microwave power cycle of 9s on/9s off of 900 W microwave output power. It was found that increased microwave power density for unit mass of the dried product resulted in higher drying rates at lower material loads and a relatively long constant rate period was observed after a short heating period. Microwave drying process reduced the material moisture contents from 4.94 to 5.11 kg [$H_2O$] $kg^{-1}$ [DM] to moisture content of 0.10 kg [$H_2O$] $kg^{-1}$ [DM] took 900–1467 min, depending on the drying conditions. A considerable difference in drying time was due to the difference in material load because the variation in the initial moisture contents of the material was less. Longer drying time of parsley leaves was recorded for higher material loads.

Ozkan *et al*. (2007) performed a study of microwave drying on spinach leaves lasted between 290 and 430 s at the microwave power levels of 1000 and 500 W, respectively, while the energy consumption was constant (0.12 kWh). Ascorbic acid loss in the product dried at power levels equal to or more than 500 W was less than those below 500 W. Colour criteria assessments showed that drying at 500 and 850 W produced the best brightness, redness and yellowness parameters. 750 W is the optimum microwave power level in the microwave drying of spinach with respect to drying time, energy consumption, ascorbic acid level and colour criteria.

Rayaguru and Routray (2011) investigated the effect of microwave drying technique on drying kinetics of aromatic *Pandanus* leaves (*Pandanusamaryllifolius*). To determine the kinetic parameters, the drying data were fitted to the semi-empirical Page model. It was shown that by increasing the microwave output powers from180-900 W, the effective moisture diffusivity values increased from 5.35E-08 to 1.99E-07

$m^2$/min. the drying time decreased from 14 to 2 min. 540 W is the optimized microwave power level of a microwave dryer to obtain the product with good quality.

Sharma and Prasad (2006) performed a study of combined 'microwave-hot air' drying technique on garlic cloves and reported that about 80–90 percent of conventional drying time was reduced by using microwaves in conventional hot air drying. Garlic cloves dried by this technique were lighter in colour when compared to hot air dried ones because of a lower drying temperature and shorter time. The retention of volatile components responsible for flavour strength was also more in 'microwave-hot air' drying. when combining microwaves at 0.4 W/g to hot air at 60–70°C, superior quality dried garlic obtained.

Skansi *et al*. (2011) compared the drying kinetics of convective, vacuum, and microwave drying of a pharmaceutical product, chlorpropamide, in the temperature interval from 40 to 60◦C, and the range of microwave heating power from 154 $W/kg_{dm}$ to 385 $W/kg_{dm}$ and reported that higher drying rates and shorter drying times were achieved at a higher temperature and microwave heating power. Lowest specific heat consumption and retention of the better quality of the product were obtained with microwave drying. Similar results were reported by Choudhary *et al*. (2013).

Therdthai and Zhou (2009) performed microwave vaccum drying (MVD) for mint leaves and concluded that after the MVD for 15 min, the lightness and yellowness of the dried mint leaves were significantly increased. It may be because of chlorophyll degradation. Finally light green–yellow coloured, dried mint leaves were obtained. In contradiction, after the hot air drying, the lightness was reduced and the redness was increased, resulting in dark green–brown colour. The degree of colour change was dependent on drying time, drying temperature and oxygen level.

Wang *et al.* (2009) stated that the microwave power significantly influences the total drying time and sensory quality of final products. Lower microwave power resulted in prolonged drying time. Reduction in dying time was achieved with the

increasing of microwave power but the quality was affected. 450 g of material load, microwave power of 450–675 W (i.e., 1.0–1.5 W/g of the microwave power density), material thickness of 15–20mm, and controlling the material temperature between 50–60°C could obtain final products with relatively short drying times and acceptable sensory quality.

In the industrial sector, microwave processing is used in some of the unit operations, while it is yet to capture a major place in the industrial applications. The major disadvantage related with microwave heating is the non-uniform temperature distribution, brings about hot and cold spots in the heated product. The non-uniform temperature distribution not only affects the quality of the food but also raises the issue of food safety when the microorganisms may not be destroyed in the cold spots. Currently there are two ways to overcome the non-uniformity issue which is resulted in microwave-assisted drying: 1) enhancing the uniformity of electromagnetic field in the microwave cavity, 2) enhancing the absorption uniformity of microwave energy by causing the physical movement of the material within the microwave cavity which is the more effective than the first in enabling inform absorption of microwave energy by the samples. When the sample is randomly or systematically moved or displaced during drying, the uniformity of drying can be significantly improved. Such a movement can lessen the dependence on the uniformity of distribution of electromagnetic field and the time/space-averaged microwave energy absorption can be considered to have the same probability (Vadivambal and Jayas, 2010).

## 2.5 Microwave assisted fluidized bed drying

Kaensup *et al.* (1998) studied the effects of air velocities (u) at 5 m/s and 8 m/s on drying time at a constant air temperature (T) of 9O°C and the effect of air temperature at 40, 60 and 90°C on the drying time at a constant air velocity of 8 m/s on pepper seeds. Inlet air temperature was found to have strongly influence on drying characteristics to reach the desired moisture content. The fluidized bed drying times

were 145, 29.7 and 17.5 minutes for the air temperature of 40, 60 and 90°C respectively. Utilized the microwave the drying times were 86.3, 25, 13 minutes for the air temperature of 40, 60 and 90°C respectively. The effect of increasing inlet air temperature is clearly to decrease the drying time in both fluidized bed drying (FBD) and combined microwave fluidized bed drying (CMFD). As the inlet air temperature increased the difference between the drying rates of two systems is decreased. At a constant inlet air temperature of 90 °C the drying times were 29.7 and 17.5 minutes for FBD having air velocities of 5 and 8 m/s, respectively whereas they were 25 and 13 minutes for CMFD. Since the high inlet air temperature were used, the drying rate applied CMFD is slightly higher than utilized FBD.

Wongwises and Kaensup (2004) performed a study on fresh ripe peppercorns using fluidized bed dryer and combined microwave fluidized bed dryer to investigate experimentally the average moisture content vs. elapsed drying time, and drying rate vs. average moisture content. It is found that the microwave field can increase the potential of the conventional fluidized bed drying. Inlet air temperature and velocity effect the drying rates of both dryers. The reduction in drying rates and saving the conventional drying time to an extent of about 80-90% achieved by combing microwaves and fluidized bed drying at the same drying air temperature and velocity. The physical structure of the product after the thorough drying process by the CMFD was found to be maintained while that by the FBD had become deformed. The colour of the product was also an attractive flaming yellow, instead of black as obtained from using the FBD.

Sumnu *et al*. (2005) conducted an investigation of microwave assisted fluidized bed drying of macaroni beads. In the tests with the microwave fluidized bed drying, three air temperatures 50, 60 and 70°C at an air speed of 2.3 m/s and microwave two power levels of 2.1 and 3.5 w/g were utilized. Drying rate enhanced with the air temperature and microwave power level. The increment in microwave power and air temperature lessened the drying time. The fluidized bed drying time

was diminished around by half with the addition of microwave power into the framework when the drying times of fluidized bed and microwave combined fluidized bed drying were compared. The effective diffusivities in the fluidized bed microwave combine fluidized bed drying were 4.125×10-11 and 8.772×10-11 m2/s, respectively.

Reyes *et al.* (2006) conducted an experiment to dry turnip seeds with microwaves in fixed and pulsed fluidized beds. Addition of microwave irradiation to the convective drying process increases water evaporation inside the particles, which causes an increase of the internal pressure, and in turn increases the diffusion of the water towards the surface of the particles. When microwaves were used, drying time decreased from 35 min to 11 min when 150 W of MW power was applied to a pulsed fluidized bed, and was further decreased to 9 min when the power was increased to 300 W. A reduction of the relative humidity of the drying air from 30 to 8% results only in a slight decrease for the time of drying.

Reyes *et al*. (2007) conducted a study on potato slices by using tunnel drier, fluidized bed drier and microwave assisted fluidized bed drier. During combinations drying, due to an increase of the temperature of the water inside the particles caused by a higher steam pressure, increases the drying rate and an average of 70% decrease in drying time. When the tunnel dryer was replaced by the fluidised bed dryer and this was attributed to the higher heat and mass transfer inside the fluid bed dryer. Drying time was further reduced to half of that time when microwaves applied to the fluidised bed, resulting in an 85% drying time reduction in total. Increase of colour parameters, the values obtained by fluidized bed drier were very similar to the fluidized bed dryer with the application of microwaves without producing an appreciable deterioration of the colour parameters.

Mowla and Souraki (2008a) conducted an experimental and theoretical investigation of drying behaviour of garlic in an inert medium fluidized bed assisted

by microwave. When sample was dried without the use of microwave energy, heat transfers from the surface to the interior of garlic sample and moisture transfers from interior to the surface. Maximum temperature of the sample would be the drying air temperature and the temperature profile inside the particle linearizes after the initial warming-up period. During drying with the use of microwave energy, used dying air temperature and microwave power densities are 40°C and 2.13 w/g respectively and an air flow rate of 5.2 m/s was maintained throughout the experiment. Models used for the estimation of heat and mass transfer coefficients are lumped parameter analysis and Chilton–Colburn analogy. Because of mixing up and agitation of inert particles in the dryer, these coefficients were higher than those in the simple convective air drying systems. The simulation was used to predict moisture and temperature distributions inside the garlic samples at different microwave power densities and drying air temperatures. The sample temperature was increased with a higher rate compared to pure convective heating. At the surface of garlic the temperatures were higher than the drying air temperature at the end of drying. Moisture distributions of garlic during drying showed that the moisture at the surface of garlic reaches its final value (equilibrium with the drying air) at the early stages of drying and this fact confirmed that in drying of garlic, the interior resistance against mass transfer controls the drying rate of this product.

Mowla and Souraki (2008b) simulated the drying behaviour of a small spherical foodstuff (green pea) in a microwave assisted fluidized bed of inert particles. In this study, three drying air temperatures of 30, 50 and 70°C were used. When drying of green peas was conducted without using microwave energy, heat transferred from the surface to the interior of green pea samples and moisture was transferred vice versa. In the earlier stages of drying, the temperature of green peas is lower than air temperature but at the end of drying process it was reached to drying air temperature. When drying of green peas was conducted with using microwave energy, microwave power densities of 0.25, 0.7 and 1.3 W/g were used. The curves

showed that increasing of drying air temperature increased the drying rate of green peas. The increasing the air velocity from 4 to 5.2 m/s or from 5.2 to 6 m/s decreased the drying rate slightly. In drying with internal heat generation due to microwave energy, the absorbed microwave energy (and its conversion to heat) and surface convective heating was higher than energy losses associated with moisture evaporation. This resulted in a rapid rise in product temperature. At the end of drying, when the moisture in the green peas reached to equilibrium with drying air, the temperature profile remains at a nearly constant level and also the evaporation rate improves in a non-shrinking material.

Zomorodian *et al*. (2011) conducted an experimental and theoretical investigation on shelled corn drying in a microwave assisted fluidized bed dryer. In this combination drier, the drying process was continued till final moisture content of shelled corn reached to a safe moisture content of 12.5 %db and the effects of various drying parameters on the drying time of shelled corn were found. Four air temperatures (30, 40, 50 and 60°C) and five powers (180, 360, 540, 720 and 900 w) were used. The results indicated that higher values of drying rate or moisture diffusivity were obtained by increasing the drying air temperature and using microwave energy power as an assisting heat source. Increasing the drying air temperature resulted in upto 5% decrease in drying time while in the microwave assisted fluidized bed system, the drying time decreased dramatically up to 50% at a given and corresponding drying air temperature at each microwave power level and the quality of the product was retained. Increasing the drying air temperature from 30 to 60 °C, a weaker influence in fluidized bed dryer compared to combined microwave power assisted fluidized bed drier.

Emam-Djomeh *et al.* (2013) developed a model to describe heat and mass transfer in apple cubes during drying in a combined microwave assisted fluidized-bed dryer. Constant air velocity of 21 m/s was maintained inside the cavity and 150 and 300 W power levels were used. At these power levels the used microwave energy

enhanced drying rate and reduced drying time. Drying times for samples dried by the application of microwave energy were decreased about 66% and 73% at 150 and 300 W (0.113 and 0.263 W/g), respectively. A numerical solution based on the finite difference method was used to develop the model for moisture distribution and temperature variation of samples. At the initial stages when the microwave power was not applied, the center and surface temperatures of the apple cubes were lower than the drying air temperature. With microwave heating at the beginning stages the temperature was rose quickly since microwave heating was more efficient and leads to a different between center and surface temperature. Center temperature showed a significant variation due to dielectric heating effect. These variations are not observed at the surface due to the cooling effects of drying air and lower moisture content. At the lower moisture contents, the effect of microwave heating on the so called temperature variation was weakened and classical drying behavior was observed.

Zare and Ranjbaran (2013) conducted a study on the simulation of energetic and exergetic performance of microwave-assisted fluidized bed drying of soybean the energetic and exergetic performance of microwave-assisted fluidized bed drying of soybeans were simulated using a validated mathematical model. The model predicted the drying performance parameters with mean relative deviation less than 14%. It was shown that the microwave power could enhance the thermodynamic efficiency of fluidized bed dryers. Applying higher levels of air temperature is recommended to increase drying efficiency and decrease the exergy destruction ratio during microwave-assisted fluidized bed drying of soybeans.

Jitendar and srivastava (2013) studied the effect of microwaves on the drying rate and quality of potato cubes in a microwave assisted fluidized bed drier. In this study, the independent variables are drying air temperature (50-70°C), inlet air velocity (20-24 m/s) and microwave power (360-720 W). The outcomes were contrasted and those dried in the same fluidized bed dryer but without microwave. Results revealed that about 1.8 to 3.6 time diminishment in drying time was occurred

in the microwave assisted fluidized bed dryer when contrasted with same fluidized bed drier without microwaves and the best combination of independent variables for drying potato cubes was 720 W microwave power, 60°C air temperature and 22 m/s air velocity. This best combination showed that the moisture content, drying time and rehydration ratio was 7.50 % (d.b.), 82.0 min and 3.135, respectively.

Patel *et al*. (2014) claimed the effect of inlet air temperature and velocity on the drying characteristics of beetroot's (*Beta vulgaris L.)* pieces dried by two unique techniques such as fluidized bed drying and microwave assisted fluidized bed drying. The two independent variables were air temperature and air velocity. The selected inlet air temperatures and inlet air velocities were 60°C, 67.50°C and 75°C and 9 m/s, 10.50 m/s and 12 m/s, respectively. At the initial stage of drying, moisture starts diffusing rapidly from the specimen to the surrounding medium because of higher partial vapor pressure difference between the specimen and environment. As a result, the partial vapor pressure difference between the product and environment diminishes quickly, which promotes slower moisture movement from the product and becomes constant at the end of drying. In both techniques, moisture lost was in great degree. In any case the outcomes demonstrated that microwave assisted fluidized bed dying offered two to three times decrease in drying time when contrasted with fluidized bed drying. Also observed that the microwave assisted dried samples had lower final moisture content than the fluidised bed dried samples.

Khoshtaghaza *et al*. (2015) studied the effects of microwave-fluidized bed drying on quality, energy consumption and drying kinetics of soybean kernels. The outcomes demonstrated that air temperature (80–140°C), velocity (1.8–4.5 m/s) and microwave power (200–500 W) altogether impacted drying time, moisture diffusivity, rehydration capacity, cracking, and specific energy consumption ($P \leq 0.05$). Page's model has been utilized to assess the microwave fluidized bed drying conduct of the soybean pieces. Moisture diffusivity values increased ($6.25\times10^{-10}$ to $42.14\times10^{-10}$ $m^2/s$) as the air velocity diminished with air temperature

and microwave power enhancement. Activation energy was found to be between 3.33 and 17.70 KJ/mol. Minimum cracking percentage of soybean kernels (12.96 %) was obtained at 80°C, 1.8 m/s and 200 W treatments. The increment in microwave power and reduction in air velocity level decreased the rehydration capacity. Specific energy consumption fluctuated from 50.94 to 338.76 MJ/kg water and the lowest specific energy consumption were obtained at 80 °C, 4.5 m/s and 500 W.

# CHAPTER III

# MATERIALS AND METHODS

In this chapter the conceptual design and development of a microwave assisted fluidized bed dryer for nutmeg are elaborated. The methodology used for the optimisation of the process parameters and the quality of the dried sample are also discussed in detail.

## 3.1 RAW MATERIAL

Fresh nutmeg mace variety 'Kaniyamkuzhiyil' procured from a progressive farmer named Saji, vettilappara near Areacode, Malappuram district located at 11.26° latitude, 76.08° longitude was used for the study. The initial moisture content, colour, essential oil and its components were estimated as per standard methods.

## 3.2 ENGINEERING PROPERTIES OF NUTMEG MACE RELEVANT TO THE DEVELOPMENT OF SYSTEM

The major engineering properties like bulk density and terminal velocity of nutmeg mace relevant to the development of microwave assisted fluidized bed drying system were studied and discussed below.

### 3.2.1 Bulk Density

The bulk density of nutmeg mace in $kg/m^3$is determined by finding the ratio of weight of mace to the volume of mace in 1000 ml cylindrical container (Divekar *et al.*, 2011).

### 3.2.2 Terminal velocity

The terminal velocity is the air velocity determined by regulating the velocity of blower so that the nutmeg mace comes under fluidization condition in a conventional fluidized bed dryer.

## 3.3TRADITIONAL DRYING METHOD OF NUTMEG MACE

At present, sun drying is carried out for nutmeg mace as a traditional drying method and hence this method was considered as one of the experiments the developed technique. Weighed mace sample was uniformly distributed as thin layer in a stainless steel tray and dried in sun. The temperature range between 27 to 32°C and humidity between 75 to 79% was recorded. The average temperature and solar intensity were measured by using a thermometer and a lux meter and it is measured as 610 $W/m^2$ and 32 to 35°C. At each 1 hour, the weight of sample was taken till the constant weight was achieved.

## 3.4 FLUDIZED BED DRYING OF MACE

To see the effect of fluidization in the drying process of nutmeg mace an existing fluidized bed dryer was used and the quality was compared with the dried sample from the developed microwave assisted fluidized bed dryer. The existing dryer was modified to reduce the energy consumption and length of the dryer. The modified fluidized bed dryer consists of 1hp blower with power source, air controlling valve, heating chamber, plenum chamber and drying chamber. In the heating chamber, a finned heating coil of 500 W capacity was arranged in a stainless steel pipe having a diameter of 77 m instead of two heating coils of 2000 watts capacity in a heating coil box of 250×110×100 mm. Weighed mace sample of 100 g was dried in fluidized bed dryer at 40, 45 and 50°C to evaluate the performance the modified dryer and the energy required for drying of the mace at these temperatures was found by using a 3-phase energy meter.

## 3.5 DEVELOPMENT OF MICROWAVE ASSISTED FLUIDIZED BED DRIER

Prior to the development of a microwave assisted fluidized bed dryer, the conventional fluidized bed dryer for nutmeg mace was evaluated and then a

laboratory microwave assisted fluidized bed dryer was developed. The system consists of a fluidized bed dryer and a microwave oven unit.

### 3.5.1 Development of fluidized bed dryer

The fluidized bed drying system consists of the following parts:

1. Drying chamber
2. Plenum chamber
3. Heating chamber
4. Blower with power source
5. Air flow control valve

#### *3.5.1.1 Drying chamber*

The drying chamber for performing the drying of nutmeg mace consists of a glass tube with a cover plate, porous plate and a silicone rubber cork. This silicone rubber cork is fixed around the stainless steel cone thereby to avoid the escape of the microwaves through the gap between the hole of the microwave oven and stainless steel cone which was connected to plenum chamber. A porous plate having a hole of diameter 1360mm and a 4 mm distance from one hole to another was placed on the cork for allowing the heated air into the glass tube from plenum chamber. A borosil glass tube of 150mm OD, 145 mm ID and 140 mm length was used for fluidizing the nutmeg mace samples inside in it. A porous cover plate was placed over the glass tube to restrict the overflow of the mace samples while drying.

#### *3.5.1.2 Plenum chamber*

A plenum chamber was constructed with stainless steel sheet formed into a cone having top diameter of 125 mm connected to the bottom of heating chamber of 77 mm diameter.

#### *3.5.1.3 Heating chamber*

Heating of cold air was conducted by passing it to the heating chamber which consists of a finned heating coil. A finned heating coil of capacity 500W and temperature range of upto 100°C was selected and arranged in the stainless steel pipe of diameter77 mm and length of 385 mm which acts as heating chamber for cold air. Also thermostat which accomplished the purpose of controlling the temperature of heater was selected. Heater selection was done based on the sample which was being dried.

### *3.5.1.4 Blower with power source*

By trial and error method, a 2800 rpm centrifugal blower with 1hp motor was selected as the source of air which is heated and then supplied to the drying chamber for drying and fluidization. The entire set up is kept at a height of 410mm from the ground level by means of an angle iron stand.

### *3.5.1.5 Air flow control valve*

In order to control the flow rate of the air and thus to maintain fluidization in the drying chamber, a ball flow control valve made up of brass was employed. The diameter of the valve is 50.8 mm. This was fitted in between the blower and heating chamber. By turning the valve handle, the amount and velocity of intake air for heating can be controlled.

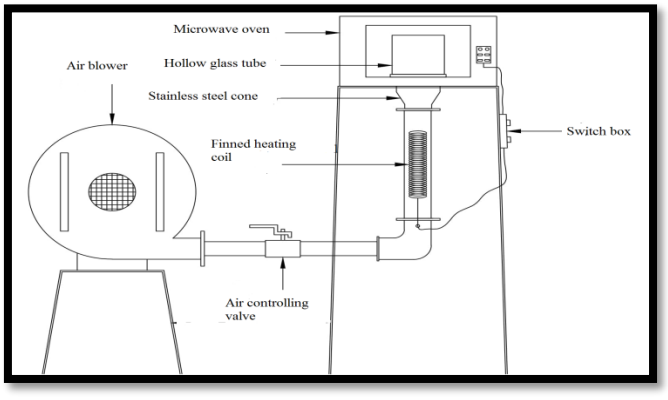


Fig. 3.1. Schematic diagram of Microwave assisted Fluidized bed Dryer

### 3.5.2 Microwave cavity

Commercially, available microwave ovens are used to adopt the microwave for performing the combination drying technique effectively in laboratory level. In microwave oven, microwaves from the magnetron of the generator are conveyed through a rectangular wave guide. The selection of microwave oven is done on the basis of high microwave power output of 800W (Wongwises and Kaensup, 2004). Accordingly, a microwave oven (IFB, model 20PM2S) with its specifications given below is used in this study as microwave source.

| | |
|---|---|
| Rating | 230V/50Hz |
| Power consumption (Microwave) | 1200W |
| Microwave output | 800W |
| Operation frequency | 2450MHz |
| Outside dimensions | 262mm(H)×452mm (W) ×395mm(D) |
| Net weight | Approx.12 kg |

It consists of control panel where cooking time, power indicators and clock time are displayed and controlled. This domestic oven was modified by making a hole of 14 cm at the bottom and inserting the fluidized bed dryer through the hole. The drying experiments were conducted at different microwave power levels such as 60%, 80% and 100%, by setting the microwave mode on P-60, P-80 and P-100.

### 3.5.3 Energy meter

A three phase energy meter was connected to the centrifugal blower to measure the energy consumed during the microwave assisted fluidized bed drying process. The energy consumed for combination drying process at different process levels as per the experimental design and for conventional fluidized bed drying,

microwave drying processes were measured for comparison of the energy efficiency of the microwave assisted process.

## 3.6 EXPERIMENTAL DESIGN

From the study the process parameters such as microwave power density and drying air temperature were chosen as independent variables. The process parameters would influence drying rate, drying temperature, energy consumption and physico-chemical parameters such as colour, moisture content, bulk density, essential oil and aromatic compounds. These parameters were chosen as dependent variables.

### 3.6.1 Independent variables

I. Microwave Power Density

The power densities are as follows

a) $D_1$: 480 W

b) $D_2$: 640 W

c) $D_3$: 800 W

II. Drying Air Temperature

The temperatures for the drying of nutmeg are as follows

a) $T_1$ : 40°C

b) $T_2$ : 45°C

c) $T_3$ : 50°C

### 3.5.2 Dependent variables

a) Drying rate

b) Drying temperature

c) Energy consumption

d) Physico-chemical parameters such as colour, final moisture content, bulk density and essential oil yield

## 3.7 EXPERIMENTAL PROCEDURE

For evaluating the developed microwave assisted fluidized dryer, about 100g of fresh mace sample was used. The heater was switched on and then the temperature inside the drying chamber was allowed to increase upto required level by setting the thermostat. After attaining the required drying temperature, the sample was loaded and the blower was switched on. The air velocity was regulated by air flow control valve and then the loaded sample was allowed to dry. At every 15 minutes interval, weight of the sample was determined and the drying process was continued.

Plate 3.1. Microwave assisted Fluidized bed Dryer

## 3.8 DEHYDRATION CHARACTERISTICS AND DATA ANALYSIS

### 3.8.1 Drying rate

Drying rate is defined as, (Helikal, 1998).

$$\frac{dm}{dt} = \frac{M_2 - M_1}{\Delta t} \qquad \text{----------} \qquad (3.1)$$

Where, $\Delta t$ = difference in time.

### 3.8.2 Moisture ratio

Moisture ratio is the ratio of the moisture content at any given time to the initial moisture content (both relative to equilibrium moisture content) (Helikal, 1998).

Moisture ratio (MR) is defined as follows,

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad \text{----------} \qquad (3.2)$$

Where,

M = Average moisture content (%db) at time t (min) during drying,

$M_0$ = Moisture content (% db) at the initiation of drying i.e. at 0 time,

$M_e$ = Equilibrium moisture content (% db).

## 3.9 QUALITY DETERMINATION OF DRIED MACE

### 3.9.1 Moisture content

Moisture content was determined by toluene distillation method using Dean Stark apparatus as per Associates of Official Analytical Chemists (AOAC, 1975) method. Toluene, measuring 100 ml, was taken in a distillation flask containing 5 g of ground nutmeg mace sample. The flask was attached to the Dean Stark apparatus with the condenser. On boiling, the water vapour along with toluene got distilled from the flask, condensed, and was trapped in the receiver of the apparatus, which contained toluene. Distillation was continued till the volume of moisture collected remained constant. The apparatus was cooled at room temperature and weight of moisture collected was noted.

The moisture content was calculated by,

$$\text{M.C. (w.b), \%} = \frac{w_w}{w} \times 100 \quad \text{------ (3.3)}$$

Where,

$W_w$ = Weight of water collected, g

W = Initial weight of sample, g

M.C (w.b) = Moisture content, % wet basis

The moisture content on dry basis of pepper was found out using the following formula

$$\text{Moisture content (d.b), \%} = \frac{100 \times \%w.b}{100 - \%w.b} \quad \text{-------- (3.4)}$$

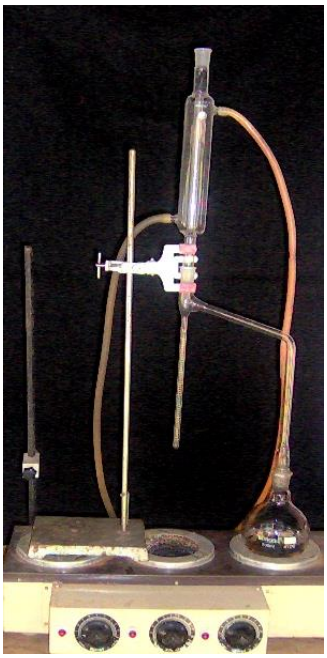

Plate 3.2 Dean Stark Apparatus

### 3.9.2 Colour

The colour values are determined by using Hunter lab colour flex meter (Hunter Association laboratory, Inc., Reston, Virgina, USA; mode). Hunter Lab's Colour Flex Spectro Colourimeter consists of 1.Sample cup port plate, 2. Glass Sample Cup and 3. Sample Cup Opaque Cover. It works on the principle of focusing

the light and measuring the energy reflected from the sample across the entire visible spectrum. The glass cup is filled with the sample and placed on the port provided and the opaque cover will act as the light source to exclude the interference of the external light. Calibration of the instrument was made prior to the actual measurement and then place it sample over the port and L*, a* and b* values were recorded. The colour difference (ΔE) was then determined using the following equation:

$$\Delta E = \sqrt{(L - L_o)^2 + (a^* - a_o)^2 + (b^* - b_0)^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

The subscript "0" in the equation represents the colour value of fresh mace.

Plate 3.3. Hunter lab Colourimeter

### 3.9.3 Essential oil

The yield of essential oil of the dried mace was determined by distillation method using Clevenger apparatus. In round bottom flask, 50 ml of ground mace and 500 ml of distilled water were taken and the setup containing Clevenger tube and condenser was placed on a heating mantle. The temperature of the heating mantle was maintained at 100 °C throughout the process. The flask was rotated occasionally to wash down any material adhering to the upper part of the wall. After the completion of the distillation process which would have taken for 3 hours, the oil was collected in the receiver of the Clevenger apparatus along with distilled water. Then the extracted oil was cooled to room temperature and allowed to stand until oil layer was clean.

The volume of oil collected after cooling was expressed as

$$\text{Volatile oil, \% (v/w)} = \frac{V}{W} \times 100 \quad \text{----------} \quad (3.5)$$

where,

V = volume of oil collected ml, assumed g

W = Total weight of the sample, g

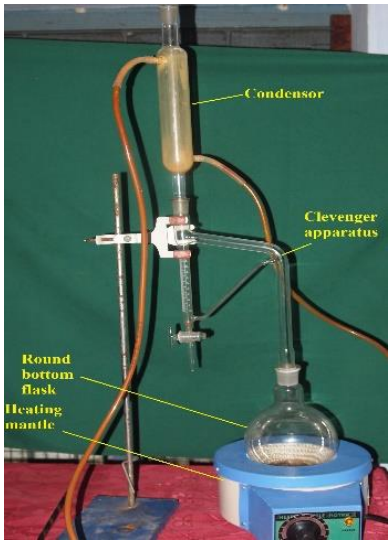


Plate 3.4. Clevenger apparatus

### 3.9.4 Determination of volatile component

The major volatile oil aroma component in the mace oil is myristicin, therefore quantification of myristicin content may be taken as a parameter for assessing the quality of the extracted oil in international market. In this study, Gas Chromatography is employed for assessing the myristicin content presented in the extracted oil through hydro distillation process. Gas Chromatography (Shimadzu GC-17A, Japan) (Plate 3.4) consists of a column (30 m in length x 0.25 mm inner dia. x 0.25 µm film thickness), a flame injection detector with an operating temperature of 280°C and an injector with a temperature of 250°C, manual injection and nitrogen as

gas carrier and the equipment can be reached upto a maximum of 350°C. Myristicin content was found by following the procedure which mentioned in Essam and Maytham (2012) and Ester *et al.* (2013).

The standard solution was first injected and the chromatograph of the standard was obtained. Then the sample was injected and its chromatograph was recorded following the same procedure. The injection was made with an initial split ratio of 1:30 with the injection port temperature of 250°C. The initial temperature was set to 100°C with an initial 1.0 min hold followed by programmed temperature (increment) at the rate of 15°C/min to 60°C followed by holding at the rate of 60°C/ 5min to 280°C. The chromatographs were then analyzed for myristicin content.

Plate 3.5. Gas chromatograph

## 3.10 MATHEMATICAL MODELING OF DRYING CHARACTERISTIC CURVES

Moisture ratio values were determined from the collected data during the drying experiments and plotted against drying time. The resulted test values were test verified with the following more frequently used proven drying models to determine the best model to describe different drying experiments.

Mathematical modeling of drying characteristic curves was performed by using the software MATLAB (version R2013a). Six selected models such as Newton, Page, Henderson and Pabis, Logarithmic, Two term and Wang and Singh were used on all drying curves and the statistical parameters were estimated by following the non linear regression procedure.

Table 3.1. Drying models considered for drying curves data

| S.No | Model name | Mathematical definition |
|---|---|---|
| 1 | Newton | $MR = exp(-kt)$ |
| 2 | Page | $MR = exp(-kt^n)$ |
| 3 | Henderson and pabis | $MR = aexp(-kt)$ |
| 4 | Logarithmic | $MR = aexp(-kt) + b$ |
| 5 | Two term | $MR = aexp(kt) + bexpk_1t$ |
| 6 | Wang and singh | $MR = a + bt + ct_2$ |

The parameters such as coefficient of determination ($R^2$), root mean square error (RMSE), standard square error (SSE) and chi square ($\chi^2$) were evaluated for determining the best model to fit the drying curves.

$$RMSE=\sqrt{\frac{\sum_{i=0}^{N}(MR_O - MR_P)^2}{df}} \qquad \text{……(3.6)}$$

$$SSE = \frac{1}{N}\sum_{i=1}^{N}(MR_o - MR_p)^2 \qquad \ldots\ldots\ldots\ldots (3.7)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_o - MR_p)^2}{N - z} \qquad \ldots\ldots\ldots (3.8)$$

Where,

$MR_o$ = observed moisture ratio

$MR_P$ = predicted moisture ratio

df= degrees of freedom

N = No. of data points

Z= No. of constants

## 3.11 STATISTICAL ANALYSIS

Statistical optimisation method was used to generate the process responses. Design Expert (Version 6.0.10) software was used for analysis of variance (ANOVA), regression analysis, and optimisation. In addition to analyzing the effects of the independent variables, this experimental methodology generates a mathematical model. The numerical optimisation of the drying process was aimed at finding the levels of microwave power and drying time (Omolola *et al.*, 2015).

A commercial statistical package, Design-Expert Version 6.0.10.0 was used for processing the collected data. Response Surface Methodology (RSM) was adopted in the experimental design as it analyses and optimizes the responses of the drying interactions. Two variables i.e. drying temperature and microwave power level at three levels were chosen based on preliminary trials. A Central Composite Design of two variables and three levels, each with three center point combinations, was used. In the above design the three levels of the process variables were coded as -1, 0, +1. The values of the independent variables at three levels were shown below.

Table 3.2 Values of independent variables at three levels

| Independent variable | Coded | Uncoded | Coded | Uncoded |
|---|---|---|---|---|
| Drying temperature | X1 | T1 | -1 | 40 |
| | | T2 | 0 | 45 |
| | | T3 | 1 | 50 |
| Microwave power | X2 | D1 | -1 | 480 |
| | | D2 | 0 | 640 |
| | | D3 | 1 | 800 |

Thirteen experiments were conducted for various responses by using Central Composite Design of two factors. These experiments were performed with two variables and three levels of each variable as shown in Table 3.2.

Optimisation of the process parameters was done by using only thirteen experimental data as per response surface methodology. In order to relate the independent process variables, a second order quadratic model was used. In the second order polynomial equation, multiple regression analysis was used to determine the coefficient of each term.

Second order non-linear regression equation (equ. 3.9) was used to fit for the optimisation between independent and dependent variables and also to check the adequacy of the variables.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_{11}X_1^2 + b_{22}X_2^2 + b_{12}X_1X_2 \quad \ldots\ldots\ldots(3.9)$$

Where,

Y is the response variable

$b_0$, $b_1$ and $b_2$ are regression coefficients of linear terms

$b_{11}$ and $b_{22}$ are regression coefficients of quadratic terms

$X_1$and $X_2$ are the coded values of the independent variables X, i.e. drying temperature ($X_1$) and microwave power density ($X_2$) respectively.

Table 3.3 Experimental design used for physico-chemical analysis of MFBD nutmeg mace

| Standard order | Run | Coded variables | | Uncoded variables | |
|---|---|---|---|---|---|
| | | Drying temperature (°C) | Microwave power (W) | Drying temperature (°C) | Microwave power (W) |
| 1 | 5 | -1 | -1 | 40 | 480 |
| 2 | 11 | 1 | -1 | 50 | 480 |
| 3 | 6 | -1 | 1 | 40 | 800 |
| 4 | 12 | 1 | 1 | 50 | 800 |
| 5 | 1 | -1 | 0 | 40 | 640 |
| 6 | 8 | 1 | 0 | 50 | 640 |
| 7 | 3 | 0 | -1 | 45 | 480 |
| 8 | 7 | 0 | 1 | 45 | 800 |
| 9 | 13 | 0 | 0 | 45 | 640 |
| 10 | 10 | 0 | 0 | 45 | 640 |
| 11 | 4 | 0 | 0 | 45 | 640 |
| 12 | 9 | 0 | 0 | 45 | 640 |
| 13 | 2 | 0 | 0 | 45 | 640 |

Analysis of variance (ANOVA) was used to check the statistical significance of the terms for each response in the regression equation. Therefore, the adequacy and significance of the quadratic model can be determined by using ANOVA. 'P' values used as a tool for checking the significance of each of the coefficients and also to understand the mutual interactions between test variables. As the 'p' values are smaller in magnitude i.e. ($p < 0.05$), the corresponding coefficient is more significant. The adequacy of regression model was checked by $R^2$, Adjusted $R^2$, Adequate Precision and Fisher's F-test (Montgomery, 2001).

## 3.11 COMPARISON OF THE PERFORMANCE OF DEVELOPED SYSTEM WITH CONVENTIONAL SYSTEM

The nutmeg mace samples of same quantity would be placed in the systems using fluidised bed drying and microwave assisted fluidized bed drying techniques under the process conditions. The energy consumption and drying kinetics of the microwave assisted fluidized bed dryer would be calculated and compared with that of the fluidized bed dryer. The comparison of the physicochemical parameters of dried product under microwave assisted fluidized bed drying technique with that of the fresh product would also be carried out.

### 3.10 Cost economics

Based on the material cost and cost of fabrication, the total cost of developed microwave assisted fluidized bed dryer was worked out. The operation cost of the machine was worked out, by including the fixed and variable costs. The benefit-cost ratio was determined by considering cost of fresh nutmeg mace and selling price of dried nutmeg mace as given in Appendix C.

# CHAPTER IV

# RESULTS AND DISCUSSION

This chapter presents the engineering properties of nutmeg mace relevant to the development of the microwave assisted fluidised bed drier and the various results obtained from the performance evaluation of the developed system towards the drying. Also, the effect of drying air temperature, microwave power levels on the responses like drying rate, drying temperature, energy consumption and physico-chemical parameters of dried nutmeg mace are discussed in detail. The effect of various process parameters on quality of dried mace are compared with the conventional drying method.

## 4.1 RAW MATERIAL

Nutmeg mace (belongs to the family Myristicaceae) procured from Areacode, is used for this study. Prior to the fabrication the relevant engineering properties such as moisture content, bulk density, terminal velocity and colour were studied and tabulated in Table 4.1.

Table 4.1 Engineering properties of fresh nutmeg mace

| Property | Value |
|---|---|
| Moisture content (%d.b.) | 66.67± 0.07 |
| Bulk density ($kg/m^3$) | 1191± 0.06 |
| Terminal velocity (m/s) | 5.1± 0.01 |
| L* | 21.28 ± 0.05 |
| a* | 22.23 ± 0.02 |

| | |
|---|---|
| b* | 9.09 ± 0.05 |
| Oil yield (%V/W) | 12.01 |

## 4.2 DRYING CHARACTERISTICS OF SUN DRIED NUTMEG MACE

In sun drying, the moisture content of nutmeg mace decreased from 66.67 %d.b. to 7.1 %d.b. in 16 hrs (Appendix A.1).Fig.4.1 showed the variation in moisture content (%d.b.) of nutmeg mace against drying time (min). The moisture content was decreased non-linearly. The initial moisture content was found as 66.67% (d.b). In sun drying, it is decreased to 7.1% (d.b) in 16 h. similar results were also reported by Naveen kumar *et al.* (2017) and Gopalakrishnan *et al.* (1980) for nutmeg mace.

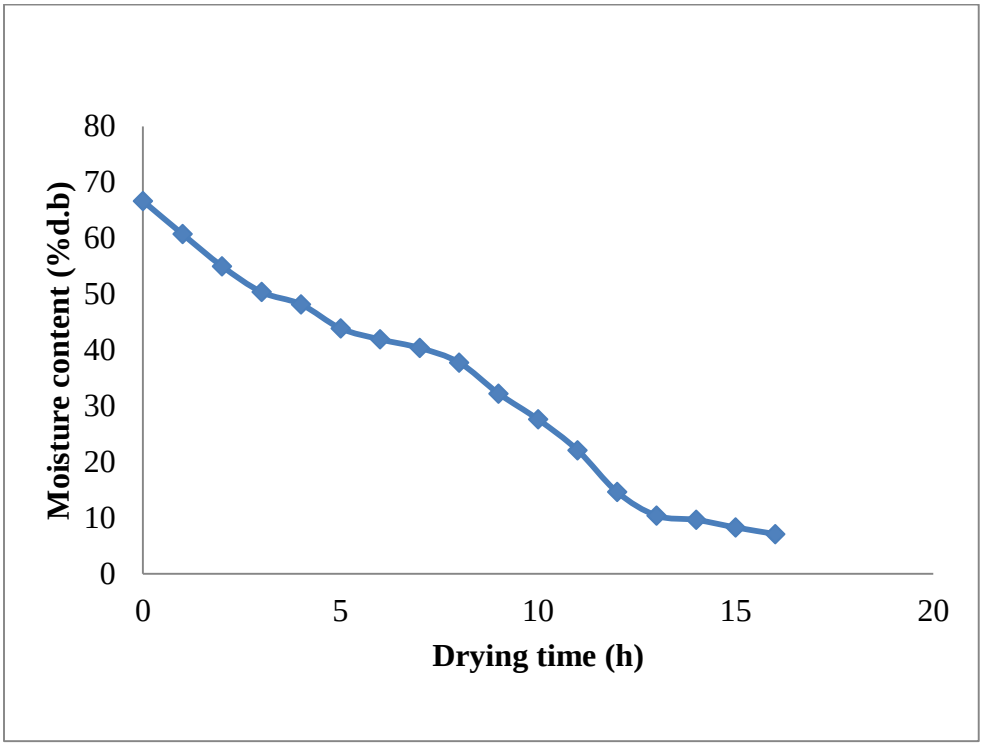


Fig. 4.1 Variation in moisture content (%d.b.) with drying time (min): sun drying

## 4.3 DRYING CHARACTERISTICS OF NUTMEG MACE UNDER FLUIDIZED BED DRYING

Fig. 4.2 showed the variation in moisture content (%d.b.) of nutmeg mace against drying time (min). The moisture content decreased from 66.67 %d.b. to 6.8% d.b. in 255 min at 40°C temperature but at 45°C it was decreased to 6.0 %d.b. in 240 min and at 50°C it decreased to 5.8 %d.b. in 235 min (Appendix A.2, A.3 and A.4). At the initial stage of drying, the moisture content decreased very rapidly. The initial moisture content was found as 66.67% (d.b). As the drying progressed, the available moisture content on the surface of the product decreased. Similar findings were reported by Parlak (2014) for ginger. Higher temperatures provide a larger water vapor pressure deficit, which is one of the driving forces for the outward moisture diffusion (Ramaswamy *et al.*, 1995).

From fig., 4.1 and 4.2 it is clear that, the drying time of mace under fluidized bed drying was less compared to mace dried under sun drying. In fluidized bed drying, more surface of the product is exposed to heat energy due to its fluidization condition (Sumnu *et al.*, 2005). So, the product dried in a very less time in fluidized bed dryer.

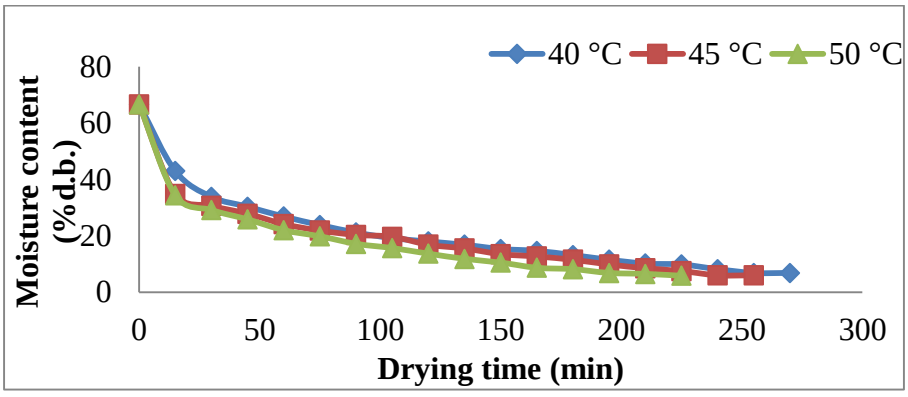


Fig. 4.2 Variation in moisture content (%d.b.) with drying time (min) at different temperatures under flluidized bed drying

## 4.4 QUALITY CHARACTERISTICS OF NUTMEG MACE DRIED UNDER FLUIDIZED BED DRYING AND SUN DRYING

The quality characteristics of the nutmeg mace dried under modified fluidized bed dryer and sun drying were tabulated in the Table 4.2.

Table 4.2 Quality characteristics of nutmeg mace dried under fluidized bed drying and sun drying

| Parameter | 40°C | 45°C | 50°C | Sun drying |
|---|---|---|---|---|
| L* | 16.23 ± 0.05 | 17.56 ± 0.05 | 18.36 ± 0.05 | 15.28 ± 0.05 |
| a* | 12.26 ± 0.02 | 14.34 ± 0.02 | 12.65 ± 0.02 | 10.56 ± 0.02 |
| b* | 7.07 ± 0.05 | 8.26 ± 0.05 | 8.76 ± 0.05 | 6.56 ± 0.05 |
| Final moisture content (%) | 7.8 ± 0.1 | 7.0 ± 0.1 | 6.8 ± 0.1 | 7.1± 0.1 |
| Oil yield (%V/W) | 11.8 ± 0.01 | 11.76 ± 0.01 | 11.33 ± 0.01 | 9.13 ± 0.02 |

From table 4.2, It is clear that at the temperature of 45°C, nutmeg mace dried under fluidized bed dryer showed highest colour values of L* 17.56 ± 0.05, a* 14.34 ± 0.02and b* 8.26 ± 0.05 and oil yield of 11.77 ± 0.01 % with lowest energy consumption of 1.8 KWh. As the temperature increases from 40 to 50°C the essential oil decreases from 11.8 to 11.33 where as for sun dried sample oil yield is only 9.13% and this may be due to the static nature of the product in the drying medium and also the prolonged drying of the product.

## 4.4 DRYING CHARACTERISTICS OF NUTMEG MACE UNDER MICROWAVE ASSISTED FLUIDIZED BED DRYING

From fig. 4.3 (a)-4.4 (c) it is observed that at initial stage of drying, moisture reduction was faster and gradually decreased with time. Also, it is observed that temperature of drying air showed a considerable effect on drying characteristics. As the air temperature increased from 40 to 50°C, the time of drying decreased. Along with this increase in power level given to microwave reduction significantly reduces the drying time. Maintaining a temperature of 40°C and the power level was varied from 480 to 800W the resultant drying time varied between 150 to 75 minutes.

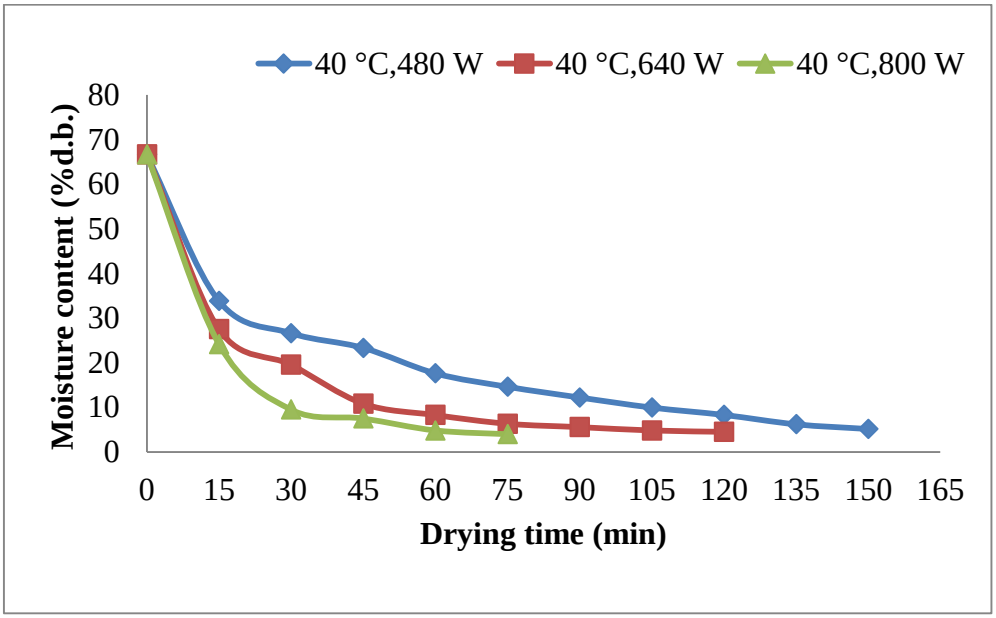


Fig. 4.3 (a) Variation in moisture content (%db) with drying time (min) at different microwave power levels at 40 °C

Fig. 4.3 (a) showed that drying at constant temperature of 40°C at varying microwave power levels from 480 to 800 W, the drying time decreased from 150 to 75 minutes. At constant temperature of 45°C and with varying microwave power levels from 480 to 800 W, the drying time decreased from 120 to 75 minutes (Fig.

4.3b) where as at 50 C and for different microwave power levels (480 to 800W) the drying time decreased from 95 to 60 minutes. Similar results were reported by Sumnu *et al*. (2005) for macaroni beads. That is the microwave power level had a positive effect on drying time. the increase in power accelerated the drying process.

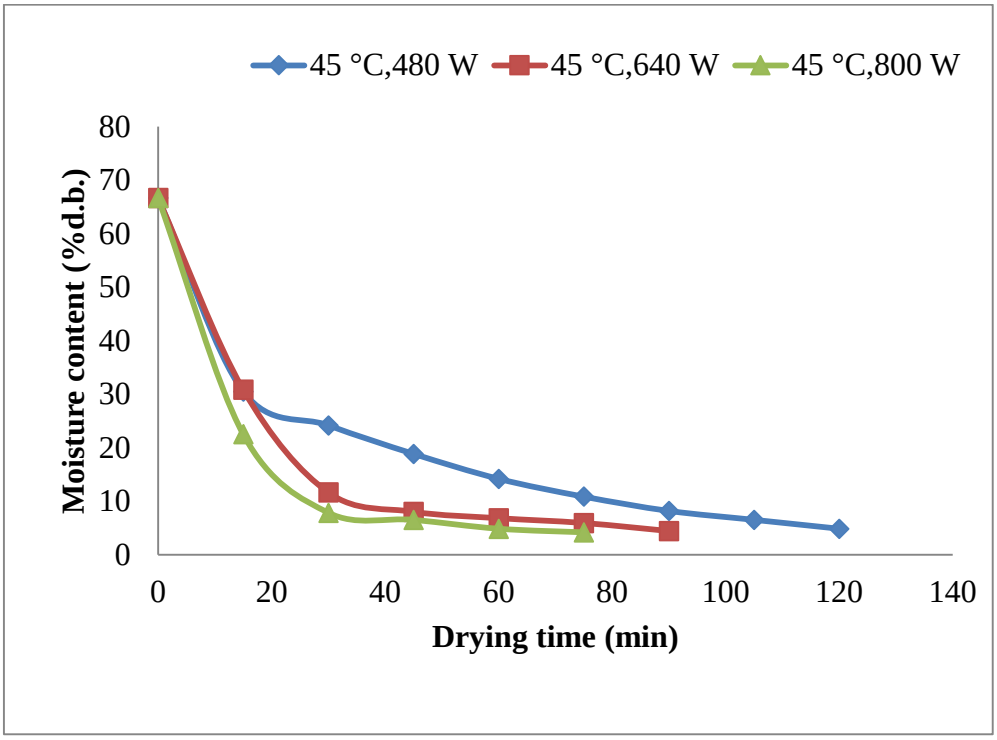


Fig. 4.3 (b) Variation in moisture content (%d.b.) with drying time (min) at different microwave power levels at 45 °C

Addition of microwave irradiation to the convective drying process increases water evaporation inside the particles, which causes an increase of the internal pressure, and in turn increases the diffusion of water towards the surface of the particles, from which it is removed convectively by drying air (Reyes *et al.*, 2006). This might be the reason for the decrease in drying time with the increase of the drying temperature and microwave power.

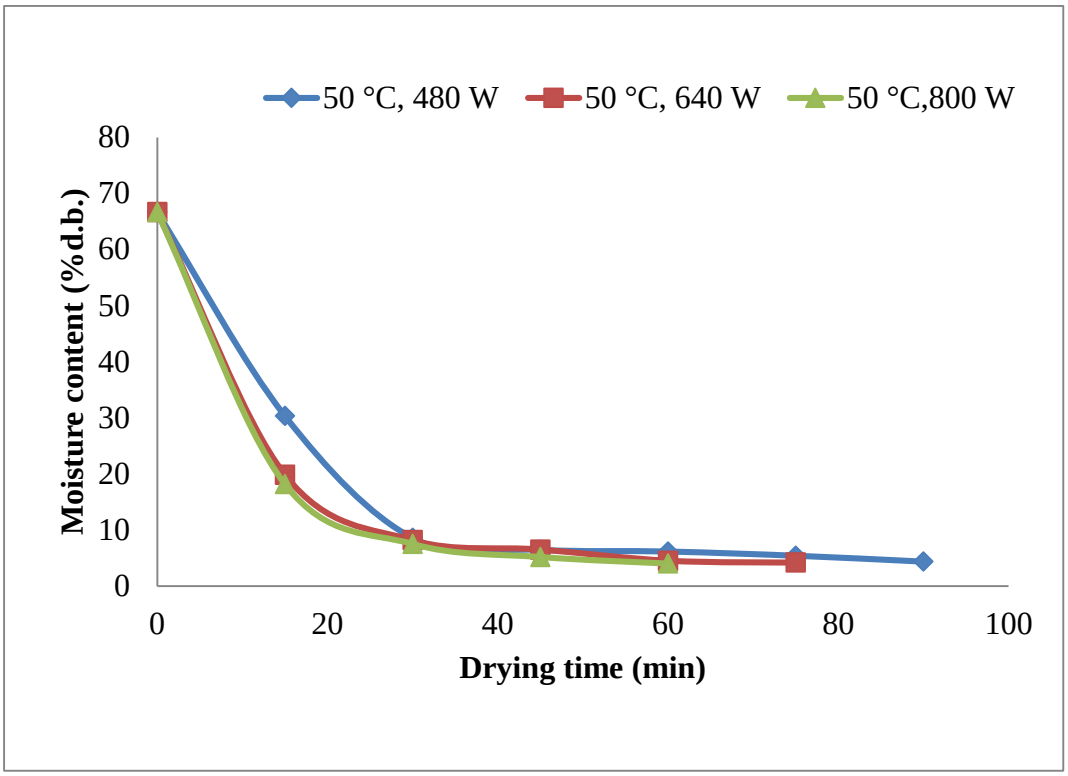


Fig. 4.3 (c) Variation in moisture content (%d.b.) with drying time (min) at different microwave power levels at 50 °C

In comparison with the fluidized bed dryer the assited fluidized bed drying enhanced heat and mass transfer within the cell structre of the mace resulting in increased drying rate and there by enegy utilization. Also, it is noticed that time taken for drying mace is less in microwave assisted fluidized than the fluidized bed dryer and it may be due to the uniform energy distribution in the oven. The fluidisation along with microwave energy increases the drying rate.

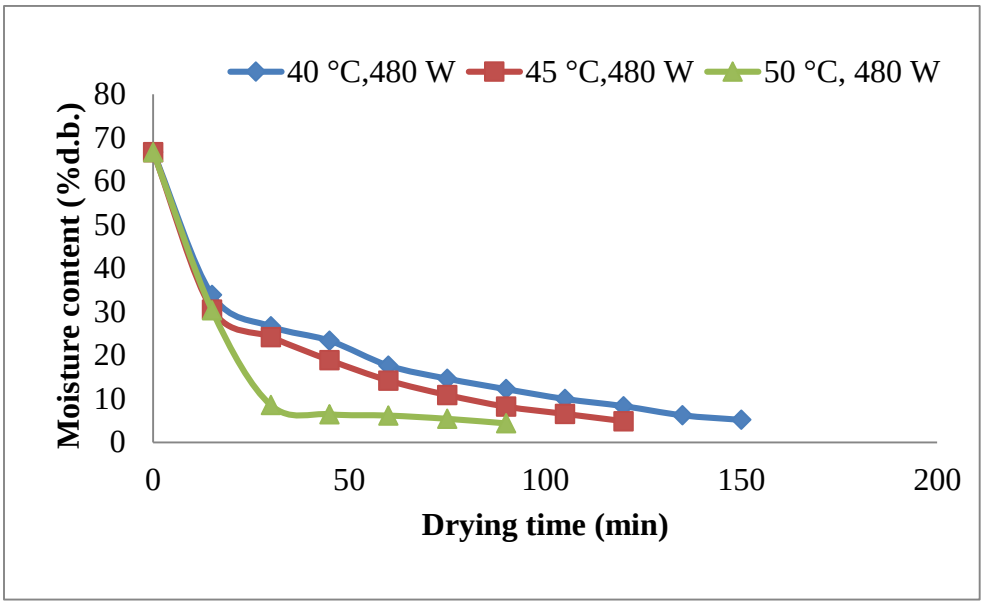


Fig. 4.4 (a) Variation in moisture content with drying time (min) at different temperatures at 480 W microwave power

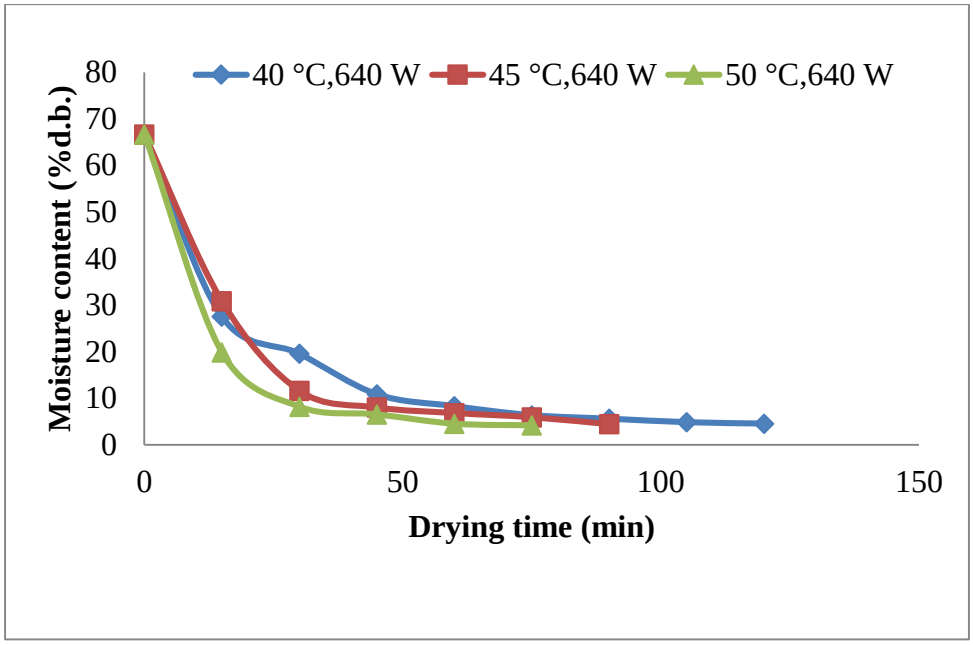


Fig. 4.4 (b) Variation in moisture content with drying time (min) at different temperatures at 640 W microwave power

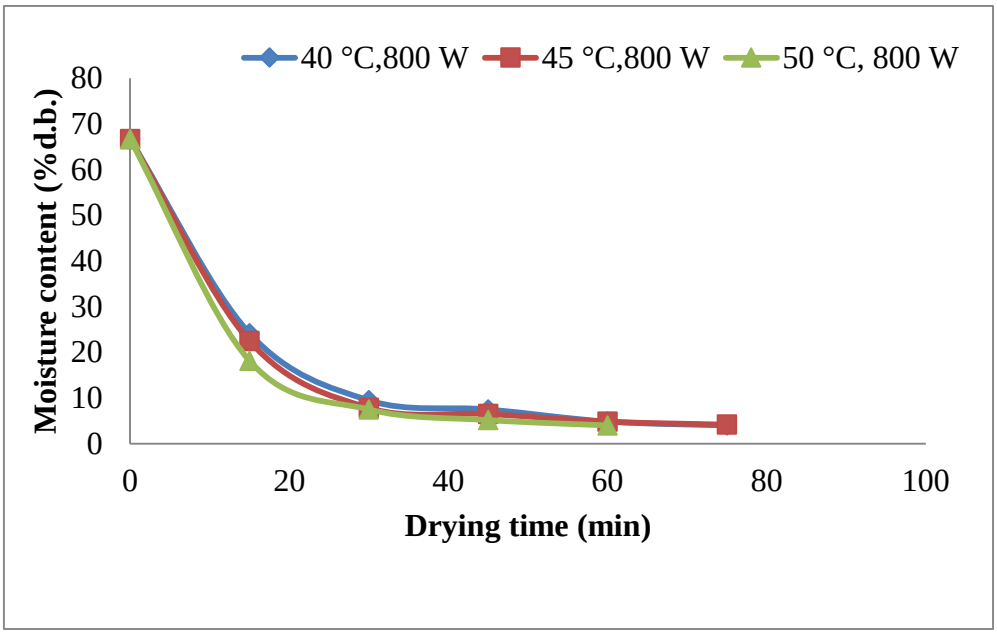


Fig. 4.4 (c) Variation in moisture content with drying time (min) at different temperatures at 800 W microwave power

In accordance with the discussion, minimum drying time among all the drying conditions including sun drying was obtained in the microwave assisted fluidized bed dryer at 50°C and 800W microwave power level.

## 4.5 MATHEMATICAL MODELING OF NUTMEG MACE AT DIFFERENT DRYING TEMPERATURES

From the drying data, moisture ratio values were determined and presented in the Table A.1. Modelling of the drying data was done by using a MATLAB R2013a software. Well established drying models namely, Newton, Page, Henderson and Pabis, Logarithmic, Two term and Wang and Singh models were considered for the modeling study. The goodness of the fit was determined using estimated values of statistical parameters viz., reduced chi-square ($\chi^2$), standard square error (*SSE*), coefficient of determination ($R^2$) and root mean square error (*RMSE*). The best fitting model was determined according to the lowest $\chi^2$, SSE and RMSE and highest $R^2$

value. The constants of various drying models for different drying temperature and microwave power levels are shown in Table 4.4. The estimated values of statistical parameters of various models for different drying temperatures and microwave power levels are presented in the Table 4.5, 4.6 and 4.7.

Among the all tested models, logarithmic model gave the better prediction of MR in all the combinations. After the logarithmic model, Page, Two term, Henderson and Pabis, Newton followed by Wang and Singh model gave the better prediction of MR.

Logarithmic model was found as the best fitting model with highest $R^2$value of 0.9996 and lowest $\chi^2$, SSE and RMSE values of 1.2588e-05, 0.0003 and 0.01respectively at 50°C drying temperature and 800 W microwave power. Similar findings were reported by Xue Hu *et al.* (2016) with highest $R^2$value of 0.9998 and lowest $\chi^2$ and SSE values of 0.00018 and 0.000038 for microwave assisted fluidized bed drying of carrot slices.

The Logarithmic model successfully describes the relationship between moisture ratio and drying time than other models. This model can be used to scale-up the microwave-assisted fluidized-bed dryer to a commercial scale.

Table 4.3 Drying models constants for MFBD at different drying temperatures at different microwave powers

| Parameter | Drying temperature | Microwave power | Newton | Page | Henderson and pabis | Logarithmic | Two term | Wang and singh |
|---|---|---|---|---|---|---|---|---|
| a | 40 | 480 | 0.06219 | 0.1334 | 0.8822 | 0.8314 | 0.2167 | -0.0168 |
| | 45 | 480 | 0.067 | 0.1511 | 0.9108 | 0.8639 | 0.2298 | -0.0197 |
| | 50 | 480 | 0.0795 | 0.09507 | 0.9986 | 0.9495 | 0.4501 | -0.0325 |
| b | 40 | 480 | | 0.5692 | 0.02052 | 0.03553 | 0.08771 | 7.53E-05 |
| | 45 | 480 | | 0.5774 | 0.02732 | 0.04324 | 0.1046 | 0.0001002 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50 | 480 | | 0.8254 | 0.05484 | 0.06645 | 0.08765 | 0.0002572 |
| c | 40 | 480 | | | | 0.1234 | | |
| | 45 | 480 | | | | 0.0103 | | |
| | 50 | 480 | | | | 0.0587 | | |
| a | 40 | 640 | 0.04309 | 0.1772 | 0.9573 | 0.9056 | 0.2681 | -0.02426 |
| | 45 | 640 | 0.05007 | 0.1084 | 0.991 | 0.9375 | 0.9325 | -0.03123 |
| | 50 | 640 | 0.07285 | 0.2676 | 0.9913 | 0.9317 | 0.3358 | -0.03918 |
| b | 40 | 640 | | 0.591 | 0.04103 | 0.05785 | 0.1224 | 0.0001448 |
| | 45 | 640 | | 0.7624 | 0.04964 | 0.06245 | 0.06213 | 0.000242 |
| | 50 | 640 | | 0.5723 | 0.07228 | 0.09329 | 0.1611 | 0.0003701 |
| c | 40 | 640 | | | | 0.08294 | | |
| | 45 | 640 | | | | 0.0675 | | |
| | 50 | 640 | | | | 0.06805 | | |
| a | 40 | 800 | 0.06219 | 0.1648 | 0.9904 | 0.9363 | 0.3383 | -0.03739 |
| | 45 | 800 | 0.067 | 0.1914 | 0.9929 | 0.9382 | 0.3573 | -0.03864 |
| | 50 | 800 | 0.0795 | 0.2527 | 0.9941 | 0.9374 | 0.3394 | -0.04677 |
| b | 40 | 800 | | 0.688 | 0.06165 | 0.07722 | 0.1365 | 0.000344 |
| | 45 | 800 | | 0.6613 | 0.06738 | 0.08414 | 0.1398 | 0.0003622 |
| | 50 | 800 | | 0.6126 | 0.07912 | 0.09945 | 0.176 | 0.000534 |
| c | 40 | 800 | | | | 0.06407 | | |
| | 45 | 800 | | | | 0.06284 | | |
| | 50 | 800 | | | | 0.06244 | | |

Table 4.4 Estimated values of statistical parameters at different drying temperatures at 480 W microwave power

| Parameter | Drying temperature | Microwave power | Newton | Page | Henderson and pabis | Logarithmic | Two term | Wang and Singh |
|---|---|---|---|---|---|---|---|---|
| SSE | 40 | 480 | 0.06699 | 0.003392 | 0.05008 | 0.02428 | 0.03192 | 0.1258 |
| | 45 | 480 | 0.0513 | 0.00268 | 0.04259 | 0.0195 | 0.02427 | 0.1194 |
| | 50 | 480 | 0.01557 | 0.01397 | 0.01557 | 0.00678 | 0.01236 | 0.05945 |
| $R^2$ | 40 | 480 | 0.906 | 0.9952 | 0.9297 | 0.9959 | 0.9552 | 0.8235 |
| | 45 | 480 | 0.9287 | 0.9963 | 0.9408 | 0.9973 | 0.9663 | 0.9341 |
| | 50 | 480 | 0.9786 | 0.9808 | 0.9786 | 0.9907 | 0.9818 | 0.9183 |
| Adj $R^2$ | 40 | 480 | 0.906 | 0.9947 | 0.9219 | 0.9574 | 0.9502 | 0.8039 |
| | 45 | 480 | 0.9287 | 0.9958 | 0.9334 | 0.9652 | 0.9621 | 0.8134 |
| | 50 | 480 | 0.9786 | 0.977 | 0.9743 | 0.986 | 0.9781 | 0.9019 |
| RMSE | 40 | 480 | 0.08185 | 0.01941 | 0.0746 | 0.05509 | 0.05956 | 0.1182 |
| | 45 | 480 | 0.0755 | 0.01831 | 0.07296 | 0.05277 | 0.05508 | 0.1222 |
| | 50 | 480 | 0.05094 | 0.05285 | 0.0558 | 0.04117 | 0.0515 | 0.109 |
| $\chi 2$ | 40 | 480 | 0.0067 | 0.00034 | 0/005 | 0.00243 | 0.00319 | 0.01256 |
| | 45 | 480 | 0.00572 | 0.00027 | 0.00474 | 0.01182 | 0.0027 | 0.01323 |
| | 50 | 480 | 0.002533 | 0.002238 | 0.002532 | 0.001058 | 0.002132 | 0.009903 |

Table 4.5 Estimated values of statistical parameters at different drying temperatures at 640 W microwave power

| Parameter | Drying temperature | Microwave power | Newton | Page | Henderson and pabis | Logarithmic | Two term | Wang and Singh |
|---|---|---|---|---|---|---|---|---|
| SSE | 40 | 640 | 0.02992 | 0.001941 | 0.028/1 | 0.00608 | 0.01492 | 0.1133 |
| | 45 | 640 | 0.01263 | 0.00774 | 0.01255 | 0.002497 | 0.00253 | 0.05071 |
| | 50 | 640 | 0.01337 | 0.001604 | 0.01129 | 0.0003 | 0.00665 | 0.06686 |
| $R^2$ | 40 | 640 | 0.9591 | 0.9917 | 0.9616 | 0.9973 | 0.9796 | 0.845 |
| | 45 | 640 | 0.982 | 0.989 | 0.9821 | 0.9964 | 0.9964 | 0.9278 |
| | 50 | 640 | 0.983 | 0.9976 | 0.9831 | 0.9996 | 0.9901 | 0.9002 |
| Adj $R^2$ | 40 | 640 | 0.9591 | 0.997 | 0.9561 | 0.9889 | 0.9767 | 0.8229 |
| | 45 | 640 | 0.982 | 0.9868 | 0.9786 | 0.9947 | 0.9957 | 0.9134 |
| | 50 | 640 | 0.983 | 0.997 | 0.9789 | 0.9993 | 0.9876 | 0.8752 |
| RMSE | 40 | 640 | 0.6116 | 0.01665 | 0.06336 | 0.03183 | 0.04617 | 0.1272 |
| | 45 | 640 | 0.04588 | 0.03934 | 0.0501 | 0.02499 | 0.02247 | 0.1007 |
| | 50 | 640 | 0.04768 | 0.02002 | 0.05313 | 0.01 | 0.04077 | 0.1293 |
| $\chi 2$ | 40 | 640 | 0.00378 | 0.00024 | 0.00355 | 0.00076 | 0.00189 | 0.01415 |
| | 45 | 640 | 0.002121 | 0.0013 | 0.002107 | 0.000421 | 0.00404 | 0.00844 |
| | 50 | 640 | 0.0023 | 0.00032 | 0.00228 | 6.034e-05 | 0.00134 | 0.01334 |

Table 4.6 Estimated values of statistical parameters at different drying temperatures at 800 W microwave power

| Parameter | Drying temperature | Microwave power | Newton | Page | Henderson and pabis | Logarithmic | Two term | Wang and Singh |
|---|---|---|---|---|---|---|---|---|
| SSE | 40 | 800 | 0.02992 | 0.001941 | 0.028/1 | 0.00608 | 0.01492 | 0.1133 |
| | 45 | 800 | 0.01263 | 0.00774 | 0.01255 | 0.002497 | 0.00253 | 0.05071 |
| | 50 | 800 | 0.01337 | 0.001604 | 0.01129 | 0.0003 | 0.00665 | 0.06686 |
| $R^2$ | 40 | 800 | 0.9591 | 0.9973 | 0.9616 | 0.9917 | 0.9796 | 0.845 |
| | 45 | 800 | 0.982 | 0.989 | 0.9821 | 0.9964 | 0.9964 | 0.9278 |
| | 50 | 800 | 0.983 | 0.9976 | 0.9831 | 0.9996 | 0.9901 | 0.9002 |
| Adj $R^2$ | 40 | 800 | 0.9591 | 0.997 | 0.9561 | 0.9889 | 0.9767 | 0.8229 |
| | 45 | 800 | 0.982 | 0.9868 | 0.9786 | 0.9947 | 0.9957 | 0.9134 |
| | 50 | 800 | 0.983 | 0.997 | 0.9789 | 0.9993 | 0.9876 | 0.8752 |
| RMSE | 40 | 800 | 0.6116 | 0.01665 | 0.06336 | 0.03183 | 0.04617 | 0.1272 |
| | 45 | 800 | 0.04588 | 0.03934 | 0.0501 | 0.02499 | 0.02247 | 0.1007 |
| | 50 | 800 | 0.04768 | 0.02002 | 0.05313 | 0.01 | 0.04077 | 0.1293 |
| $\chi 2$ | 40 | 800 | 0.001739 | 0.000456 | 0.00172 | 0.00012 | 0.00086 | 0.0094 |
| | 45 | 800 | 0.00190 | 0.00068 | 0.00189 | 0.0001402 | 0.0116 | 0.0107 |
| | 50 | 800 | 0.00162 | 0.000162 | 0.00161 | 1.2588e-05 | 0.00081 | 0.0089 |

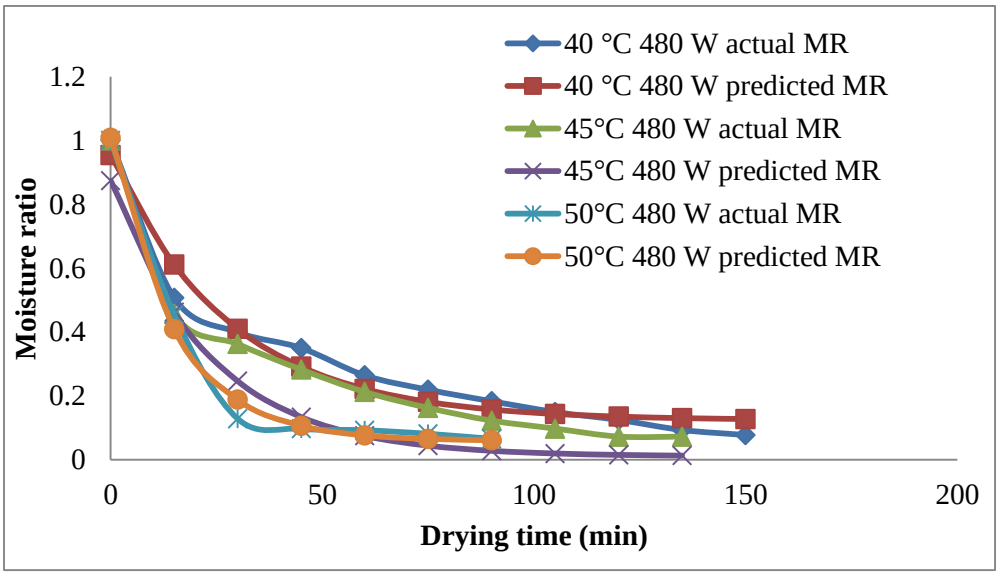


Fig. 4.5 Experimental and logarithmic model predicted moisture ratio at 480 W microwave power at different drying temperatures

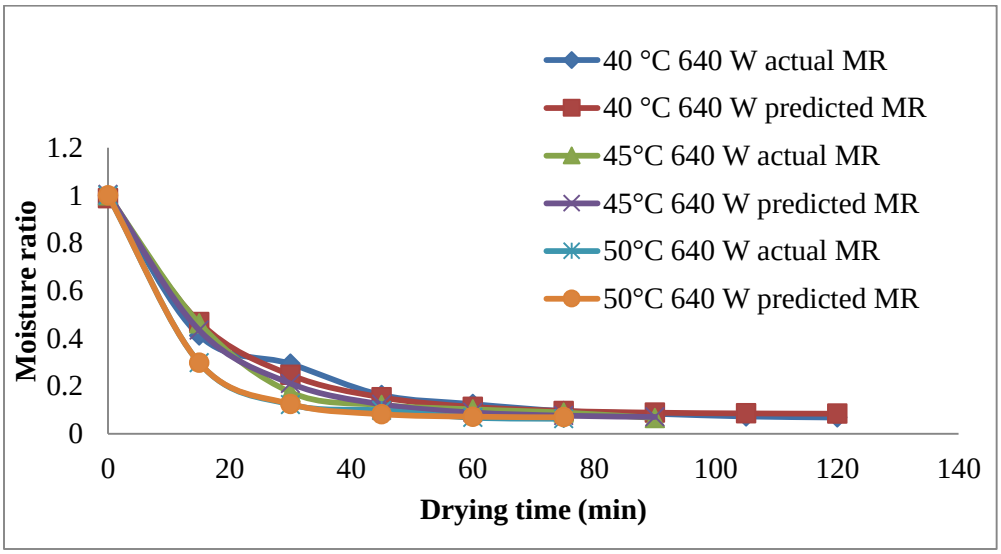


Fig. 4.6 Experimental and logarithmic model predicted moisture ratio at 640 W microwave power at different drying temperatures

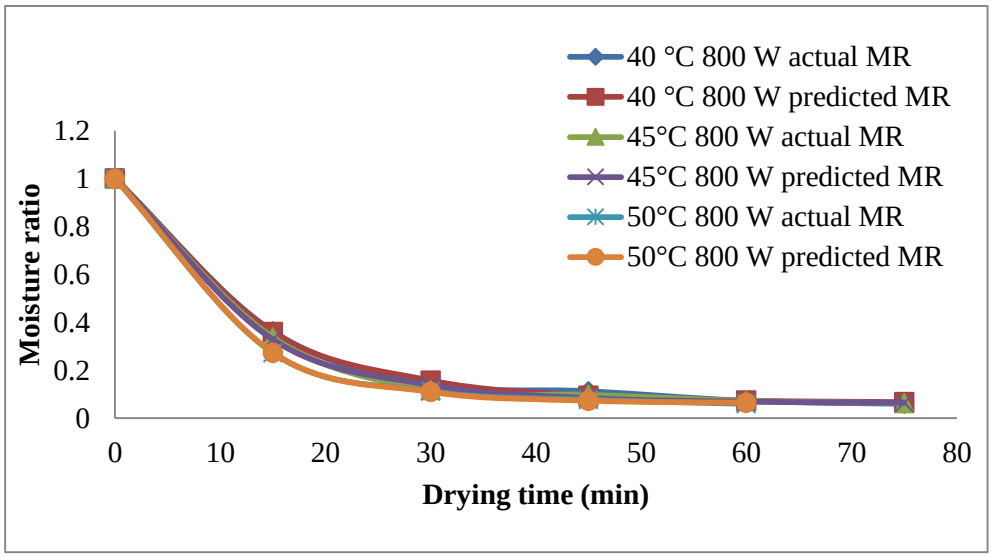


Fig. 4.7 Experimental and logarithmic model predicted moisture ratio at 800 W microwave power at different drying temperatures

## 4.6 STANDARDIZATION OF THE PROCESS PARAMETERS OF THE MICROWAVE ASSISTED EXTRACTION SYSTEM

A series of experiments with drying temperatures 40, 45 and 50°C and microwave power levels of 480, 640 and 800 W as input variables were performed to evaluate the performance of the microwave assisted fluidised bed dryer and for optimising the process. The experimental procedure which was mentioned in section 3.6 is followed to perform the experiments. The results of the experiments were presented in Table 4.7.

The results obtained for various experiments (Table 4.7) were used as responses for optimising the process parameters. To optimise the model partial differentiation of the process parameters was done with respect to each parameter. The obtained function was solved by equating the equation to zero. Regression coefficients were used to perform the statistical calculation and to produce three-dimensional plots for the regression model.

**Table 4.7 Effect of process parameters towards the physico-chemical characteristics of nutmeg mace**

| Standard order | Drying temperature (°C) | Microwave power (W) | L* | a* | b* | Colour difference (ΔE) | Final moisture content (%) | Bulk density ($kg/m^{3)}$ | Drying temperature (°c) | Oil yield (%V/W) | Energy consumption (KWh) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 40 | 480 | 18.42 | 15.6 | 7.38 | 7.42028 | 8.1 | 1105 | 37 | 11.82 | 2.2 |
| 2 | 50 | 480 | 20.43 | 14.9 | 8.45 | 7.40682 | 6.5 | 961 | 47 | 11.86 | 2.11 |
| 3 | 40 | 800 | 19.88 | 15.31 | 7.92 | 7.15649 | 7.8 | 854 | 38 | 11.76 | 1.98 |
| 4 | 50 | 800 | 21.27 | 14.1 | 9.02 | 8.13031 | 6 | 733 | 48 | 11.85 | 1.88 |
| 5 | 40 | 640 | 19.13 | 18.08 | 7.86 | 4.833 | 7.8 | 869 | 38 | 11.72 | 1.82 |
| 6 | 50 | 640 | 20.67 | 16.59 | 8.96 | 5.67438 | 6.2 | 781 | 48 | 11.93 | 1.55 |
| 7 | 45 | 480 | 19.98 | 16.5 | 8.11 | 5.95679 | 7.1 | 1156 | 43 | 11.96 | 2.15 |
| 8 | 45 | 800 | 20.39 | 15.09 | 8.46 | 7.22278 | 6.3 | 756 | 43 | 11.87 | 1.85 |
| 9 | 45 | 640 | 20.23 | 18.36 | 8.37 | 4.07404 | 6.2 | 851 | 43 | 11.83 | 1.65 |
| 10 | 45 | 640 | 20.15 | 17.56 | 8.11 | 4.90369 | 6.4 | 831 | 42 | 11.84 | 1.68 |
| 11 | 45 | 640 | 20.23 | 17.86 | 8.33 | 4.55818 | 6.2 | 795 | 42 | 11.81 | 1.58 |
| 12 | 45 | 640 | 20.37 | 18.16 | 8.37 | 4.23219 | 6.4 | 795 | 42 | 11.98 | 1.61 |
| 13 | 45 | 640 | 20.37 | 18.06 | 8.2 | 4.35994 | 6.2 | 780 | 42 | 11.85 | 1.66 |

## 4.8 OPTIMISATION OF PROCESS PARAMETERS OF MFBD SYSTEM

### 4.8.1 Effect of process parameters on colour value L*

The effect of drying temperature and microwave power on the L* value of the dried mace is explained by plotting 3D graphs representing the response surface generated by the model Equation 4.1. The 3D response for *L** was shown in Fig. 4.8.

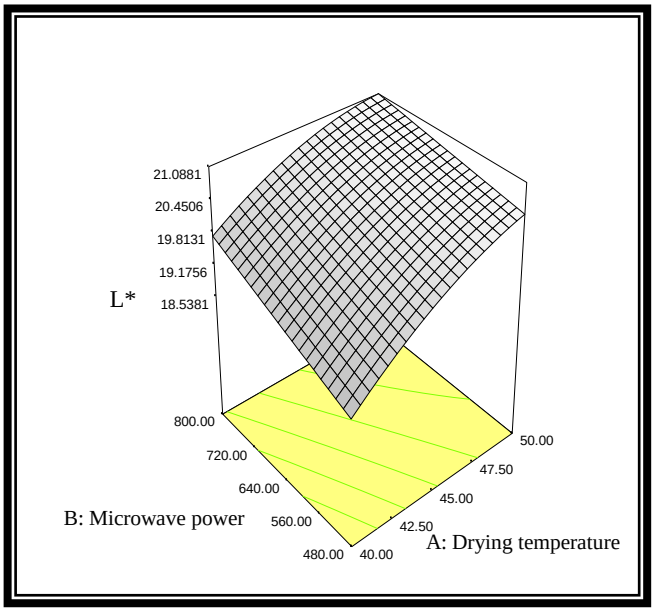


Fig 4.8 Effect of process parameters on L* value

It is illustrated that the process parameters had a significant effect on the L* value (whiteness/darkness). The L* value varied from 18.72 to 21.27. The maximum of L* value was obtained when the drying temperature was 50°C and the microwave power was 800W.With an increase of microwave power and drying temperature, the colour of nutmeg mace became darker implying that more browning of the product occurred (Inchuen *et al.*, 2010). This might be the reason for the increase in darkness of the product. Similar results were reported by Mahendran *et al.* (2016) for nutmeg mace.

Using the design expert 6.0 (Stat-Ease) RSM, the summary output, as shown in appendix C.1 indicates that a quadratic model is adequate for modeling the colour values. Test for significance of the regression model and the lack-of-fit test were also performed.

In order to enquire the relationship between the independent and dependent variables Response Surface Methodology is used. The ANOVA table for the response "L value" is given in Appendix B. The second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the colour (L) value of mace, the regression model is obtained and is given below.

$$L^* = +19.82 - 0.36 * A - 0.49 * B + 0.89 A^2 - 0.68 * B^2 - 0.072 * A * B \quad \ldots\ldots\ldots \quad (4.1)$$

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table B.1, it can be concluded that the values of $R^2$, Adj $R^2$ and Pred $R^2$ for the L value were 0.933021, 0.885179 and 0.576731respectively.The coefficient of determination ($R^2$) of the regression model for Colour (L) value was 93.3 per cent. It indicates that the model could account 93.30 per cent variability in data. The Model F-value of 19.5 implies the model is significant. Lack of Fit is not significant and F-value suggested that model is significant at 2.01476 level of significant. The adequate precision (15.4973) value for L* value of mace indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the darkness of mace. Table C.1 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on darkness of mace at $p<0.001$.

### 4.8.2 Effect of process parameters on colour value a*

The effect of drying temperature and microwave power on the a* value of the dried mace is explained by plotting 3D graphs representing the response surface generated by the model Equation 4.2. The 3D response for a* was shown in Fig. 4.9.

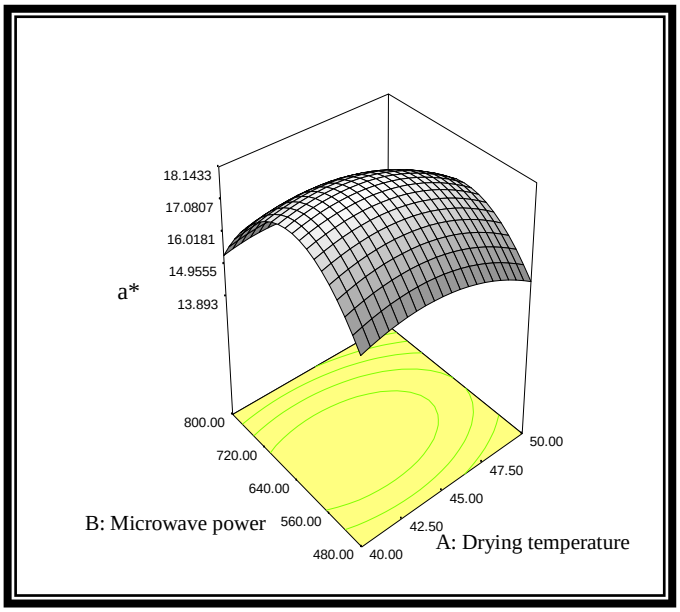


Fig 4.9 Effect of process parameters on a* value

It is illustrated that the process parameters had a significant effect on the a* value (greenness/redness). The a* value varied from 14.1 to 18.367. The maximum of a* value was obtained when the drying temperature was 45°C and the microwave power 640 W.T his indicated that colour of nutmeg mace became more red, implying that more browning of the product occurred (Inchuen *et al.*, 2010). This might be the reason for increase in redness of the product. Similar results were reported by Mahendran *et al.* (2016) for nutmeg mace.

In order to enquire the relationship between the independent and dependent variables Response Surface Methodology is used. The ANOVA table for the response "a* value" is given in Appendix C.2 The second order non-linear regression equation

was fitted between dependent and independent variables using the experimental values. To predict the colour (a*) value of mace, the regression model is obtained and is given below.

$$a^* = +18.02 - 0.57^* A - 0.42^* B - 0.74^* A^2 - 2.28^* B^2 - 0.13^* A * B \quad \ldots\ldots\ldots \quad (4.2)$$

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table C.2, it can be concluded that the values of $R^2$, Adj $R^2$ and Pred$R^2$ for the colour (a*) value were 0.972289, 0.952495 and 0.842577 respectively. The coefficient of determination ($R^2$) of the regression model for Colour (a) value was 93.26 per cent. It indicates that the model could account 97.22 per cent variability in data. The Model F-value of 49.12 implies the model is significant. The Pred R-Squared of 0.842577 is in reasonable agreement with the Adj R-Squared of 0.952495. Lack of Fit is not significant and F-value suggested that model is significant at 1.29 level of significant. The adequate precision (18.77948) value for 'a' value of mace indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the colour (a*) value of mace. Table B.2 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on redness of mace at $p<0.001$.

### 4.8.3 Effect of process parameters on colour value b*

The effect of drying temperature and microwave power on the b* value of the dried mace is explained by plotting 3D graphs (Fig. 4.10 ) representing the response surface generated by the model Equation 4.3 and is illustrated that the process parameters had a significant effect on the b* value(blueness/yellowness).

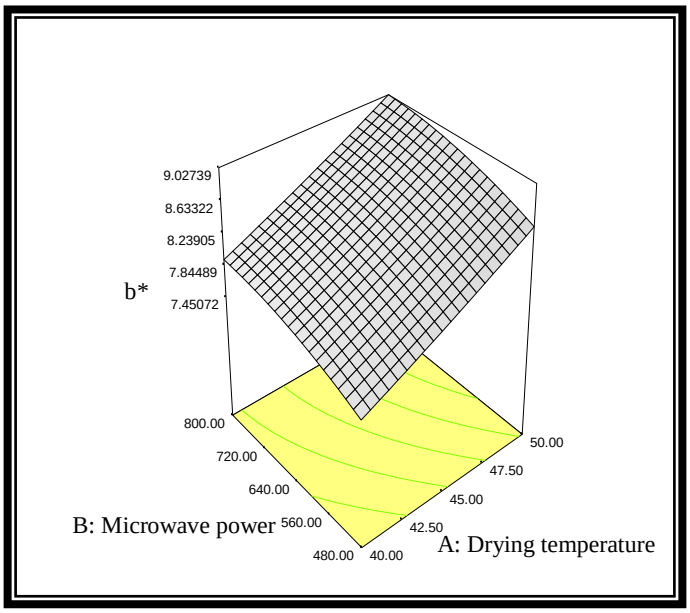


Fig 4.10 Effect of process parameters on b* value

The b* value varied from 7.21 to 9.02. The minimum of b* value was obtained when the drying temperature is 40°C and the microwave power 480 W (Table 4.7).Yellowness of mace was more with increased temperature and microwave power. Similar results were reported by Mahendran *et al.* (2016) for nutmeg mace. Increase in yellow colour could imply the more pigment destruction had occurred (Inchuen *et al.*, 2010).

Browning and carotenoid pigment destruction increased with an increase in the drying temperature and time. Therefore, the undesirable browning and increased yellow colour of the microwave-dried product occurred in samples because of the high temperature generated by the microwaves (Suresh Prasad and Sharma, 2001).

The ANOVA table for the response “b* value” is given in Appendix C.3. The second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the colour (b*) value of mace, the regression model is obtained and is given below.

$$b^* = +8.26 - 0.57^* A + 0.19^* B + 0.15^* A^2 - 0.27^* B^2 + 0.035^* A * B \quad \ldots\ldots \quad (4.3)$$

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table C.3, it can be concluded that the values of $R^2$, Adj $R^2$ and Pred$R^2$ for the colour (b*) value were 0.912866, 0.850627 and 0.462096respectively.The coefficient of determination ($R^2$) of the regression model for Colour (b*) value was 91.28 per cent. It indicates that the model could account 91.28 per cent variability in data. The Model F-value of 14.67 implies the model is significant. Lack of Fit is not significant and F-value suggested that model is significant at 1.65981level of significant. The adequate precision of 12.538 for b value of mace indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the yellowness of mace. Table C.3 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on yellowness of mace at $p<0.001$.

### 4.8.4 Effect of process parameters on colour difference ΔE

The effect of drying temperature and microwave power on the b* value of the dried mace is explained by plotting 3D graphs (Fig. 4.11 ) representing the response surface generated by the model Equation 4.4. The lowest ΔE value (4.07404) was recorded at 45°C temperature at 640W microwave power level. Browning and Carotenoid pigment destruction increased with an increase in the drying temperature and time (Suresh Prasad and Sharma, 2001).

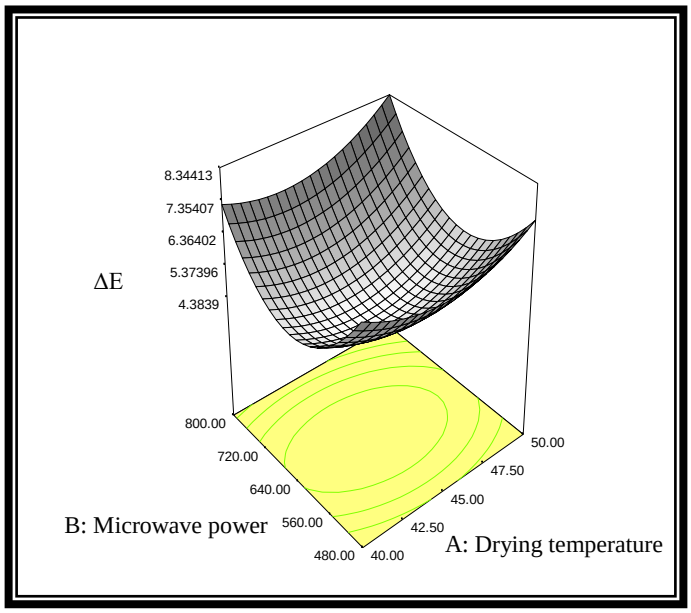


Fig 4.11 Effect of process parameters on ΔE value

The ANOVA table for the response "ΔE value" is given in Appendix C.4. The second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the colour difference (ΔE) value of mace, the regression model is obtained and is given below.

$$\Delta E = +4.41 - 0.30*A + 0.29*B + 0.88*A^2 - 2.22*B^2 + 0.25*A*B \quad \ldots\ldots\ldots \quad (4.4)$$

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table C.4, it can be concluded that the values of $R^2$, Adj $R^2$ and Pred$R^2$ for the colour difference (ΔE) value were 0.9676, 0.9444 and 0.8126 respectively. The coefficient of determination ($R^2$) of the regression model for Colour difference (ΔE) value was 96.76 per cent. It indicates that the model could account 96.768 per cent variability in data. The Model F-value of 41.75 implies the model is significant.

The adequate precision of 16.905 for ΔE value of mace indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the yellowness of mace. Table C.4 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on yellowness of mace at $p<0.001$.

### 4.8.5 Effect of process parameters on final moisture content of dried mace

The effect of drying temperature and microwave power on the final moisture content of the dried mace is explained by plotting 3D graphs representing the response surface generated by the model Equation 4.5. The 3D response for final moisture content was shown in Fig. 4.12.

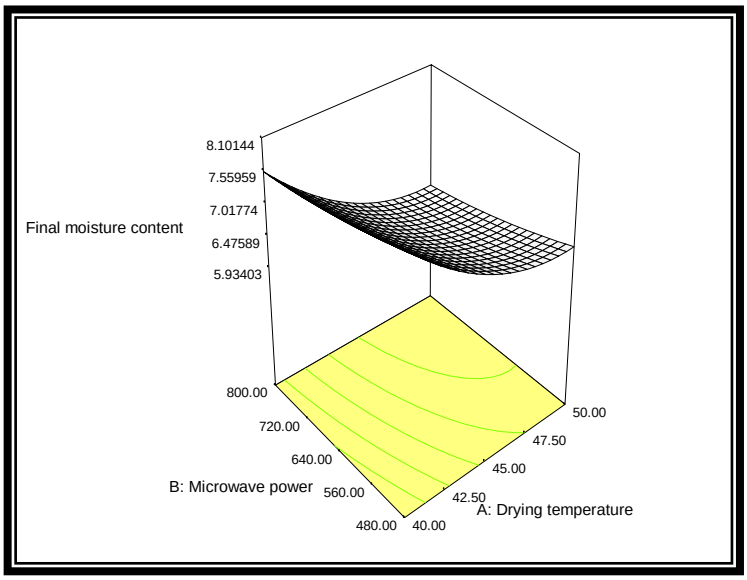


Fig 4.12 Effect of process parameters on final moisture content of mace

It is illustrated that the process parameters had a significant effect on the final moisture content of dried mace. With the increase in drying temperature from 40 to 50°C and microwave power from 480 to 800 W, the final moisture content of mace decreased from 8.1 to 6 %.The minimum moisture content was obtained when the

drying temperature is 50°C and the microwave power 800 W (Table 4.7). At higher temperatures, the driving force was higher due to larger water vapour pressure deficit. This causes the removal of higher amount of moisture from the product within less time (Ramaswamy *et al.,* 1995). This might be the reason for the decreased moisture content with the increased temperature and microwave power level. Patel *et al*. (2014) reported that beetroot samples obtained from the MAFBD system had lower final moisture content than those obtained from the FBD system.

In order to enquire the relationship between the independent and dependent variables Response Surface Methodology is used. The ANOVA table for the response "Final Moisture Content" is given in Appendix C.5. The second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the final moisture content of mace, the regression model is obtained and is given below.

Final Moisture Content = +6.53-0.78* A -0.30* B +0.43* $A^2$+ 0.079* $B^2$ -0.02*A*B …. (4.5)

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table C.5, it can be concluded that the values of $R^2$, Adj $R^2$and Pred$R^2$for the final moisture content were 0.972651, 0.953116 and 0.823945 respectively. The coefficient of determination ($R^2$) of the regression model for final moisture content was 97.26 per cent. It indicates that the model could account 97.26 per cent variability in data. The Model F-value of 49.79 implies the model is significant. The Pred R-Squared of 0.823945 is in reasonable agreement with the Adj R-Squared of 0.953116. Lack of Fit is not significant and F-value suggested that model is significant at3.53576 level of significant. The adequate precision (20.46409)

value for final moisture content of mace indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the total final moisture content of mace.

From equation 4.5, it is clear that final moisture content of mace was in positive correlation with drying temperature and microwave power. Table C.5shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on final moisture content of mace at $p<0.001$

### 4.8.6 Effect of process parameters on bulk density of dried mace

The effect of drying temperature and microwave power on the bulk density of the dried mace is explained by plotting 3D graphs representing the response surface generated by the model Equations 4.6. The 3D response for final moisture content was shown in Fig. 4.13.

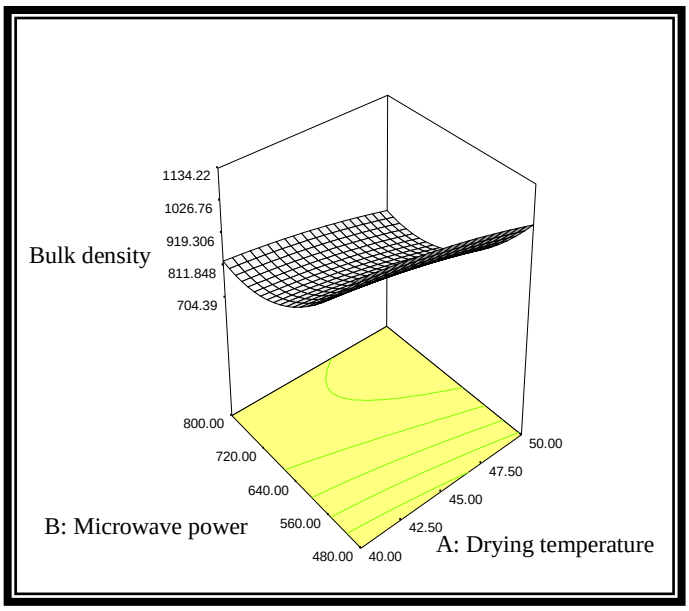


Fig 4.13 Effect of process parameters on bulk density of mace

Also, it is illustrated that the process parameters had a significant effect on bulk density of dried mace through MFBD system. As the drying temperature and microwave power increases bulk density of dried mace decreased.

The bulk density of dried mace varied from 733 to 1156 kg/m$^3$ (Table 4.7). The minimum bulk density was obtained when the drying temperature is 50°C and the microwave power 800W. With the increased microwave power and drying temperature, the bulk density of mace decreased. This decrease in bulk density might be due to the increase of the volume of the dried mace.

The ANOVA table for the response "Bulk density" is given in Appendix C.6 and second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the bulk density of dried mace, the regression model is obtained and is given below.

Bulk density =+0.82+0.059*A+0.15* B-0.013*A$^2$+0.12* B$^2$+5.750E-003*A*B …. (4.6)

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table C.6, it can be concluded that the values of $R^2$, Adj $R^2$and Pred$R^2$ for the bulk density of dried mace were 0.927369, 0.87549 and 0.444225 respectively. The coefficient of determination ($R^2$) of the regression model for the bulk density of dried mace was 92.73 per cent. It indicates that the model could account 92.73 per cent variability in data. The Model F-value of 17.8755 implies the model is significant. Lack of Fit is not significant and F-value suggested that model is significant at 4.42311 level of significant. The adequate precision (13.06432) value for final moisture content of mace indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order

model was adequate in describing the bulk density of mace. Table C.6 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on bulk density of mace at $p<0.001$.

### 4.8.7 Effect of process parameters on drying air temperature

The effect of drying temperature and microwave power on the drying air temperature of the dried mace is explained by plotting 3D graphs and it is shown in fig. 4.14.

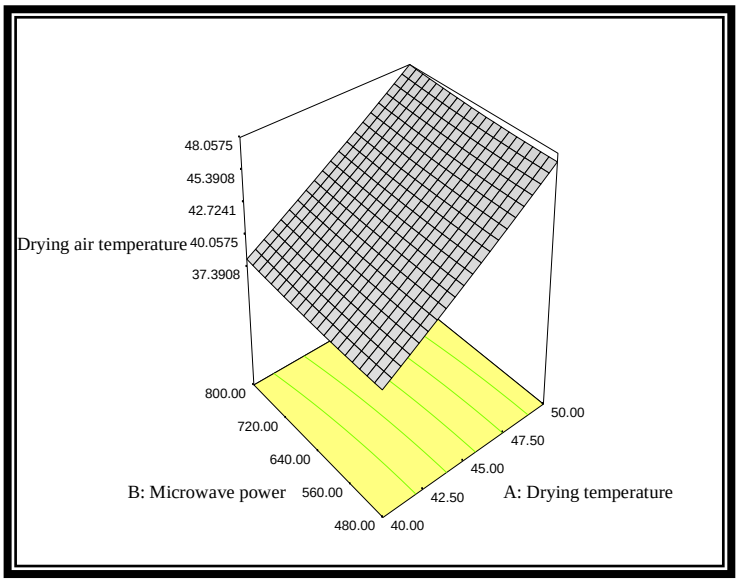


Fig 4.14 Effect of process parameters on drying air temperature

From fig. 4.14, it is illustrated that the microwave power had not significant effect on the drying air temperature. It varied from 37 to 48°C (Table 4.7). The minimum temperature in the system was obtained when the drying temperature is 40°C and the microwave power 480 W and the maximum temperature obtained when the drying temperature is 50°C and the microwave power 800 W.

In order to enquire the relationship between the independent and dependent variables Response Surface Methodology is used. The ANOVA table for the response

"Drying air temperature" is given in Appendix C.6. The second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the drying air temperature, the regression model is obtained and is given below.

Drying air temperature = +42.38 + 5.00*A + 0.33*B + 0.17*$A^2$ + 0.17*$B^2$ +0.000*A*B …… (4.7)

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table C.7, it can be concluded that the values of $R^2$, Adj $R^2$ and Pred$R^2$ for the drying air temperature were 0.984997, 0.974281 and 0.918385respectively. The coefficient of determination ($R^2$) of the regression model for drying air temperature was 98.49 per cent. It indicates that the model could account 98.49 per cent variability in data. The Model F-value of 91.91754 implies the model is significant. The Pred R-Squared of 0.918385is in reasonable agreement with the Adj R-Squared of 0.974281. Lack of Fit is not significant and F-value suggested that model is significant at 2.498084 level of significance. The adequate precision (27.39797) value for drying air temperature indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the drying air temperature of mace. Table C.7 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on drying air temperature of mace at $p<0.001$.

### 4.8.8 Effect of process parameters on the oil yield of dried mace

Fig. 4.15 showing the effect of drying temperature and microwave power on the oil yield of the dried mace.

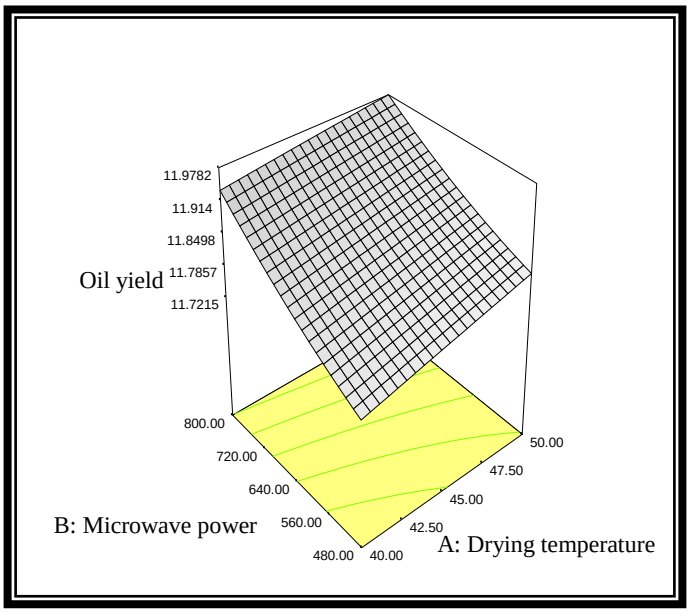


Fig 4.15 Effect of process parameters on the oil yield of mace

From fig. 4.15, it is illustrated that the process parameters had a significant effect on the oil yield of the dried mace. The oil yield of nutmeg mace obtained during various combinations of process parameters are presented in Table 4.7. The oil yield varied from 11.72 to 11.98%.

With an increase in microwave power upto 800 W and drying temperature upto 50°C, the oil yield increased to 11.98%. Partially dried surface layer limits the diffusion of high molecular weight volatiles and the loss of volatile components. So the conditions that improve plant materials drying are the most protective of the volatile compounds content (Goulas *et al.*, 2015).

The ANOVA table for the response Oil yield is given in Appendix C.8. The second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the oil yield of dried mace, the regression model is obtained and is given below.

Oil yield = +11.85 + 0.032*A + 0.097*B – 5.720*$A^2$ – 0.014*$B^2$ – 1.000*A* B …… (4.8)

Where

A = Drying temperature (°C)

B = Microwave power (W)

From Table C.7, it can be concluded that the values of $R^2$, Adj $R^2$ and Pred$R^2$ for the oil yield were o.9892, 0.9815 and 0.9614 respectively. The coefficient of determination ($R^2$) of the regression model for the oil yield was 98.92 per cent and it indicates that the model could account 98.92 per cent variability in data. The Model F-value of 128.61 implies the model is significant. The Pred R-Squared of 0.9614 is in reasonable agreement with the Adj R-Squared of 0.9815. Lack of Fit is not significant. The adequate precision (38.126) value for oil yield of dried mace indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the oil yield of mace. Table C.8 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on oil yield of mace at $p<0.001$.

### 4.8.9 Effect of process parameters on the energy consumption

The 3D response for the energy consumption was shown in Fig. 4.16. It is illustrated that the process parameters had a significant effect on the energy consumption. With an increase in drying temperature upto 45°C and microwave power upto 640 W, the consumption of energy by the MFBD system decreased and later this consumption of energy increased with the increased drying temperature and microwave power.

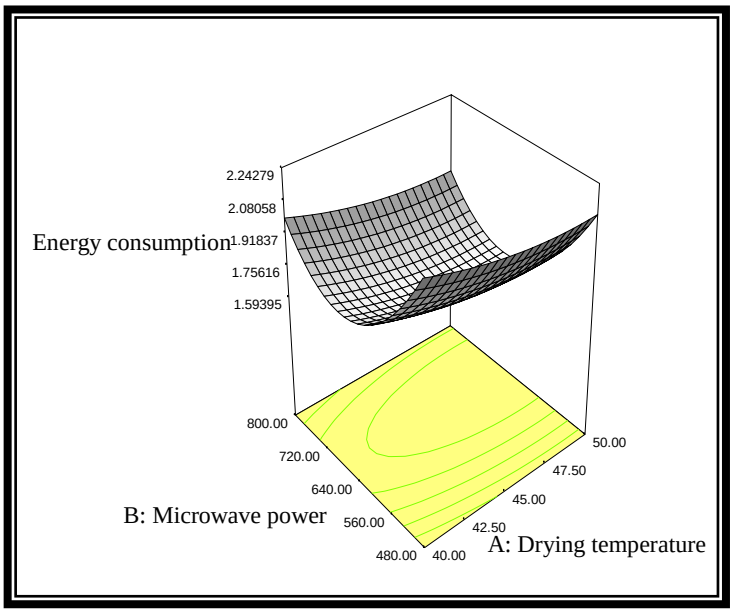


Fig 4.16 Effect of process parameters on the energy consumption

With the increasing microwave power, the more microwave generate the more heat inside of the product and the moisture from the center to surface can be removed within lesser time. There by the energy consumption decreased due to the decrease of the drying time of the mace. This might be the reason for the decreasing of the energy consumption. With the increasing temperature, mace was exposed to more heat energy for the removal of moisture from the surface to center. So the energy consumption increased. This might be the reason for the increase of the energy consumption.

The energy consumption obtained during various combinations of process parameters are presented in Table 4.7. The energy consumption varied from 1.03 to 1.43 KWh. The minimum energy consumption was obtained when the drying temperature is 45°C and the microwave power 640 W.

In order to enquire the relationship between the independent and dependent variables Response Surface Methodology is used. The ANOVA table for the response

Energy consumption is given in Appendix C.9. The second order non-linear regression equation was fitted between dependent and independent variables using the experimental values. To predict the energy consumption of MFBD system, the regression model is obtained and is given below.

Energy consumption = +1.06 - 0.053*A- 0.042*B + 0.22*$A^2$ + 0.061*$B^2$
- 2.500E03*A* B …… (4.9)
Where, A = Drying temperature (°C)

B = Microwave power (W)

From Table C.9, it can be concluded that the values of $R^2$, Adj $R^2$ and Pred$R^2$ for the energy consumption were 0.969749, 0.948141 and 0.784477respectively.The coefficient of determination ($R^2$) of the regression model for the energy consumption was 99.19 per cent. It indicates that the model could account 99.19 per cent variability in data. The Model F-value of 44.879 implies the model is significant. The Pred R-Squared of 0.968261 is in reasonable agreement with the Adj R-Squared of 0.986128. Lack of Fit is not significant and F-value suggested that model is significant at 0.8345 level of significance. The adequate precision (18.16526) value for energy consumption indicates that the model can be used to predict the response within the design space as it is greater than 4.0. Therefore, second order model was adequate in describing the energy consumption of mace. Table C.9 shows that, the linear (A, B), interactive (AB) and quadratic ($A^2$, $B^2$) terms had a significant effect on energy consumption of mace at $p<0.001$.

### 4.8.7 Desirability

Design expert software was employed to perform the desirability analysis. For any given response, desirability ranges from 0 to 1. A value of one represents the ideal case. A zero indicates that one or more responses fall outside desirable limits (Myers *et al.,* 2009). Using the desirability analysis, the optimal level of various

parameters were found and presented in Table 4.8. From the analysis drying temperature of 47.76°C and microwave power of 681.73W were found to be the optimum values. The L*, a*, b*, ΔE values, final moisture content, oil yield and energy consumption for microwave assisted fluidised bed dried sample were 20.7105, 17.126, 8.713, 5.177, 5.96796%, 11.88%(V/W) and 1.59703 kWh respectively whereas the same for fluidized bed dried sample at 45°C were found to be 17.56 ± 0.05, 14.34 ± 0.02, 8.26 ± 0.05, 7%, 7.0 ± 0.1, 11.77% and 1.8 KWh respectively. Results showed that about 66% reduction in the drying time was occurred as in the case of MFBD mace when compared to conventional FBD mace. The desirability of the optimisation was found to be 0.844 and is close to 1.0. So, the optimized values could be considered ideal.

Table 4.8. Optimal level obtained from the desirability analysis

| Sl. No | Response | Desirability | Optimum level | Low level | High level |
|---|---|---|---|---|---|
| 1 | L* | Maximize | 20.7357 | 18.42 | 21.27 |
| 2 | a* | Maximize | 17.1262 | 14.1 | 18.36 |
| 3 | b* | Minimize | 8.71343 | 7.38 | 9.02 |
| 4 | ΔE | Minimize | 5.17796 | 4.07404 | 7.42028 |
| 5 | Final moisture content | Minimize | 5.96796 | 6 | 8.1 |
| 6 | Bulk density | Minimize | 748.873 | 733 | 1156 |
| 7 | Drying temperature | is in range | 45.6866 | 37 | 48 |
| 8 | Oil yield | Maximize | 11.8878 | 11.72 | 11.98 |
| 9 | Energy consumption | Minimize | 1.59703 | 1.55 | 2.2 |

## 4.9. CHEMICAL ANALYSIS

Myristicin is the main flavour compound present in the nutmeg mace oil and is usually taken as a standard for comparison. Myristicin was determined by extracting the oil through hydro distillation process for optimized values of MFBD and FBD mace. The presence of myristicin was analyzed by comparing with the chromatograph of myristicin standard (Fig. 4.17). The chromatograph of the myristicin standard, optimally produced MFBD nutmeg mace essential oil and FBD mace oil were shown in Fig. 4.17, 4.18 and 4.19. The myristicin content of MFBD mace oil was then compared with the FBD mace oil which were extracted through hydro distillation process.

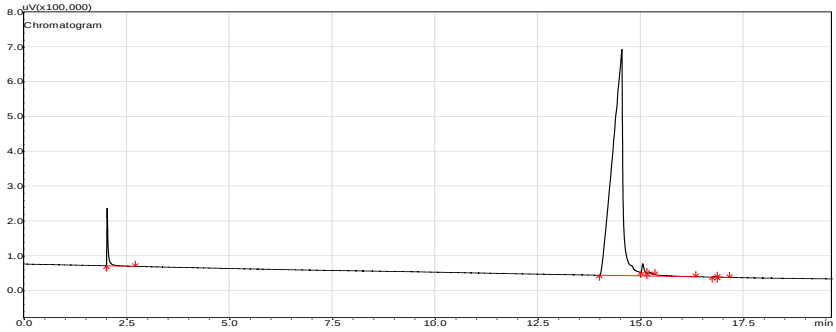


Fig. 4.17. Gas chromatograph of myristicin standard

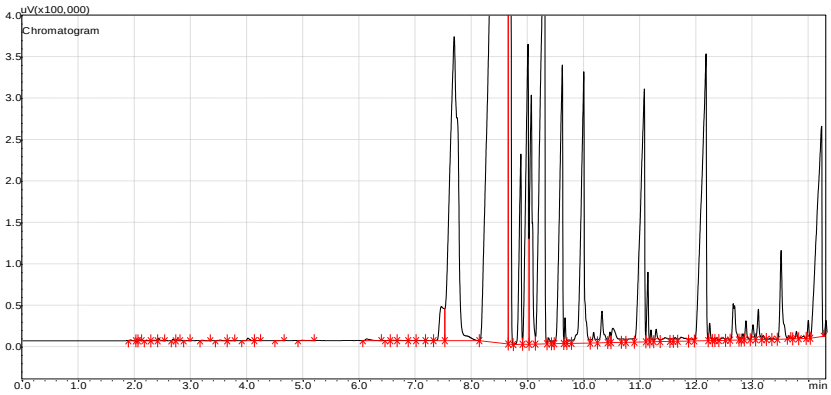


Fig. 4.18. Gas chromatograph of MFBD nutmeg mace oil

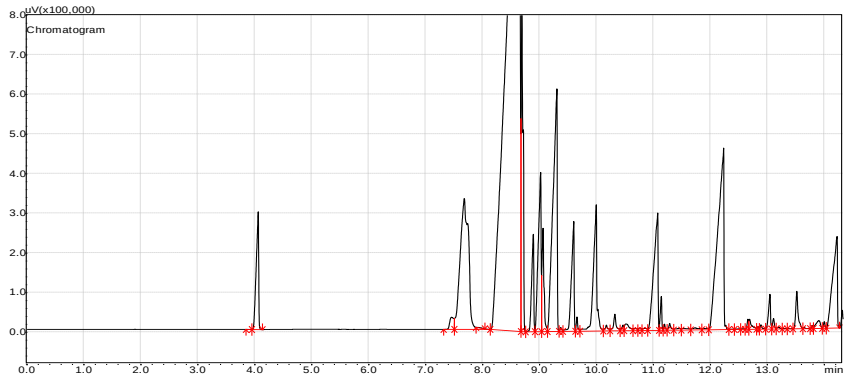


Fig. 4.19. Gas chromatograph of FBD nutmeg mace oil

## 4.10 COMPARISON OF DRYING METHODS FOR NUTMEG MACE

The quality characteristics of dried nutmeg mace under different drying methods were tabulated in Table 4.9.

Table 4.9 Comparison of the quality parameters of the dried mace under different drying methods

| Parameter | Sun drying | Fluidized bed drying | Microwave assisted fluidized bed drying |
|---|---|---|---|
| Drying time (h) | 16 | 4.15 | 1.3 |
| Final moisture content (%d.b) | 10± 0.01 | 7.0± 0.01 | 5.97723 |
| L* | 15.28 ± 0.05 | 17.56 ± 0.05 | 20.7357 |
| a* | 10.56 ± 0.02 | 14.34 ± 0.02 | 17.1262 |
| b* | 6.56 ± 0.05 | 8.26 ± 0.05 | 8.71343 |
| Oil yield (%V/W) | 9.13 | 11.77 | 11.8878 |
| Energy consumption (KWh) | - | 1.8 | 1.59703 |

From Table 4.9 it is clear that the drying time of nutmeg mace is highest in sun drying and lowest in microwave assisted fluidized bed drying. The lowest final moisture content and ΔE is recorded in MFBD mace followed by FBD mace and sun dried mace. Microwave assisted fluidized bed drying reduces the drying time by 90.62% and 64.7% than sun drying and fluidized bed drying respectively. Hence, the microwave assisted fluidized bed dryer for nutmeg mace is considered as one of the best drying techniques to retain better quality of the product.

# CHAPTER V

## SUMMARY AND CONCLUSIOS

India is the Home of Spices. India produces almost all the known spices and is the largest exporter. Nutmeg and mace are used more in drugs than as condiments because of their valuable medicinal properties. The availability of nutmegs starts from June and ends in August. The production of nutmeg is more in rainy season than during the other months of the year. Drying is one of the most important unit operations adopted for agricultural commodities for enhancing the shelf life. Dried mace possess great importance in international trade and are used in the preparation of extractives and volatile oils.

Among various hot air drying methods, the more efficient method is fluidized bed drying for drying of foods, fruits and vegetables. Due to the fluidization of the product surface area increases there by decrease the drying time.

Microwave drying, relatively a new technology gained the popularity for the drying of food products is adopted. In microwave heating, heat generation takes place from inside to outside of the material due to the absorption of microwave energy by the regions with higher moisture levels. Application of microwaves solely, can result in uneven heating of certain products, depending on their dielectric and thermo physical properties. Thus, combining microwave radiation with hot air fluidization provides an effective means of overcoming the non-uniform heating problems in conventional microwave heating.

The present study is to develop the microwave assisted fluidized bed dryer for nutmeg mace and to optimize the drying parameters and compare the performance of the developed system with conventional fluidized bed drying system.

The microwave assisted fluidized bed drying system consists of a fluidized bed dryer and a microwave oven unit. The microwave oven unit consists of control

panel where cooking time, power indicators and clock time are displayed and controlled. This domestic oven was modified by making a hole of 14 cm at the bottom and inserting the fluidized bed dryer through the hole. The main components of a fluidized bed dryer are drying chamber, plenum chamber, heating chamber, blower with power source and an air flow control valve. The drying chamber for performing the drying of nutmeg mace consists of a glass tube with its cover and a porous plate surrounded by a silicone rubber cork. Heating of cold air was conducted by passing it to the heating chamber which consists of a finned heating coil. Also thermostat which accomplished the purpose of controlling the temperature of heater was provided. A 2800 rpm centrifugal blower with 1hp motor was used as the source of air which is heated and then supplied to the drying chamber for drying and fluidization. In order to control the flow rate of the air and thus to maintain fluidization in the drying chamber, a ball flow control valve made up of brass was employed. A three phase energy meter was connected to the centrifugal blower to measure the energy consumed during the microwave assisted fluidized bed drying process. The energy consumed for combination drying process at different process levels as per the experimental design and for conventional fluidized bed drying, were measured for comparison of the energy efficiency.

From the study the process parameters such as microwave power density and drying air temperature were chosen as independent variables. The process parameters would influence drying rate, drying temperature, energy consumption and physico-chemical parameters such as color, moisture content, bulk density, essential oil and volatile components. Based on the preliminary studies, the levels of process parameters were fixed as microwave power (480, 640 and 800 W) and drying temperatures (40, 45 and 50°C).

For evaluating the developed microwave assisted fluidized dryer, about 100g of fresh mace sample was used. The heater was switched on and then the temperature inside the drying chamber was allowed to increase upto required level by setting on

the thermostat. After attaining the required drying temperature, the sample was loaded and the blower was switched on. The air velocity was regulated by air flow control valve and then the loaded sample was allowed to dry. At every 15 minutes interval, weight of the sample was determined and the drying process was continued. Sun drying and fluidized bed drying of nutmeg mace were also carried out for comparing the performance evaluation of the developed technique.

The drying curves were plotted between the moisture content and drying time at different temperatures and microwave powers to find the drying time of mace and to examine the decreasing trend of the moisture content of the mace. Mathematical modeling of drying characteristic curves was performed by using the software MATLAB (version R2013a). Six selected models such as Newton, Page, Henderson and Pabis, Logarithmic, Two term and Wang and Singh were used on all drying curves and the statistical parameters were estimated by following the nonlinear regression procedure.

Response surface methodology (RSM) was used for designing of the experiments and to select the optimum levels of variables. Central Composite Design was chosen to design and determine the combination of variables and levels in each experiment. For optimization of the process parameters and to check the sufficiency of the experimental design, the second order non-linear regression equation was fitted between dependent and independent variables. Analysis of variance (ANOVA) for the final predictive equation is done using design expert (Version 6.0.10) software. Oil was extracted for optimized sample and fluidized bed mace sample through hydro distillation process

Results of the study showed that the measured bulk density and colour (L*, a*, b*) values of the fresh mace sample were 1191 kg/m$^3$, 20.7357, 22.23 ± 0.02, and 9.09 ± 0.05 respectively. At 5.1 m/s the fresh mace sample attained the fluidization condition. The drying time decreased from 150 to 60 minutes for microwave assisted

fluidized bed dryer with the increasing microwave power and drying temperature and this was 255 minutes for fluidized bed dryer. Sun drying took more time 16 hrs for drying the mace.

Logarithmic model was found as the best fitting model for the drying data with highest $R^2$value of 0.9996 and lowest $\chi^2$, SSE and RMSE values of 1.2588e-05, 0.0003 and 0.01 respectively at 50°C drying temperature and 800 W microwave power.

L*, a*, b* and ΔE values of dried mace range between 18.42-21.27, 14.10-18.36, 7.38-9.02 and 4.074-7.420 respectively. The final moisture content, bulk density and energy consumption of dried mace decreased from 8.1 to 6%, 1156 to 733 kg/$m^3$ and 1.43 to 1.03 kWh respectively. The drying air temperature ranges between 37 to 48°C. The yield of oil increased from 11.72 to 11.98 %(V/W).

The L*, a*, b*, ΔE values, final moisture content, oil yield and energy consumption for optimized microwave assisted fluidised bed dried sample were 20.73, 17.1262, 8.71343, 5.1779, 5.97723, 11.8878%, 1.59703 kWh respectively whereas the same for fluidized bed dried sample at 45°C were found to be17.56 ± 0.05, 14.34 ± 0.02, 8.26 ± 0.05, 7.0 ± 0.01, 11.33, 1.8 KWh respectively. Myristicin was increased in optimized mace oil than the fluidized bed dried mace oil.

On the basis of the experimental results and data analysis the following conclusions could be drawn,

1. Microwave assisted fluidized bed drying reduces the drying time by 90.62% and 64.7% than sun drying and fluidized bed drying respectively.
2. Drying time decreased with the increased drying temperature and microwave power.

3. Logarithmic model was found as the best fitting model with highest $R^2$value and lowest $\chi^2$, SSE and RMSE values of at 50°C drying temperature and 800 W microwave power.
4. The colour of the nutmeg mace retained much as in the case of MFBD mace than the FBD mace. Since colour is the most important factor to detect the quality, the sample dried in MFBD shows a L* of 21.27, a* of 18.36, b* 9.02 and ΔE of 5.1779.
5. The bullk density decreased as in the case of MFBD mace than the FBD mace**.**
6. The energy consumption decreased as in the case of MFBD than the FBD.
7. The oil yiled increased as in the case of MFBD than the FBD.
8. The optimized conditions of drying temperature and microwave power for MFBD were found to be 47.76 °C and 681.73 W.

**Suggestions for future work**

1. Studies on the shelf life of the essential oil at different storage conditions cabe carried out.
2. Drying characteristics studies for some other product in the developed dryer

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## APPENDIX A

### Table A.1 Drying experiment data of nutmeg mace in sun drying

| Time (h) | Weight (g) | M.C (%db) |
|---|---|---|
| 0 | 100 | 66.67 |
| 1 | 96.45 | 60.7533 |
| 2 | 93 | 55.0033 |
| 3 | 90.23 | 50.3867 |
| 4 | 88.91 | 48.1867 |
| 5 | 86.33 | 43.8867 |
| 6 | 85.15 | 41.92 |
| 7 | 84.23 | 40.3867 |
| 8 | 82.67 | 37.7867 |
| 9 | 79.34 | 32.2367 |
| 10 | 76.56 | 27.6033 |
| 11 | 73.26 | 22.1033 |
| 12 | 68.77 | 14.62 |
| 13 | 66.23 | 10.3867 |
| 14 | 65.78 | 9.63667 |
| 15 | 64.966 | 8.28 |
| 16 | 64.26 | 7.10333 |

**Table A.2 Drying experiment data of nutmeg mace in fluidized bed dryer at 40°C**

| Time (min) | Weight (g) | M.C (%d.b.) |
|---|---|---|
| 0 | 100 | 66.67 |
| 15 | 85.8 | 43.00333 |
| 30 | 80.3 | 33.83667 |
| 45 | 78.2 | 30.33667 |
| 60 | 76.1 | 26.83667 |
| 75 | 74.3 | 23.83667 |
| 90 | 72.7 | 21.17 |
| 105 | 71.5 | 19.17 |
| 120 | 70.8 | 18.00333 |
| 135 | 70.1 | 16.83667 |
| 150 | 69.2 | 15.33667 |
| 165 | 68.8 | 14.67 |
| 180 | 67.9 | 13.17 |
| 195 | 66.9 | 11.50333 |
| 210 | 66.1 | 10.17 |
| 225 | 65.9 | 9.836667 |
| 240 | 64.9 | 8.17 |
| 255 | 64.1 | 6.836667 |
| 270 | 64.1 | 6.836667 |

**Table A.3 Drying experiment data of nutmeg mace in fluidized bed dryer at 45°C**

| Time (min) | Weight (g) | M.c (%db) |
|---|---|---|
| 0 | 100 | 66.67 |
| 15 | 80.9 | 34.83667 |
| 30 | 78.4 | 30.67 |
| 45 | 76.7 | 27.83667 |
| 60 | 74.5 | 24.17 |
| 75 | 73.1 | 21.83667 |
| 90 | 72.2 | 20.33667 |
| 105 | 71.8 | 19.67 |
| 120 | 70.1 | 16.83667 |
| 135 | 69.3 | 15.50333 |
| 150 | 68.1 | 13.50333 |
| 165 | 67.6 | 12.67 |
| 180 | 66.9 | 11.50333 |
| 195 | 65.9 | 9.836667 |
| 210 | 65.1 | 8.503333 |
| 225 | 64.5 | 7.503333 |
| 240 | 63.6 | 6.003333 |
| 255 | 63.6 | 6.003333 |

**Table A.4 Drying experiment data of nutmeg mace in fluidized bed dryer at 50°C**

| Time (min) | Weight (g) | M.C. (%db) |
|---|---|---|
| 0 | 100 | 66.67 |
| 15 | 80.6 | 34.33667 |
| 30 | 77.5 | 29.17 |
| 45 | 75.5 | 25.83667 |
| 60 | 73.2 | 22.00333 |
| 75 | 71.9 | 19.83667 |
| 90 | 70.3 | 17.17 |
| 105 | 69.4 | 15.67 |
| 120 | 68.2 | 13.67 |
| 135 | 67.1 | 11.83667 |
| 150 | 66.3 | 10.50333 |
| 165 | 65.2 | 8.67 |
| 180 | 64.9 | 8.17 |
| 195 | 64.1 | 6.836667 |
| 210 | 63.9 | 6.503333 |
| 235 | 63.5 | 5.836667 |

**Table B.1 Drying data of mace in microwave assisted fluidized bed dryer**

**Experiment no 1**

| Drying temperature **– 40 °C**, Microwave power – **480 W** | | | |
|---|---|---|---|
| Time (min) | Weight, g | M.C. (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 80.3 | 33.83667 | 0.507525 |
| 30 | 75.5 | 26.62946 | 0.399422 |
| 45 | 73.3 | 23.32616 | 0.349875 |
| 60 | 69.5 | 17.62045 | 0.264294 |
| 75 | 67.5 | 14.61745 | 0.219251 |
| 90 | 65.9 | 12.21505 | 0.183217 |
| 105 | 64.4 | 9.962793 | 0.149434 |
| 120 | 63.3 | 8.311141 | 0.124661 |
| 135 | 61.9 | 6.209039 | 0.093131 |
| 150 | 61.2 | 5.157988 | 0.077366 |
| 165 | 61.2 | 5.157988 | 0.077366 |

**Experiment no 2**

| Drying temperature **– 40 °C**, Microwave power – **640 W** | | | |
|---|---|---|---|
| Time (min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 76.5 | 27.5033 | 0.41253 |
| 30 | 71.2 | 19.5454 | 0.29317 |
| 45 | 65.4 | 10.8367 | 0.16254 |
| 60 | 63.7 | 8.28411 | 0.12426 |
| 75 | 62.4 | 6.33216 | 0.09498 |
| 90 | 61.9 | 5.58141 | 0.08372 |
| 105 | 61.4 | 4.83066 | 0.07246 |
| 120 | 61.2 | 4.53036 | 0.06795 |
| 135 | 61.2 | 4.53036 | 0.06795 |

**Experiment no 3**

| Drying temperature **– 40 °C**, Microwave power – 80**0 W** | | | |
|---|---|---|---|
| Time 9(min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 77.5 | 29.17 | 0.437528 |
| 30 | 67.7 | 12.83667 | 0.19254 |
| 45 | 64.4 | 7.336667 | 0.110044 |
| 60 | 62.1 | 3.503333 | 0.052547 |
| 75 | 61.2 | 2.003333 | 0.030048 |
| 90 | 61.2 | 2.003333 | 0.030048 |

**Experiment no 4**

| Drying temperature **– 45°C**, Microwave power – **480 W** | | | |
|---|---|---|---|
| Time (min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 75.5 | 25.83667 | 0.387531 |
| 30 | 70.2 | 17.00333 | 0.255037 |
| 45 | 64.4 | 7.336667 | 0.110044 |
| 60 | 63.1 | 5.17 | 0.077546 |
| 75 | 62.1 | 3.503333 | 0.052547 |
| 90 | 61.8 | 3.003333 | 0.045048 |
| 105 | 61.4 | 2.336667 | 0.035048 |
| 120 | 61.2 | 2.003333 | 0.030048 |
| 135 | 61.2 | 2.003333 | 0.030048 |

**Experiment no 5**

| Drying temperature **– 40°C**, Microwave power – 64**0 W** | | | |
|---|---|---|---|
| Time (min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 79.5 | 32.50333 | 0.487526 |
| 30 | 66.7 | 13.28411 | 0.199252 |
| 45 | 64.3 | 9.680511 | 0.1452 |
| 60 | 62.5 | 6.977808 | 0.104662 |
| 75 | 61.9 | 6.076907 | 0.091149 |
| 90 | 61.2 | 5.025856 | 0.075384 |
| 105 | 61.2 | 5.025856 | |

**Experiment no 6**

| Drying temperature **– 45°C**, Microwave power – **800 W** | | | |
|---|---|---|---|
| Time (min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 72.5 | 20.83667 | 0.312534 |
| 30 | 68.4 | 14.00333 | 0.210039 |
| 45 | 64.2 | 7.003333 | 0.105045 |
| 60 | 61.8 | 3.003333 | 0.045048 |
| 75 | 61.2 | 2.003333 | 0.030048 |
| 90 | 61.2 | 2.003333 | |

**Experiment no 7**

| Drying temperature **– 50°C**, Microwave power – **480 W** | | | |
|---|---|---|---|
| Time (min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 78.5 | 30.83667 | 0.462527 |
| 30 | 66.1 | 12.21805 | 0.183262 |
| 45 | 63.3 | 8.013844 | 0.120202 |
| 60 | 62.1 | 6.212042 | 0.093176 |
| 75 | 61.8 | 5.761592 | 0.08642 |
| 90 | 61.2 | 4.860691 | 0.072907 |
| 105 | 61.2 | 4.860691 | |

**Experiment no 8**

| Drying temperature **– 50°C**, Microwave power – 6**40 W** | | | |
|---|---|---|---|
| Time (min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 71.5 | 19.17 | 0.287536 |
| 30 | 66.4 | 10.67 | 0.160042 |
| 45 | 64 | 6.67 | 0.100045 |
| 60 | 62.5 | 4.17 | 0.062547 |
| 75 | 61.2 | 2.003333 | 0.030048 |
| 90 | 61.2 | 2.003333 | |

**Experiment no 9**

| Drying temperature **– 50°C**, Microwave power – **800 W** | | | |
|---|---|---|---|
| Time (min) | Weight (g) | M.c (%db) | MR |
| 0 | 100 | 66.67 | 1 |
| 15 | 70.5 | 17.50333 | 0.262537 |
| 30 | 64.4 | 7.336667 | 0.110044 |
| 45 | 62.7 | 4.503333 | 0.067547 |
| 60 | 61.3 | 2.17 | 0.032548 |
| 75 | 61.3 | 2.17 | 0.032548 |

**ANOVA of output characteristics of MFBD system**

**Table C.1 ANOVA for colour value 'L'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob> F | |
|---|---|---|---|---|---|---|
| Model | 5.51276 | 5 | 1.10255 | 19.5021 | 0.0006 | Significant |
| *A* | *0.51042* | *1* | *0.51042* | *9.02833* | *0.0198* | |
| *B* | *1.57082* | *1* | *1.57082* | *27.7848* | *0.0012* | |
| *A2* | *1.07649* | *1* | *1.07649* | *19.0411* | *0.0033* | |
| *B2* | *3.19582* | *1* | *3.19582* | *56.5282* | *0.0001* | |
| *AB* | *0.08702* | *1* | *0.08702* | *1.53931* | *0.2547* | |
| Residual | 0.39575 | 7 | 0.05654 | | | |
| *Lack of Fit* | *0.23815* | *3* | *0.07938* | *2.01476* | *0.2543* | *not significant* |
| *Pure Error* | *0.1576* | *4* | *0.0394* | | | |
| Cor Total | 5.90851 | 12 | | | | |

$R^2$ - 0.933021 Adj $R^2$- 0.885179 Pred $R^2$ - 0.576731 Adeq Precision – 15.4973

**Table C.2 ANOVA for colour value 'a'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob> F | |
|---|---|---|---|---|---|---|
| Model | 25.7133 | 5 | 5.14266 | 49.1211 | < 0.0001 | Significant |
| A | 1.92667 | 1 | 1.92667 | 18.4029 | 0.0036 | |
| B | 1.04167 | 1 | 1.04167 | 9.94967 | 0.0161 | |
| A2 | 1.50679 | 1 | 1.50679 | 14.3923 | 0.0068 | |
| B2 | 14.3401 | 1 | 14.3401 | 136.972 | < 0.0001 | |
| AB | 0.06502 | 1 | 0.06502 | 0.6211 | 0.4565 | |
| Residual | 0.73286 | 7 | 0.10469 | | | |
| Lack of Fit | 0.36086 | 3 | 0.12029 | 1.29339 | 0.3914 | not significant |
| Pure Error | 0.372 | 4 | 0.093 | | | |
| Cor Total | 26.4462 | 12 | | | | |

$R^2$ - 0.972289 Adj $R^2$- 0.952495 Pred $R^2$ - 0.842577 Adeq Precision - 18.77948

**Table C.3 ANOVA for colour value 'b'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob> F | |
|---|---|---|---|---|---|---|
| Model | 2.11477 | 5 | 0.42295 | 14.6672 | 0.0014 | Significant |
| A | 1.78215 | 1 | 1.78215 | 61.8012 | 0.0001 | |
| B | 0.1734 | 1 | 0.1734 | 6.01315 | 0.0440 | |
| A2 | 0.09559 | 1 | 0.09559 | 3.31473 | 0.1115 | |
| B2 | 0.1206 | 1 | 0.1206 | 4.18226 | 0.0801 | |
| AB | 0.00202 | 1 | 0.00202 | 0.07022 | 0.7986 | |
| Residual | 0.20186 | 7 | 0.02884 | | | |
| Lack of Fit | 0.11194 | 3 | 0.03731 | 1.65981 | 0.3111 | not significant |
| Pure Error | 0.08992 | 4 | 0.02248 | | | |

$R^2$ - 0.912866 Adj $R^2$- 0.850627 Pred $R^2$ - 0.462096 Adeq Precision - 12.53806

**Table C.4 ANOVA for colour value 'ΔE'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F | |
|---|---|---|---|---|---|---|
| Model | 24.49 | 5 | 4.9 | 41.75 | < 0.0001 | Significant |
| A | 0.54 | 1 | 0.54 | 4.61 | 0.0689 | |
| B | 0.5 | 1 | 0.5 | 4.23 | 0.0787 | |
| A2 | 2.15 | 1 | 2.15 | 18.29 | 0.0037 | |
| B2 | 13.58 | 1 | 13.58 | 115.77 | < 0.0001 | |
| AB | 0.24 | 1 | 0.24 | 2.08 | 0.1927 | |
| Residual | 0.82 | 7 | 0.12 | | | |
| Lack of Fit | 0.41 | 3 | 0.14 | 1.33 | 0.3826 | not significant |
| Pure Error | 0.41 | 4 | 0.1 | | | |
| Cor Total | 25.31 | 12 | | | | |

$R^2$– 0.9676 Adj $R^2$- 0.9444 Pred $R^2$ - 0.8126 Adeq Precision – 16.905

**Table C.5 ANOVA for 'Final Moisture Content'**

| `Source | Sum of Squares | DF | Mean Square | F Value | Prob> F | |
|---|---|---|---|---|---|---|
| Model | 6.23394 | 5 | 1.24679 | 49.7898 | < 0.0001 | Significant |
| A | 4.16667 | 1 | 4.16667 | 166.393 | < 0.0001 | |
| B | 0.42667 | 1 | 0.42667 | 17.0387 | 0.0044 | |
| A2 | 0.88328 | 1 | 0.88328 | 35.2734 | 0.0006 | |
| B2 | 0.19471 | 1 | 0.19471 | 7.77574 | 0.0270 | |
| AB | 0.01 | 1 | 0.01 | 0.39934 | 0.5475 | |
| Residual | 0.17529 | 7 | 0.02504 | | | |
| Lack of Fit | 0.12729 | 3 | 0.04243 | 3.53576 | 0.1270 | not significant |
| Pure Error | 0.048 | 4 | 0.012 | | | |
| Cor Total | 6.40923 | 12 | | | | |

$R^2$–0.972651Adj $R^2$- 0.953116Pred $R^2$ - 0.823945Adeq Precision –20.46409

**Table C.6 ANOVA for 'Bulk density'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob> F | |
|---|---|---|---|---|---|---|
| Model | 0.19 | 5 | 0.038 | 17.88 | 0.0007 | significant |
| A | 0.021 | 1 | 0.021 | 9.7 | 0.017 | |
| B | 0.13 | 1 | 0.13 | 60.15 | 0.0001 | |
| A2 | 4.73E-04 | 1 | 4.73E-04 | 0.22 | 0.6526 | |
| B2 | 0.038 | 1 | 0.038 | 17.94 | 0.0039 | |
| AB | 1.32E-04 | 1 | 1.32E-04 | 0.062 | 0.8108 | |
| Residual | 0.015 | 7 | 2.14E-03 | | | |
| Lack of Fit | 0.012 | 3 | 3.84E-03 | 4.42 | 0.0925 | not significant |
| Pure Error | 3.47E-03 | 4 | 8.68E-04 | | | |
| Cor Total | 0.21 | 12 | | | | |

$R^2$ - 0.927369 Adj $R^2$-0.87549 Pred $R^2$ -0.444225 Adeq Precision - 13.06432

**Table C.7 ANOVA for 'Drying Air Temperature'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob> F | |
|---|---|---|---|---|---|---|
| Model | 150.9319 | 5 | 30.18638 | 91.91754 | < 0.0001 | significant |
| A | 150 | 1 | 150 | 456.75 | < 0.0001 | |
| B | 0.666667 | 1 | 0.666667 | 2.03 | 0.1972 | |
| A2 | 0.082102 | 1 | 0.082102 | 0.25 | 0.6324 | |
| B2 | 0.082102 | 1 | 0.082102 | 0.25 | 0.6324 | |
| AB | 0 | 1 | 0 | 0 | 1.0000 | |
| Residual | 2.298851 | 7 | 0.328407 | | | |
| Lack of Fit | 1.498851 | 3 | 0.499617 | 2.498084 | 0.1987 | not significant |
| Pure Error | 0.8 | 4 | 0.2 | | | |
| Cor Total | 153.2308 | 12 | | | | |

$R^2$ -0.984997 Adj $R^2$-0.974281 Pred $R^2$ -0.918385 Adeq Precision - 27.39797

**Table C.8 ANOVA for 'Oil Yield'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F | |
|---|---|---|---|---|---|---|
| Model | 0.06314 | 5 | 0.01263 | 128.61 | < 0.0001 | significant |
| A | 0.00602 | 1 | 0.00602 | 61.2734 | 0.0001 | |
| B | 0.05607 | 1 | 0.05607 | 570.98 | < 0.0001 | |
| A2 | 7.4E-07 | 1 | 7.4E-07 | 0.00753 | 0.9333 | |
| B2 | 0.00058 | 1 | 0.00058 | 5.89967 | 0.0455 | |
| AB | 0.0004 | 1 | 0.0004 | 4.07358 | 0.0833 | |
| Residual | 0.00069 | 7 | 9.8E-05 | | | |
| Lack of Fit | 0.00017 | 3 | 5.6E-05 | 0.42912 | 0.7435 | not significant |
| Pure Error | 0.00052 | 4 | 0.00013 | | | |
| Cor Total | 0.06383 | 12 | | | | |

$R^2$ - 0.989232 Adj $R^2$- 0.98154 Pred $R^2$ - 0.961447 Adeq Precision - 38.1262

**Table C.9 ANOVA for 'Energy Consumption'**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob> F | |
|---|---|---|---|---|---|---|
| Model | 0.59729 | 5 | 0.11946 | 44.879 | < 0.0001 | significant |
| A | 0.03527 | 1 | 0.03527 | 13.2493 | 0.0083 | |
| B | 0.09375 | 1 | 0.09375 | 35.2208 | 0.0006 | |
| A2 | 0.00581 | 1 | 0.00581 | 2.18245 | 0.1831 | |
| B2 | 0.35966 | 1 | 0.35966 | 135.12 | < 0.0001 | |
| AB | 2.5E-05 | 1 | 2.5E-05 | 0.00939 | 0.9255 | |
| Residual | 0.01863 | 7 | 0.00266 | | | |
| Lack of Fit | 0.01211 | 3 | 0.00404 | 2.47699 | 0.2008 | not significant |
| Pure Error | 0.00652 | 4 | 0.00163 | | | |
| Cor Total | 0.61592 | 12 | | | | |

$R^2$ - 0.969749 Adj $R^2$-0.948141 Pred $R^2$ -0.784477 Adeq Precision - 18.16526

Table C.1 Cost Economic of Microwave assisted fluidised bed dryer

| **Cost of machineries** | |
|---|---|
| Microwave oven | Rs.5,990/- |
| Drying chamber assembly | Rs.3,000/- |
| Heating chamber assembly | Rs.1,180/- |
| Blower with valve assembly | Rs.14,000/- |
| Miscellaneous works | Rs.4,000/- |
| Total cost | Rs.28,170/- |

Assumptions

| | |
|---|---|
| Life span (L) | 10 years |
| Annual working hours (H) | 275 days (per day 6 hrs) = 1650 h |
| Salvage value (S) | 10% of initial cost |
| Interest on initial cost (i) | 10% annually |
| Repair and maintenance | 5% of initial cost |
| Insurance and taxes | 2% of initial cost |
| Electricity charge | Rs.7/unit |
| Labour wages/person | Rs.500/day |

**Fixed cost per hour**

1. Depreciation cost (D) per hour $= \frac{C-S}{L \times H}$

$$= \frac{28170-2817}{10 \times 1650}$$

= Rs. 1.53

2. Interest (E)/h $= \frac{C+S}{2} \times \frac{i}{H}$

$$= \frac{(28170+2817)}{2 \times 1650} \times \frac{10}{100}$$

= Rs. 0.939

3. Insurance, shelter etc. (F)/h $= \frac{C}{H} \times \frac{i}{100}$

$$= \frac{28170}{1650} \times \frac{2}{100}$$

= Rs. 0.341

4. Total fixed cost per hour = (D + E + F)

= 1.53 + 0.939 + 0.341

= Rs. 2.81/h

**Variable cost per hour**

1. Wages of worker (G)/h = 500/day
2. Repair and maintenance cost (H)/h $= \frac{C}{H} \times \frac{i}{100}$

$$= \frac{28170}{1650} \times \frac{5}{100}$$

= Rs. 0.85

3. Energy consumption

Energy consumption per hour = 1.5 KWh

Cost of energy consumption/day = 9 × 7 × 6 = Rs. 378/day

Cost of fresh mace/h = Rs. 300

Total variable cost = 500 + 0.85 + 378 + 300

= Rs. 1178

Total operating cost of the machine per hour = (Fixed cost+ Variable cost)

= 2.81 + 1178.85

= Rs. 1181

The market selling price of 1kg of dried nutmeg mace = Rs.1500/kg

Benefit -cost ratio == 1500/1181

= 1.27

Therefore the total production cost of 1kg of dried nutmeg mace in Microwave assisted fluidized bed drier was found to be Rs.1181/-. The benefit cost ratio was found to be 1.27:1.

# DEVELOPMENT OF MICROWAVE ASSISTED FLUIDISED BED DRYER FOR NUTMEG MACE

**by**

**YARRAKULA SRINIVAS**
**(2015-18-001)**

## ABSTRACT OF THE THESIS

**Submitted in partial fulfilment of the requirement for the degree of**

**MASTER OF TECHNOLOGY**

**IN**

**AGRICULTURAL ENGINEERING**

**(Agricultural Processing and Food Engineering)**

**Faculty of Agricultural Engineering & Technology**
**Kerala Agricultural University**


**DEPARTMENT OF FOOD AND AGRICULTURAL PROCESS ENGINEERING**
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**2017**

## ABSTRACT

Dried mace possess great importance in international trade and are used in the preparation of extractives and volatile oils. Among various hot air drying methods, the more efficient method is fluidized bed drying for drying of foods, fruits and vegetables. Microwave drying, an alternative method for the drying of food products has gained popularity and is widely adopted. In microwave heating, heat generation takes place from inside to outside of the material due to the absorption of microwave energy by the regions with higher moisture levels. Application of microwaves solely, can result in uneven heating of certain products, depending on their dielectric and thermo physical properties. Thus, combining microwave radiation with hot air fluidization also provides an effective means of overcoming the non-uniform heating problems in conventional microwave heating. The bulk density, L*, a* and b* values of the fresh mace sample were 1191 kg/$m^3$, 21.28, 22.23, and 9.09 respectively. At 5.1 m/s the fresh mace sample attained the fluidization condition. The developed microwave assisted fluidized bed drying system consists of a fluidized bed dryer and a microwave oven unit. The microwave oven unit consists of control panel where cooking time, power indicators and clock time are displayed and controlled. This domestic oven was modified by making a hole of 14 cm at the bottom and inserting the fluidized bed dryer through the hole. The main components of a fluidized bed dryer are drying chamber, plenum chamber, heating chamber, blower with power source and an air flow control valve. Logarithmic model was found as the best fitting model for the drying data with highest $R^2$ value of 0.9996 and lowest $\chi^2$, SSE and RMSE values of 1.2588e-05, 0.0003 and 0.01 respectively at 50°C drying temperature and 800 W microwave power. In order to evaluate the developed microwave assisted fluidized bed dryer for nutmeg mace, the process parameters such as microwave powers of 480, 640 and 800W and drying air temperatures of 40, 45 and 50°C were chosen as independent variables. The process parameters would influence drying rate, drying temperature, energy consumption and physico-chemical

parameters such as colour, moisture content, bulk density and essential oil yield. These parameters were chosen as dependent variables. The optimized conditions of drying temperature and microwave power for microwave assisted fluidized bed dryer were found to be 47.76 °C and 681.73W.