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Solar-biomass and dielectric drying of mace: An investigation on renewable and fourth generation drying technologies

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ABSTRACT

This study aimed to dry mace under solar and microwave assisted convective drying system to assess the quality of end products and the process sustainability. Conventionally, mace is dried under sun and solar drying conditions due to its easiness and economic feasibility. However, owing to the harvest of nutmeg during monsoon season, drying of nutmeg and mace under alternate drying methods is adopted among the farmers and industrialists. Dielectric drying reduced the duration to 41.6 % with enhanced rate of drying. Moisture diffusivity values of solar-biomass and dielectric dried nutmeg mace were 2.30 $^{-8}$ m^2/s and 1.72×10^{-7} m^2/s respectively. Instantaneous drying efficiencies under solar and microwave modes were in the range of 26.4 – 33.4 % and 32.5 – 41.2 %, respectively. The values of economic attributes indicated the benefit cost ratio of 2.4 and 1.9 and payback period of 1.6 and 2.1 years respectively, under solar and microwave drying conditions. The sustainability index and environment destruction coefficient was determined to be 1.54 and 1.10 and 1.86 and 2.41 respectively for solar biomass and microwave drying conditions. The exergy efficiency of the solar and microwave assisted drying of mace was observed to be 18.52 and 26.74 %, repectively Techno-economic feasibility studies on solar and dielectric dried nutmeg mace suggested that solar-biomass dehydration is more economically viable than dielectric drying for the industrial scale dried mace production.

1. Introduction

Nutmeg, also known as the twin spice is commercially important for its kernel and mace. Though nutmeg has its origin in Indonesia, it is widely cultivated along the Southern states of India mainly along the Eastern slopes of Nilgiris. Mace is the red waxy aril covering the seed and is economically important for its intense aroma and higher concentration of essential oils [1]. Mace has a spicy unique and delightful aroma that makes it applicable in flavor additives, perfumes and cosmetics [2]. Mace is an important component in therapeutic industry due to its stimulant, sedative, lipid-lowering, anti-thrombotic and flatus-relieving features [3]. However, mace is highly perishable owing to its higher moisture content (45 – 52 % w.b.) at harvest, and needs to be dried to make it microbiologically and shelf stable.

Solar energy is the ultimate and unlimited energy source for our planet and its living things (Rodziewicz *et al.*, 2016). It is the sole form of renewable energy with with global annual insolation of 5600 ZJ (Moriarty and Honnery, 2019). Conventional drying systems utilizing electricity, fossil fuels or LPG are commercially not applicable due to higher operational costs, energy requirements, and environmental impacts (Esen et al., 2013; [4]. Hence, dryers utilizing renewable energy sources were found to be techno economically feasible for the sustainable production of dehydrated products with higher operational efficiencies. A major lacuna of solar dryers is the longer duration leading to case hardening that adversely affect the quality of dried products.

The advent in research on food drying has mentioned dielectric drying as a fourth generation drying technology with minimum drying times and maximum drying efficiencies. Dielectric heating comprises of microwave and radio frequency radiations [4]. Microwaves occupy the electromagnetic spectrum at frequencies of 300 MHz – 300,000 MHz, with a wavelength of 1 mm – 1 m. By means of dipole rotation and ionic polarization, they penetrate dielectric materials to a thickness of 50 – 80 mm.

Combining hot air with microwaves is novel method to enhance the effectiveness of drying foods with improved qualities. Meetha et al. [1] investigated on mace drying under three MW power levels followed by hot air drying and reported good color retention and myristicin contents. MW assisted convective drying of coriander leaves indicated lower color change as compared to convectively dried samples. [5]. Microwave

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Nomenclature

Δ E	Total color change
EO	Essential oil
EMD	Effective moisture diffusivity (m^2s^{-1})
η	Efficiency (%)
L*, L_0	Lightness values of dried and fresh products respectively
E_{pb}	Pump/blower energy consumption (W)
E_{sc}	Solar collector energy consumption (W)
I	Irradaiation (W/m^2)
IMC	Initial moisture content
LH	Latent heat of vaporization (kJ/kg)
MW	Microwave
MWD	Microwave dried
MWHA	Microwave assisted hot air drying
M_w	Mass of moisture removed from sample (kg)
P	Microwave power (W)
RH	Relative humidity (%)
SD	Solar drying
SBM	Solar biomass

intensity of 40 W with hot air drying (MWHA) at 40—70 °C of garlic cloves were found to be better in quality as compared to other drying methods [6].

Moses et al [7] reported that nearly 20 % of the energy consumption in food processing industries owes to drying process. Although more than 400 types of food dryers are available, only less than fifty accounts in major applications. Soaring energy prices, climate change scenarios attributed to global warming and carbon emissions have necessitated in research on sustainable drying system for foods [8]. A drying system is sustainable when it meets with minimum energy consumption as well as maximum retention of nutrients. Energy consumption is associated with duration of drying and hence fourth generation drying technologies such as dielectric and radio frequency systems need to be validated with respect to energy, exergy and environmental impact [9]. Exergy quantifies the maximum useful work that can be extracted from the system. It is a powerful tool in validating the energy flows in the drying system and improves the overall energy efficiency (Akpinar et al., 2006).

Dielectric based drying systems have emerged to reduce the drying times and enhance drying rates of foods. However, higher power requirements and partial loss of sensory attributes confines the application of microwaves in food industry. Nearly 20% of the energy consumption in food processing industries owes to drying process. Although more than 400 types of food dryers are available, only less than fifty accounts in major applications. Microwave assisted hot air drying basically reduced drying times for high moisture food to the range of 18 – 36 % [7]. Traditionally mace is dried under the sun for a longer period of 5 – 6 days. This prolonged duration adversely affected the color and flavor of the dried mace [10]. As color and flavor are the important parameters that determine the market price of the mace, it is important to dry them under controlled conditions and reduced drying times [11]. Also, the harvest of nutmeg coincides with the monsoon season of major growing areas which lowers the applicability of drying under the sun. Aflatoxin contamination is another serious problem if harvested nutmeg is not dried in time. No literatures are available on the quality, energy, exergy, environmental impact and economic details of adopting microwave assisted drying system for mace or other spices. Though elaborate studies are available on specific application of solar and dielectric drying in foods, less literature is available on comparison of these technologies for spices. Hence, this study is aimed to evaluate the quality of dried nutmeg mace under the solar (renewable) and microwave (dielectric) drying technologies. The drying characteristics and quality attributes such as essential oil, oleoresin, and color of the dried products are compared and discussed in detail under both drying conditions.

2. Materials and methods

2.1. Material

Mace of nutmeg variety 'Vishwasree' was procured from the Experimental farm, ICAR – IISR, Chelavoor during July – August 2022 for the study. Dimensions (length, width and thickness) of mace were 4.72 ± 1.03 cm, 2.89 ± 0.195 cm, and 0.75 ± 0.145 cm respectively. The weight of single mace was 4.1 ± 1.35 g which was about 4 – 6 % of the total weight. IMC of mace was found to be 45.66 ± 1.14 % by toluene distillation method.

2.2. Drying conditions

Solar-biomass dryer installed at ICAR – Indian Institute of Spices Research of capacity 40 – 50 kg was used in the study. Solar radiation intensity inside the solar biomass dryer was in range of 400 – 600 W/m^2. Hence the dryer was provided with an auxiliary heating back-up using biomass in form of coconut husk and wooden logs as the secondary energy source. Nutmeg mace (2000 g) was placed in thin layer on the stainless-steel trays of 90 × 90 × 0.45 cm dimension for solar tunnel drying. Schematic representation of the solar dryer with biomass back-up is shown in Fig. 1. The specifications of the solar biomass dryer are given in Table 1. The physiological loss of weight of the samples were noted in an interval of 3 h, until constant weight was obtained. (SBM drying of mace is shown in Fig. 2).

Microwave assisted (MW) hot air drying (HA) of mace was carried out by initially exposing the mace to microwave radiations of intensity of 320 W followed by drying in HA dryer at temperature, air velocity and RH of 45 ± 02 ^{0}C, 1–1.5 m/s and 60 – 65 %, respectively.

2.3. Drying studies

Drying kinetics of mace during drying was studied by measuring the physiological loss of weight in every 30 min and 3 h intervals for microwave and solar conditions, respectively. The drying rate and moisture ratio were determined and model fitting was done with thin layer drying models. The final products were analyzed for essential oil, oleoresin, proximate contents, rehydration ratio and color values.

2.3.1. Moisture content

The mass of moisture (moisture content, MC) in the product is determined by the following equation:

$$M_w = \frac{M_I - M_F}{M_I} \times 100 \quad (1)$$

$$M_d = \frac{M_I - M_F}{M_F} \times 100 \quad (2)$$

Where,

M_w: Wet basis MC (%).
M_d: MC, db (%).
M_I: Mass of sample before drying (g).
M_F: Mass of sample at the end of drying (g).

2.3.2. Drying rate

The mass of water removed with respect to time is given by drying rate and is determined as follows:

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (3)$$

Where

Fig. 1. Solar – biomass dryer installed at ICAR-Indian Institute of Spices Research.

Table 1
Uncretainities associated with drying parameters.

S. No.	Parameter	Value
	Solar radiation	±01.5 W/m^2
	Tempertaure	±0.40 °C
	Weight loss	±0.55 g
	Air velocity	±0.14 ms^{-1}
	Relative humidity	±1.5 %
	Moisture content	±0.29 %
	Drying rtae	±0.10
	Drying efficiency	±2.46
	Moisture content	±1.14 %
	Microwave power	±2.4 W
	Essential oil	±0.50 %
	Oleoresin	0.035 %
	Rehydration ratio	±0.24
	Colour	±1.5

DR: Rate of drying (kg/kgh).

M_{t+dt}: MC at time, t + dt.

2.3.3. Moisture ratio

The moisture ratio was estimated as follows:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{4}$$

Where

MR: Moisture ratio.

M_0, M_e and M_t: MC initial, equilibrium and at time t respectively.

Equation (4) takes the form as equation (5) by omitting the term M_e, as it is negligible with M_0 and M_t values (Sacilik *et al.*, 2006).

$$MR = \frac{M_t}{M_0} \tag{5}$$

2.3.4. Effective moisture diffusivity

Rate of moisture migration during drying is expressed as diffusion and is determined with reference to the moisture loss from the sample. Diffusion is quantified as the effective moisture diffusivity which is determined from Fick's law of diffusion. Moisture movement inside hygroscopic material during falling rate drying is given by Fick's law as:

$$\frac{\delta M}{\delta t} = \nabla.(D_{eff}\nabla M) \tag{6}$$

where M denotes MC of the product, t and D_{eff} denotes drying time in s and EMD in m^2/s respectively.

Diffusivity calculations were done assuming the samples to be cylindrical. For an infinite cylinder the assumptions were [12]and the final equation is obtained as:

$$D_{eff} = -\frac{Br^2}{b_1^2} \tag{7}$$

Where B is the shape factor, r is the radius and b is equal to 2.41.

2.3.5. Efficiency of solar-biomass drying

The biomass utilized was taken as the product of the biomass (kg) with its heat value (Lopez et al., 2013) in MJ. Efficiency of drying is the energy needed to the energy utilized for drying [13].

$$Drying\ efficiency(\%) = \frac{Energy\ required\ (M_w \times L_H)}{Energy\ supplied\ (E_{bm} + E_{sc} + E_{pb})} \times 100 \tag{8}$$

Here, M_w stands for water removed (kg), L_H, is the LH of vaporization of water (kJ/kg) and E_{bm}, E_{sc} and E_{pb} and are the energy provided by biomass, collector and blower.

2.3.6. Microwave drying efficiency

Efficiency of microwave drying is the ratio of energy required to the energy spent during drying operation (Soysal et.al., 2006).

$$\eta = \frac{Mw \times L}{P \times t} \tag{9}$$

where where η is the HAMW drying efficiency (%); P is the MW power (W); m_w is the mass of water evaporated (kg), and L is the latent heat of vaporization of water (2257 kJ/kg), t is the drying time (s).

2.4. Mathematical modelling of drying behavior

To predict the drying behavior and improve the efficiency of drying, the drying data were substituted in the thin layer drying equations. Nonlinear regression analysis was performed and solutions to the model constants were obtained using MATLAB (R2021b) software [4]. The best fit drying model was predicted with respect to higher coefficient of determination (R^2) reduced chi-square ($\chi 2$) and lower percentage root mean square (RMSE).

Fig. 2. Solar – biomass drying of mace.

2.5. Biochemical analysis

Biochemical qualities were estimated with respect to primary and secondary metabolites. Anthrone method, Lowry's method and Soxhlet extraction was done for carbohydrates, protein and fat respectively [14]. Essential oil and oleoresin were estimated by steam distillation and solvent extraction techniques.

2.6. Essential oil profiling

Essential oil profiling of mace under solar and microwave dried conditions were done by GC/MS analysis: Shimadzu GC–MS QP – 2010, RT X-5 colomn (0.25 μm × 0.32 mm × 30 m). Ignition port temperature 250 °C, carrier gas – Helium, flow rate 1 g/ml, split ration 1:40. Ionization energy: 70 eV, mass range 40 – 50 amu.

2.7. Rehydration ratio

Rehydration ratio measures the cellular and structural degradation of the sample due to the drying conditions. Rehydration ratio was obtained by standard protocols adopted by [15].

$$Rehydration\ ratio = \frac{Weight\ of\ rehydrated\ sample\ (g)}{Weight\ of\ dried\ sample\ (g)} \tag{10}$$

2.8. Total colour change

Color degradation of dried mace samples was analyzed by a colorimeter (Hunterlab, Colorflex: EZ) using L*, a* and b*. The total color change ΔE, is given as:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \tag{11}$$

where L*, a*, b*: Color parameters for dried samples

2.9. Uncertainty analysis

Uncertainty analysis is crucial for determining the accuracy of measurements involved in solar and microwave assisted drying studies [16]. The uncertainties involved in the parameter like temperature, microwave power, moisture content, weight loss, air velocity, relative humidity, air velocity moisture content, drying rate and drying efficiency and other parameters are estimated by procedure reported by Murali et al. [17]. The values of uncertainties of various parameters are tabulated in Table 1. Factors during experiments like selection, calibration, reading, observation, procedures, environment etc. can contribute to uncertainties [18,19]. Denoting W as total uncertainty of the nth factor, uncertainty can be expressed by the equation:

$$W = [(X_1)^2 + (X_2)^2 + (X_3)^2 + \cdots ..(X_n)^2]1/2 \tag{12}$$

2.10. Exergy analysis

The component of energy that can be utilized for useful electrical/ mechanical work is termed 'exergy' or usable energy. Fraction of energy not fit for useful work is taken as wasted exergy. Efficinecy of thermal energy based systems is better interpreted using exergy analysis. Entropy or randomness resulting in irreiversibilites makes exergy at the output of the system to be lower than the exergy at the input [20]. However, estimation of exergy is dterimental in assessing the potential of extracting useful work from a system. Overall exergy is calculated as:

$$E_x = mC_p\,[(T - T_a) - T_a \ln(\frac{T}{T_a})] \tag{13}$$

$$Ex_{loss} = E_{xi} - E_{xo} \tag{14}$$

$$\eta_{Ex} = \frac{E_{xo}}{E_{xi}} = 1 - \frac{Ex_{loss}}{Ex_i} \tag{15}$$

2.11. Environmental impact analysis (EIA)

The sustainability of drying systems is assessed by its economic viability and environmental stability. Environmnetal stability of a microwave assisted drying system is detremined by its carbondioxide emission, which depends on embodied energy. Embodied energy represents energy imput from sources like firewood/fuel electricity as well as the energy embeded in the raw material. EIA is calculated based on formulas tabulated in Table 2.

2.11.1. Economic returns

Life cycle cost analysis (Singh et al., 2021) was carried out to check the economy of the process. Esen et al. [16] also presented a detailed cost analysis for ground source heat pump using annualized costing method.

$$\text{Life cycle cost (LCC)} = \text{Initial investment} + \text{Operation and maintenance cost} - \text{Salvage value} \tag{16}$$

Life cycle benefit is determined as the total annual benefit from the dried product. Benefit cost ratio is the ratio of discounted benefits to the discounted values of all costs and is expressed as

$$Benefit - cost\ ratio = \frac{Life\ cycle\ benefit}{Life\ cycle\ cost} \tag{17}$$

Payback period is the length of time from the beginning of the project before the net benefits return the cost of capital investments.

$$Pay\ back\ period = -Life\ cycle\ cost + Life\ cycle\ benefits = 0 \tag{18}$$

3. Result and discussion

3.1. Drying rate curves

Variation in MC of mace against the time is represented in Fig. 3. Initial moisture content of mace was 45.66 ± 1.14 %. w.b. which was reduced to 7.15 and 8.42 % respectively under solar and microwave drying conditions. The longer duration for solar dried samples was due to their higher initial MC values as drying time is directly related to initial moisture levels [21]. Also, solar drying involves heating of the medium (air) which further prolongs the drying period. The drying rate for mace under solar and microwave drying was found to be 0.97 and 2.41 g/gh respectively. The polarity of water molecules in the mace samples is continuously changed leading to friction and heat generation from within [22]. This volumetric heating has removed moisture from the mace that resulted in final lower drying times. Similar reports were published by Alibas [23] for MWHA drying of chard leaves. MC of coriander was reduced from 91.20 to 11.49 % within 21 min in MW whereas it took 236 min in HA drying [5].

Maximum ambient temperature of of 30.53 °C was obtained at 1:00 p.m. and minimum of 26.46 °C was recorded at 9:00 a.m. the highest RH of 89.31 % was obtained at 9:00 a. m. and minimum of 83.41 % was obtained at 1:00 p. m. (Fig. 4). The solar biomass dryer worked on hybrid mode with solar heating contributing to 70 % of operation. The biomass input was coconut husk and wood at was 69.93 kg/ day.

Table 2
Environmatal impact analysis of micraowave assited drying of nutmeg mace.

S. No.	Sustainability criteria	Formula
	Energy payback period	$EBPT = \frac{Embodied\ energy}{Annual\ energy\ output}$
	Sustainability index	$\frac{1}{1-\eta_{Ex}}$
	Environmental destruction cefficient	$\frac{1}{\eta_{Ex}}$
	Waste energy ratio	$\frac{E_{xloss}}{E_{xin}}$
	Environmental impact factor	$\text{WER} \times \frac{1}{\eta_{Ex}}$
	Improvement potential	$1-\eta_{Ex} \times E_{xloss}$

3.2. Effective moisture diffusivity

EMD is considered as a major factor for optimizing the drying process. It is estimated from the slope value obtained from the plot of ln (MR) against drying time. EMD values were determined to be 1.728 × 10 $^{-7}$ and 2.3 × 10 $^{-8}$ m^2/s respectively under microwave and SBM drying conditions (Fig. 6). Anuar et al [24] reported EMD for drying of rambutan at 250 and 1000 W MW power levels to be 3.13 × 10 $^{-7}$ m^2/s and 1.59 × 10 $^{-7}$ m^2/respectively, which is on par with the obtained values for mace. This higher moisture evaporation rate caused a higher rate of moisture diffusion from the internal regions of the mace to the surface which increased the diffusion coefficients. The increase in moisture diffusivity value with increase in temperature is similar to observations for dried pestil published by Maskan et al. [25] and Capsicum annuum (Ertekin 2002).

3.3. Efficiency

Instantaneous drying efficiencies under solar and microwave modes were in the range of 26.4 – 33.4 % and 32.5 – 41.2 % respectively (Fig. 7). However, the efficiency was proportional to radiation intensity received which was from 12:30 PM to 1:30 PM. [26] reported efficiencies of 21–69 % in the cherry tomatoes drying works. The atmospheric conditions during drying is shown in Fig. 5. The efficiency of mace drying was determined by considering the energy supplied by the collector, pump, blower, exhaust and biomass. The lesser the initial moisture content of the sample, lesser was the microwave drying efficiency [27]. Shreeelavaniya et al (2021) published that solar biomass hybrid drying of small cardamom obtained overall efficiency of 28.63 % with a drying time of 19 h. Jaishree et al (2005) studied on hybrid solar and biomass drying of ginger and reported drying efficiency of 18 %. All these are in agreement with the results of the present study. Bena et al (2002) published that drying of pineapple under natural convection solar hybrid dyers exhibited an overall efficiency of 22 %.

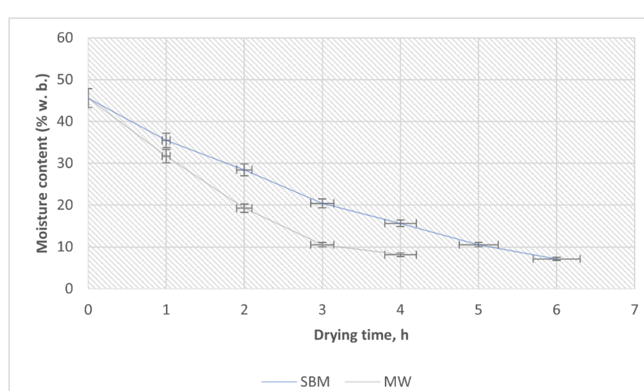

Fig. 3. Moisture content versus drying time.

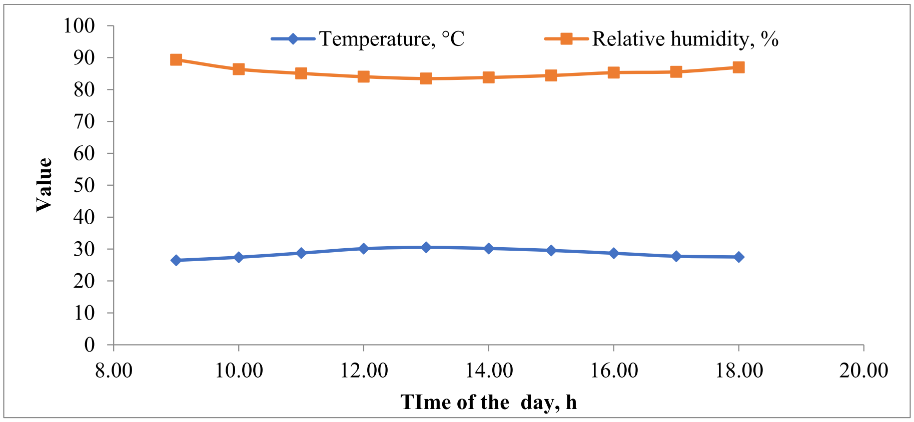

Fig. 4. Ambient temperature and relative humidity.

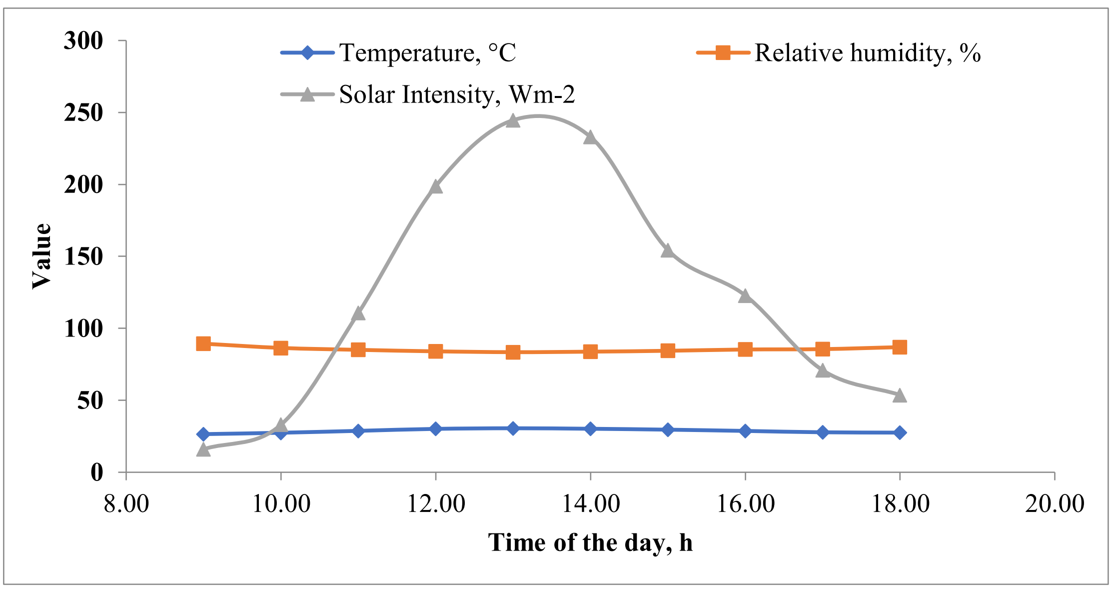

Fig. 5. Solar radiation intensity, temperature and relative humidity inside solar-biomass dryer.

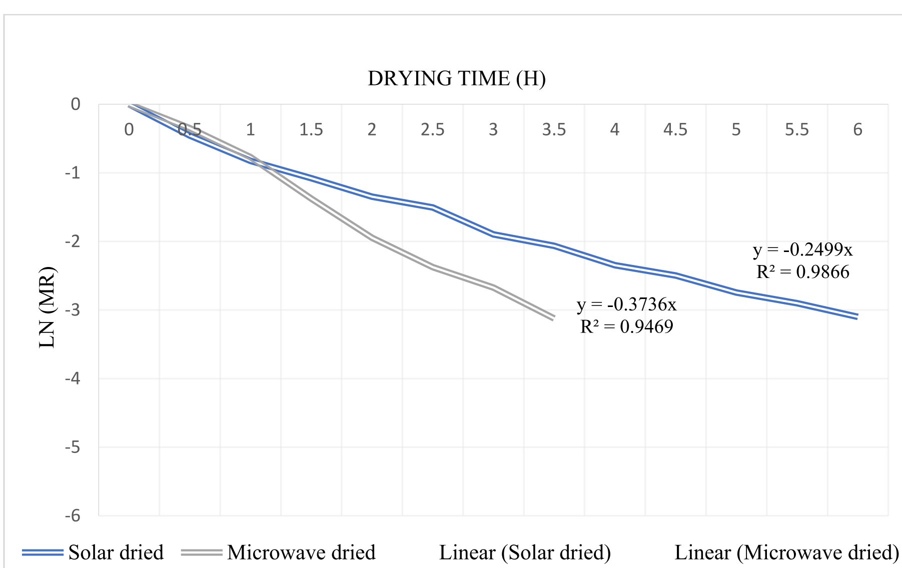

Fig. 6. Plot of LN MR versus drying time for solar-biomass and microwave drying of mace.

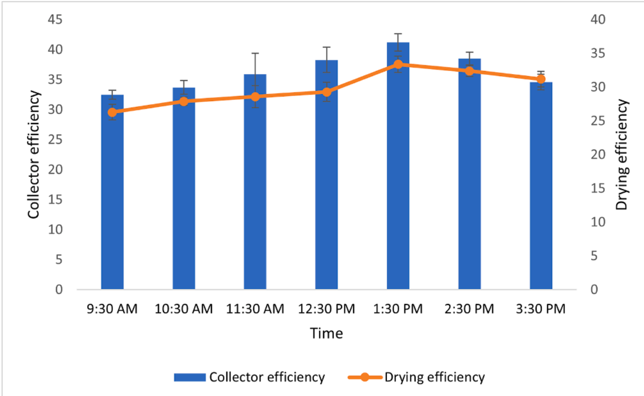

Fig. 7. Drying efficiencies under solar a drying of mace.

Table 3
Modeling of drying behavior for mace under solar biomass drying.

S. No.	Model name (Reference)	R^2	RMSE	Reduced χ2	Constants
1	Modified page (Karacabey and Buzurul, 2017)	0.9051	0.09507	0.0005537	k = 0.6393 n = 0.6869
2	Henderson and Pabis [30]	0.9715	0.05211	0.000466	a = 1.295 k = 0.5876
3	**Logarithmic** [31]	**0.9967**	**0.01938**	**0.000405**	**a = 1.362 c = -0.1624 k = 0.9494**
4	Two-term exponential (Togrul and Pehlivan, 2004)	0.9616	0.0471	0.000567	a = 43.49 b = -42.21 k1 = 0.4058 K2 = 0.4017
5	Wang and Singh [32]	0.9248	0.02244	0.001144	a = -0.3906 b = 0.04663
6	Verma *et al* (Yaldys and Ertekýn, 2001)	0.9051	0.1041	0.000478	a = -0.007179 b = 0.3826 g = 0.4387

3.4. Evaluation of drying models

Moisture ratio obtained in drying were fitted into drying models by non-linear regression analysis. Logarithmic model and Two-term exponential model fitted the drying data for solar and microwave drying conditions, respectively (Tables 3 and 4). To verify the acceptance of selected models under various drying conditions, observed and predicted values of moisture ratio were plotted and was found to be close to each other. The predicted moisture ratios are in good agreement with the observed values and therefore it can be concluded that selected models are relatively better in prediction of drying times under solar biomass and microwave drying techniques. Wang and Singh model fitted well for MW drying of banana (Omoloa et al., 2014) and Page model was the best fit model for MW drying of apple [28]. However, no relevant research has been made on the modeling of mace under microwave drying conditions. Erenturk et al. [29] observed Page model as the best fit model for drying mace under reverse air flow drying system. However, it is clear from the results that the method of heating has a relationship with drying time which further predicts the best thin layer model for drying under specific conditions.

Table 4
Modeling of drying behavior of mace under microwave drying.

S. No.	Model name (Reference)	R^2	RMSE	Reduced χ2	Constants
1	Modified page (Karacabey and Buzurul, 2017)	0.9447	0.06961	0.001	k = 0.8588 n = 0.6829
2	Henderson and Pabis [30]	0.9503	0.066	0.0003	a = 0.949 k = 0.5508
3	Logarithmic[31]	0.9957	0.02106	0.00047	a 0.8333 c = -1785 k = 0.9942
4	**Two-term exponential (Togrul and Pehlivan, 2004)**	**0.9986**	**0.01328**	**0.00014**	**a = 0.9722 b = 0.03289 k1 = 0.7825 K2 = 0.4224**
5	Wang and Singh[32]	0.9829	0.03866	0.00022	a = -0.5482 b = 0.09089
6	Verma *et al* (Yaldys and Ertekýn, 2001)	0.6446	0.07525	0.000.0021	a = 13.81 b = 0.5714 g = 0.5704

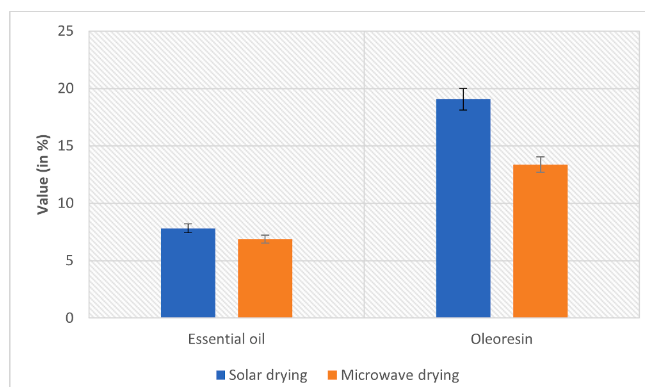

Fig. 8. Variation in essential oil and oleoresin t under various drying conditions.

Table 5
Variation in mean values of essential oil.

Drying conditions	DF	Mean
Solar biomass dried mace	3	7.82^a
Microwave dried mace	3	6.89^b

Note: Means with different subscript letters are significantly ($p < 0.05$) different.

3.5. Essential oil and oleoresin content

Solar-biomass dried mace samples showed a higher yield of essential oil (EO) as compared with MWD samples (Fig. 8). Essential oil content of SBM and MWD mace were 7.82 and 6.89 %, respectively (Tables 5 and 6). The oleoresin contents of SBM and MWD mace were 8.89 and 8.11 %, respectively (Tables 7 and 8). The moisture pumping effect of microwaves reduced the thermal stress on the material. However, the heating and tempering processes involved in solar-biomass drying achieved in higher retention of essential oil [33]. Srinivas et al [34] reported oil

Table 6
ANOVA table for variation in essential oil contents.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
DC	3	94.91	31.636	11.23	*0.003*
Error	8	22.53	2.817		
Total	11	117.44			
Variation in mean values of oleoresin contents					
Drying conditions		DF		Mean	
Solar biomass dried mace		3		19.0667^{a}	
Microwave dried mace		3		13.8333^{b}	

Note: Means with different subscript letters are significantly ($p < 0.05$) different.

Table 7
ANOVA table for variation in oleoresin contents.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
DC	3	94.91	31.636	11.23	0.003
Error	8	22.53	2.817		
Total	11	117.44			

Table 8
Proximate analysis of mace under various drying conditions.

Drying conditions	N	CHO	Protein	Fat	Ash
Solar-biomass drying	3	48.8833^{a}	6.76333^{b}	29.3167^{c}	2.24433^{d}
Microwave drying	5	48.8367^{a}	6.61333^{b}	28.0133^{c}	2.15333^{d}

Note: Means with different subscript letters are significantly ($p \leq 0.05$) different.

yield in range of 9.4 – 13.5 % during microwave assisted fluidized bed drying of nutmeg mace and oleoresin yield of 22.4 % at MW power of 637 W during MW assisted fluidized bed drying of mace. Microwave drying process yielded higher contents of oleoresin due to faster heat and mass transfer, reduced drying times and thermal stresses [35] and [36].

3.6. Essential oil profiling of mace

Results obtained from the chromatograms of essential oil profiling of mace oil produced from solar and microwave dried mace is represented in Fig. 9. The essential oils obtained through SBM and MWD mace is depicted in Fig. 10. Volatile oil composition of oil from mace under solar and microwave drying produced six major compounds namely sabinene (24.61 – 24.73 %), α-pinene (14.2 – 14.65 %), β-pinene (11.61 – 12 %), limonene (7.94 – 8.07 %), terpineol (6.81 – 7.25 %) and elemicin (4.02 – 4.05 %). Whereas, oil obtained from mace under microwave drying consisted of mainly sabinene (24.52 %), α-pinene (14.24 %) and β-pinene (11.59 %). Saputro et al. (2016) reported that the chemical compounds in mace essential oil comprised of α-pinene (19.77 %), β-pinene (14.77 %), sabinene (12.77 %) and myristicin (13.83 %). Silva et al. (2011) published that the aromatic compounds in the essential oil of mace are more sensitive to temperature under the conventional convective drying systems that leads to deterioration of the major

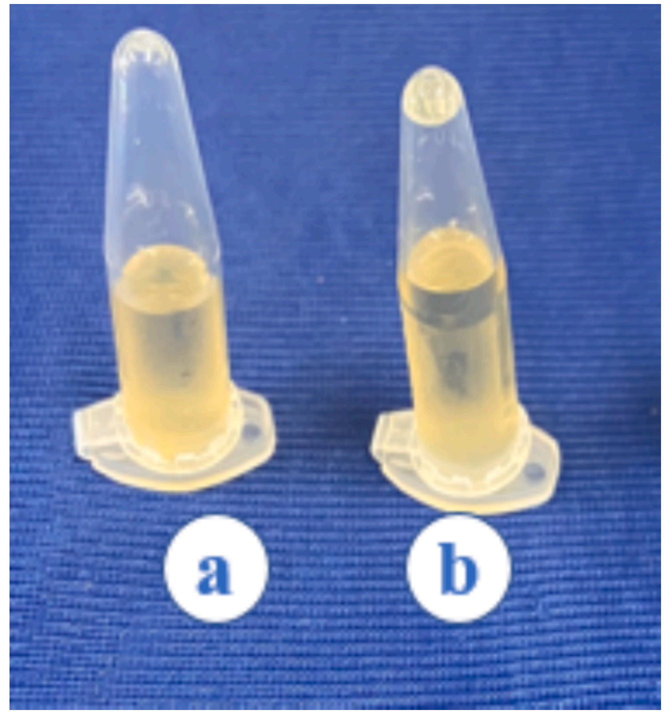

Fig. 10. Essential oil extracted from mace under a) Microwave drying b) Solar drying.

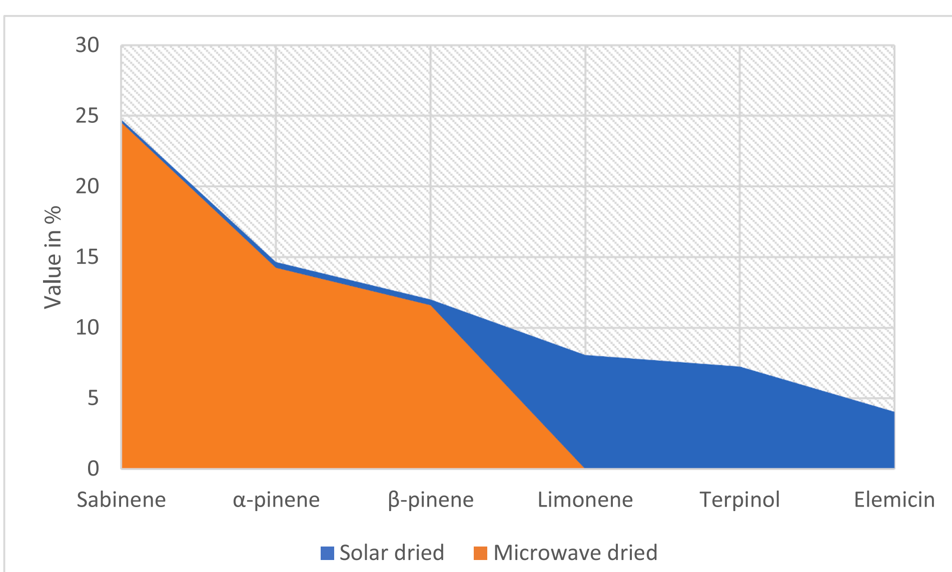

Fig. 9. Essential oil composition of oil from mace dried under solar and microwave drying.

components present. Also, the microwaves penetrate within the material simultaneously expanding the internal structure imparting thermal stress that slows down the release of oil.

3.7. Proximate analysis

Proximate analysis of mace dried under solar and microwave showed no significant difference *($p \leq 0.05$)* in values of the constituents. Carbohydrate, protein, fat and ash contents of mace dried under solar and microwave drying conditions are summarized in Table 8. The final quality of dried product is assessed by the method of application of heat energy at the later stages of drying. Since the temperature of drying is controlled at 50 ± 0.5 °C in both the cases, there is no major changes in values of proximate components of the dried product.

3.8. Rehydration ratio

Rehydration ratio of dried mace under solar and microwave drying was 2.64 and 2.49 respectively (Fig. 11). The volumetric heating of MW resulted in formation of non-uniform pores due to sudden and fast water movement during the early stages of drying that reduced the rehydration rates as compared to solar dried mace. Solar drying owing to its controlled heating and tempering resulted in uniformly sized pored with higher rehydration potential. Similar range of rehydration ratio (2.42 – 3.42) was reported by [37] for MW drying of potato slices.

3.9. Colour

SBM dried mace retained more redness in the dried mace as compared to microwave dried mace (Table 9). The total color change was significant when the means of solar and microwave dried mace were compared. The L*, a* and b* values showed a decrease in range of 45–50, 42 – 45 and 41 – 43 % than the fresh sample. Microwave dried mace were more reddish when compared to the solar dried samples (Fig. 12). This was due to the darkening of the product under microwave drying due to higher heat intensity. Though drying under direct sun reduced the redness of the mace, controlled temperatures under solar-biomass drying resulted in enhanced retainment of redness. [1] reported that microwave pretreated mace exhibited more redness as compared to conventionally dried samples. The colour value is a representation of moisture content inside the dried mace The colour degradation of mace is attributed to its reduction in sugar content by

Table 9
Color variation in mace drying.

Drying conditions	Colour value
Solar dried mace	29.48 ± 0.57^{b}
Microwave dried mace	23.15 ± 0.15^{a}

Note: Means with different subscript letters are significantly ($p < 0.05$) different.

Maillard reaction during the drying process [38]. Similar degradation in the colour values were reported by Seeranguryar et al. [39] for solar drying of dates.

3.10. Exergy analysis

The exergy efficiency of the solar and microwave assisted drying of mace was observed to be 18.52 and 26.74 %, repectively. The part of exergy represents useful work that can be extracted from the present drying systems. Nduwku et al. (2022) reported exergy efficiency of 19.09 to 52.00 % for natural and forced convection solar dryers for drying of chilli, potato, plantain and cocoyam. The exergy loss for SBM and microwave drying system were estimated to be 0.69 and 0.74 kW, repectively. The results are in agreement with the findings of Mugi et al (2021) and suggests scope for commercial scale adoption of the present system for quality production of dried mace.

3.11. Environmental impact analysis

The sustainability of any drying system is determined by its environmental impact and stability. The calculations for environmatal sustainability comprised of energy pay back period, sustainability index, environmental destruction potential, waste energy ratio, environmental impact factor and improvement potential. The enrgy payback period for the SBM and mirowave assisted drying of mace is found to be 1.6 and 2.1 years, repectively which is turn validates the sutainability of the drying system. Energy pay back period of solar dryers was found to be 0.78 years [40]. The sustainability index of SBM and dilectric drying system were found to be 1.54 and 1.10 respectively. Environment destruction coefficient were detrmined to be determined to be 1.86 and 2.41, respectively for SBM and dielectic drying with microwaves. Waste energy ratio, environmental impact factor and improvement potential for solar biomass drying system was estimated 0.72, 1.52 and 0.46,

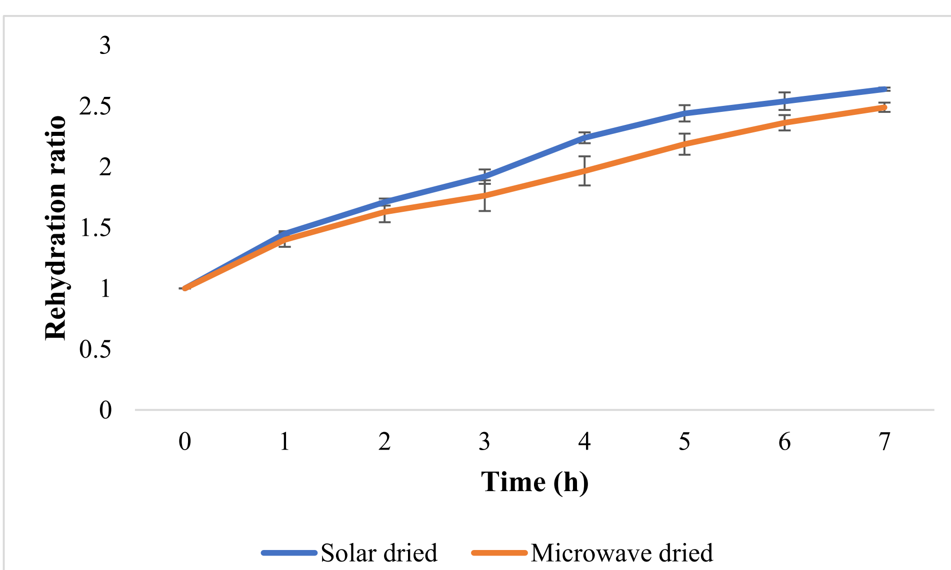

Fig. 11. Rehydration ratio of mace under various drying conditions.

Fig. 12. Photographs of mace dried under a) solar-biomass drying and b) microwave drying.

Table 10
Solar and microwave dried mace – Economic analysis.

Parameters	Values Solar –biomass dryer	Microwave drying with the accompanying hot air system
Machinery cost (₹)	4,00,000	3,50,000
Operational costs (₹)	1,50,000	2,10,000
Salvage cost(₹)	40,000	35,000
Life cycle cost (₹)	3,10,500	4,65,500
Benefits (₹)*	8,45,000	7,66,150
B-C ratio	2.4	1.9
Payback period (years)	1.6	2.1

respectively. All the values obtained for environmental impoact analysis are in line to the findings of Ndukwu et al [41].

3.12. Economic returns

Economic analysis was carried out for the microwave drying of mace and the result is summarized in Table 6. The values of economic attributes indicated the benefit cost ratio of 1.9 and payback period of 2.1 years. Alfiya et al [4] reported benefit cost ratio and payback period of 1.31 and 1.48 years for hot air assisted microwave drying of shrimp. Sreekumar (2010) studied on the techno-economic feasibility of operating renewable energy-based dryers for pineapple and reported a payback period of 0.54 years.

3.13. Economic analysis

Results of economic analysis of mace is shown in Table 10. However, MW drying completely relied on electricity which was the reason for the increase in operational costs and decrease in B-C ratio and pay-back periods. The quality of the mace was satisfactory under both drying techniques as per the investigation. But as a successful production lies in the sustainability of the process, SBM is found to be more recommendable than MW drying system for quality and large-scale production of mace for the farming as well as the industrial community.

4. Conclusions

Drying kinetics, quality, energy and exergy analysis of mace dried under solar biomass and microwave drying techniques were evaluated. Renewable and dielectric drying efficiency for mace were in range of 26.4 – 33.4 % and 32.5 – 41.2 % respectively Logarithmic model and two-term exponential model fitted the drying characteristic data under solar and microwave drying, respectively with minimum error values. Essential oil content of SBM and MWD mace were 7.82 and 6.89 %, respectively. The oleoresin contents of SBM and MWD mace were 19.09 and 13.38 %, respectively. Rehydration ratio of dried mace under solar and microwave drying was 2.64 and 2.49 respectively. Solar dried mace retained more redness in the dried mace as compared to microwave dried mace. Renewable energy-based dryers were found to be economically suitable than fourth generation dryers for the quality production of dried mace with a benefit cost ratio of 2.4 and payback period of 1.6 years. The sustainability index and environment destruction coefficient was determined to be 1.54 and 1.10 and 1.86 and 2.41 respectively for solar biomass and microwave drying conditions. The exergy efficiency of the solar and microwave assisted drying of mace was observed to be 18.52 and 26.74 %, repectively Waste energy ratio, environmental impact factor and improvement potential of the solar biomass drying process was 0.72, 1.52 and 0.46, respectively However, hybrid drying systems incorporating solar and microwave heat sources can produce dried mace with lower drying time and improved product quality.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

All authors significantly contributed to the scientific study and writing. Dr. P V Alfiya carried out the experiments and made first draft of the manuscript whereas the others author supported in methodology and writing the manuscript.

Availability of data and materials.

The authors confirm that the data supporting the findings of this study are available with the authors and will be made available upon reasonable request.

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