3E (Energy, Exergy and Economic) Analyses and Kinetic Studies on Microwave Drying of Star Fruit

Sayan Mandal, Koushik Jena, and V. Prabu

Abstract Star fruit (*Averrhoa carambola*) is beneficial for humans as it is enriched in natural antioxidants. However, due to its seasonal availability, drying of star fruit is essential for storage purposes. This study is focussed on microwave drying of star fruit such as estimation of kinetic parameters, effective moisture diffusivity, and activation energy and model predictions by standard thin layer models. Further, a 3E analysis (energy, exergy and economic) is performed to examine the feasibility of commercial implementation. The outcomes revealed, that the drying time has remarkably reduced by 11–16 times and the moisture diffusivity has raised by 50–250 times in contrast with convectional drying method. Energy efficiency is found to be 16.74% at 150 W power level, which is further raised to 26% at 525 W power level. The exergy efficiency of the microwave drier is found to be 3.93% at 150 W, which is further raised to 11.99% at 525 W microwave power level. From the economic analysis of microwave drier, it is found that the cost of microwave drying reduced below 1 INR at every microwave power level with enhanced capacity of the plant.

Keyword Activation energy · Effective moisture diffusivity · Energy and exergy analyses · Microwave drying · Star fruit

1 Introduction

Star fruit scientifically known as *Averrhoa carambola*, is mainly found in Southeast Asia, Brazil, Micronesia, the United States, parts of East Asia, etc. [1]. In India, star fruit trees are grown in the southern states and on the west coast, from Kerala to West

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Bengal [2]. The star fruit has a mixed taste of sweet and sour and it can be utilized for making chutney, pastry and curry [3]. Due to the presence of carotenoids, star fruits possess natural antioxidant properties and help to treat various diseases like nausea, mouth ulcers, diarrhoea, toothache, ascites, etc. [4]. Star fruit has the property to alleviate pain from bleeding haemorrhoids [5]. As the star fruit is seasonal in nature, its preservation is highly essential. One of the primordial and classical preservation techniques employed in cultivated processing field is drying.

The microwave method has several benefits including low drying time, enhanced product quality, and improved energy efficiency, in comparison to other processes [6]. As microwave drying considerably decreases the processing period, it is an appealing source for saving thermal energy [7]. The traditional technique used for drying of foodstuffs is convective drying [8]. Food colours, flavour and nutritional alteration, shrinkage, surface textural alteration occur upon convective drying and thereby affect the quality of dried foods [9–11]. Alternatively, these effects can be reduced through a strong microwave-material interaction in microwave-assisted drying process [12].

The outcomes of various pre-treatment methods on the drying of star fruit such as submerging in sugar solution and hot water blanching and drying kinetics and associated product quality have been reported in the literature [13]. Star fruit undergoes shrinkage with significant colour change on drying [13]. Kinetics of star fruit has been reported [14]. Further, blanching of star fruit in microwave and its quality was studied. It was reported that prior to microwave blanching, the ascorbic acid and oxalic acid were found to be 7.4 (mg/g dm) and 28.04 (mg/g dm) respectively. After microwave blanching, the ascorbic acid was found to be altered to 5.8–6.6 (mg/g dm) and oxalic acid reached to the value range of 15.8–25.86 (mg/g dm) [15]. Even though few studies reported upon star fruit drying, microwave drying of star fruit has not been targeted. Hence, the present study is focussed on utilization of microwave heating for the elimination of moisture in the star fruit at different input power level. Feasibility of the operation is analysed in terms of 3E analyses such as energy, exergy also economic assessment has been performed. Further, kinetic parameters are evaluated for the microwave drying process of star fruit using different models reported in the literature. Effective moisture diffusivity and activation energy required for microwave-dried star fruit are assessed.

2 Materials and Methods

2.1 Star Fruit Sample Preparation

Star fruit is collected from the local vendors of Kamrup district, Assam, India. The fruit samples are washed and cut into slices. For each experiment, almost 25 g of fruit samples are used. The average initial moisture content is estimated by a hot air oven operated at 105 °C for 3 h. It is found that the star fruit contains an initial

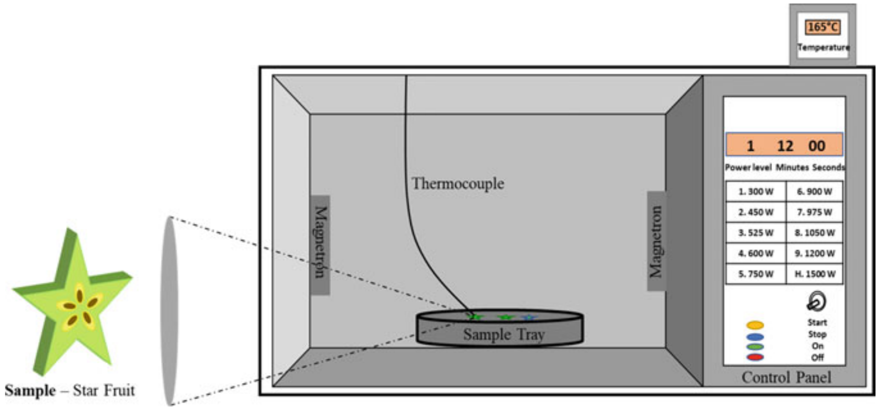

Fig. 1 Schematic view of microwave reactor

moisture of 91.5% on a wet basis (g of water/g of fruit). A slice thickness of 10 mm of the star fruit has been maintained in all experiments.

2.2 Experimental Procedure

A microwave oven (RAGA'S microwave dryer) with a power input capacity ranging from 150 to 1500 W at 915 MHz is used for star fruit drying. The layout of the microwave set-up is presented in Fig. 1. The moisture released from the drying chamber is discharged using a fan installed in the oven. A weighing balance is used externally to measure the loss of moisture by measuring the difference in the mass of fruit samples at different time intervals. The surface temperature of the star fruit is monitored using a K-type thermocouple as shown in Fig. 1. The desired sample is equally distributed in a sample tray and the loss in the moisture content is measured at various power levels of 150, 300, 450, and 525 W.

2.3 Drying Kinetics

Moisture ratio (θ) is defined as the ratio of moisture retained at a specific period to the total moisture present in the fruit with respect to the equilibrium conditions. It is expressed as:

$$\theta = \frac{(m_t - m_e)}{(m_0 - m_e)} \tag{1}$$

m_t = Moisture content of the sample at any moment.

Table 1 Various tested kinetic model equations in the present study

Model name	Model equation	References
Henderson and Pabis	$\theta = ae^{-kt}$	[17]
Newton	$\theta = e^{-kt}$	[18]
Wang and Singh	$\theta = 1 + at + bt^2$	[19]
Page	$\theta = e^{-kt^n}$	[20]
Logarithmic	$\theta = ae^{-kt} + b$	[21]
Midilli	$\theta = ae^{-kt^n} + bt$	[22]

Whereas letter *a*, *b*, *n* and *k* are constants and "*t*" is the dried time

m_0 = Initial moisture content.

m_e = Equilibrium moisture content.

All moistures are expressed in (g of water/g of dm). Table 1 shows various kinetic models from the literature to estimate the characteristics of the dried fruit [16].

All parameters of these model equations are calculated by nonlinear regression. Lower RMSE (root mean square error), χ^2 (reduced chi-square), and R^2 (coefficient of determination) confirm upon the best-fit model. These have been determined using the expression:

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(\theta_{\text{pre},i} - \theta_{\exp,i}\right)^2}{N - Z} \tag{2}$$

$$\text{RMSE} = \left(\frac{\sum_{i=1}^{\text{N}} \left(\theta_{\text{pre},i} - \theta_{\exp,i}\right)^2}{N}\right)^{\frac{1}{2}} \tag{3}$$

$$R^2 = I - \frac{\sum_{i=1}^{N} \left(\theta_{\text{pre},i} - \theta_{\exp,i}\right)^2}{\sum_{i=1}^{N} \left(\overline{\theta_{\text{pre},i}} - \theta_{\exp,i}\right)^2} \tag{4}$$

where θ_{pre} = Predicted moisture ratio, $\theta_{\exp}$ = Experimental moisture ratio, N = Total number of experimental data points and Z = Total number of parameters of the model.

2.4 Drying Rate, Effective Moisture Diffusivity and Activation Energy

The ratio of removal of moisture from wet solid per unit time is known as the rate of drying. The drying rate can be estimated with the succeeding equation:

$$DR = \frac{m_{t+\Delta t} - m_t}{\Delta t} \tag{5}$$

where m_t and $m_{t+\Delta t}$ are the moisture content of the specimen fruit at any instant "t" and "$t + \Delta t$".

Moisture diffusivity is assessed using Eq. 6, which is applicable for the falling rate period and for the scenario in which moisture content is below the critical limit [23]. This equation is precise to use in the microwave drying of the food samples.

$$\ln(\theta) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)\mathrm{t} \tag{6}$$

where L = One-half thickness of the sample, t = Dried time (s) and D_{eff} = Effective moisture diffusivity of the sample.

Activation energy is calculated by using the effective moisture diffusivity and with the succeeding "Eq. 7". [24]

$$D_{eff} = D_0 \exp\left(-\frac{E_a m}{P}\right) \tag{7}$$

where E_a = Activation energy (W/g), m = mass of sample (g) and P = Microwave power level (Watt) and D_0 = Intercept.

2.5 Energy Analysis

During microwave drying, the fraction of heat used for removing water to the amount of heat provided is known as energy efficiency. It can be written as,

$$\eta_{\text{drying}}(\%) = \frac{m_{wt} \times \lambda_{wf}}{P \times t} \tag{8}$$

where m_{wt} = Mass of water removed (kg), λ_{wf} = latent heat of vaporization of free water (J/kg), P = Input microwave power level (W) and t = Dried time (s).

Specific energy consumed (E_{consumed}) is the energy needed to dry a kg of sample. It can be estimated with the following equation:

$$E_{\text{consumed}}(\text{MJ/kg water}) = \frac{P \times t \times 10^{-6}}{m_{wt}} \tag{9}$$

Specific energy loss (E_{loss}) during drying is calculated using the following expression given by Darvishi et al. [25]:

$$E_{\text{loss}} = \left(1 - \eta_{\text{drying}}\right) \times \frac{P_{in} \times t}{m_{wt}} \tag{10}$$

where m_{wt} = Amount of water removed (kg), P_{in} = Input microwave power (W), t = dried time (s) and η_{drying} = energy efficiency.

2.6 Exergy Analyses

Exergy efficiency of the drying process is estimated as follows [26],

$$\eta = \frac{\boldsymbol{EX_{evap}}}{P_{in}} \tag{11}$$

where $\boldsymbol{EX_{evap}}$ = rate of utilisation of exergy for removal of moisture (J/s) and P_{in} = input microwave power level (W). The $\boldsymbol{EX_{evap}}$ is calculated using the expression:

$$EX_{evap} = \left(1 - \frac{T_0}{T_P}\right) \times m_w \lambda_{\text{sample}} \tag{12}$$

where λ_{sample} = Latent heat of the sample (J/kg), T_0 = Room temperature (K), T_P = Temperature of product (K) and m_w = Removal rate of water vapour (kg/s).

Exergy loss (expressed in MJ/Kg) can be calculated using the following equation:

$$EX_{\text{loss}} = \left(\frac{P_{in} - EX_{\text{evap}}}{m_w}\right) \times 10^{-6} \tag{13}$$

2.7 Economic Analyses

Economic analysis is performed for the microwave drying of star fruit by considering all the expenses in the drying operation. The annualized cost of the microwave is estimated with the following equation:

$$C_a = C_{ac} + C_m + C_e - V_a \tag{14}$$

where (C_a) = Annualized cost of the dryer, (C_{ac})= Annualized capital cost, (C_m) = Annualized maintenance cost, (C_e) = Annualized electricity cost and (V_a) = Annualized salvage value [27].

The payback period is estimated as per the following equation:

$$\text{Payback period(No interest charge)} = \frac{\textbf{Depreciable fixed capital investment}}{\textbf{Avg profit/year + Avg depreciation/year}} \tag{15}$$

The cost of the microwave equipment at different capacities is found by using the cost of the known equipment and as per the following equation [28]:

$$\text{Cost of equipment X} = \text{Cost of equipment Y} * \left(\frac{\text{Capacity of equipment X}}{\text{Capacity of equipment Y}}\right)^{0.6} \tag{16}$$

3 Results and Discussion

Fresh and microwave-dried fruit sample is presented in Fig. 2. Initial moisture content of the fruit is decreased from 91.5% to a final moisture in the range of 19–24%. The fruit sample did shrink significantly due to the evaporation of moisture content.

3.1 Drying Curves

Drying curve of star fruit at several input microwave power levels is presented in Fig. 3. During microwave drying process, heating of fruit sample occurs in volumetric manner. This in turn creates variation in vapour pressure from the centre to the outer surface of the fruit.

It is quite evident that for the microwave drying of star fruit, the moisture ratio is gradually decreasing with a rise in the drying time. From this curve, it can be noticed that in the early phase of drying, there is an increasing amount of input

(a) (b)

Fig. 2 Snapshot of **a** fresh and **b** microwave dried star fruit sample

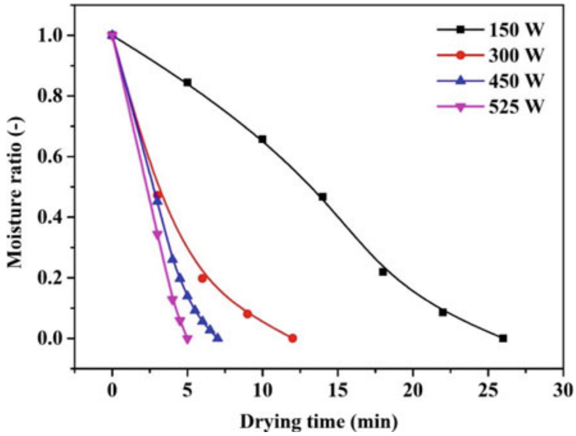

Fig. 3 Drying curve of star fruit at alternate microwave power levels

microwave power absorption due to higher moisture content and consequently, a higher rate of drying is noticed due to soaring moisture diffusion in the fruit. As drying proceeds, due to lesser moisture content, the absorption input microwave power reduced and therefore the drying rate falls. The relationship between drying time and input microwave power can be explained in Fig. 4. Drying time reduces consequently with the input microwave power level. Time needed for removing the moisture from 91.5% to the final moisture of 19–24% is found as 26, 12, 7 and 5 min at 150, 300, 450, and 525 W, respectively. As input microwave power level rises, the removal of moisture is rapid due to the higher heat generation by volumetric heating of the fruit sample. The dried time got reduced by 5 times at 525 W in comparison to that at 150 W.

For conventional hot air oven based drying, the maximum drying time for star fruit was reported as 425 min [13]. In the case of tray drying of the star fruit, the

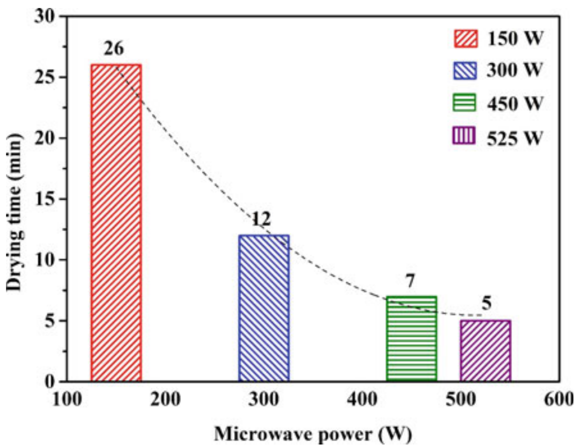

Fig. 4 Drying time versus microwave power levels

maximum drying time was reported as 300 min at 50 °C and the minimum reported drying time was 150 min at 80 °C [14]. Hence, the drying time of star fruit using a microwave oven is reduced almost by 11–16 times at 150 W microwave power level in contrast to conventional drying methods. Also, it was reported in the literature that at the 120 W input microwave power, the microwave blanching time was found to be in the extent of 300–720 s [15]. Hence, the microwave drying time of star fruits is 5 times higher than their blanching time. The microwave drying time for star fruit is found less, compared to apple pomace. During microwave drying of apple pomace, a longer drying time from 21 to 77 min is reported to remove the moisture content from 80.2 to 5% (db). For pre-treated apple slices, the total drying time was reported in the range of 6.5–23 min [18].

3.2 Drying Rate

The change of drying rate with their moisture content at various input microwave power level is presented in Fig. 5. It is noticed that there exist at least two different drying periods such as constant rate period and falling rate period. Warming up period is invisible due to the rapid absorption of input microwave power by excessive initial moisture content of the fruit. An extended constant rate period can be seen for 150 W power level, whereas this period is reduced in other power levels. An abrupt falling rate drying period is found during the power level higher than 150 W. This shows the progressive rise in the inner resistance of the fruit for the diffusion of moisture. This appears due to the immediate absence of free moisture on the surface of the fruit.

Due to the formation of pressure difference between the centres of the fruit to its surface, a rapid diffusion of moisture takes place at the constant rate period. As soon as the free moisture gets evaporated, there appears a falling rate period. In microwave drying of star fruit, the constant rate period is only visible in lower microwave power

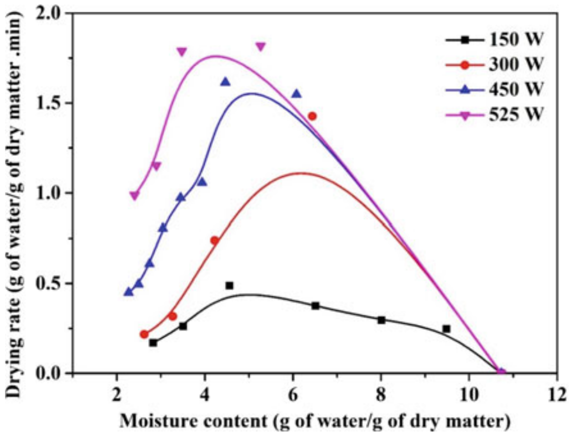

Fig. 5 Drying rate versus moisture content curve for star fruit at various microwave power levels

of 150 W. But in the higher microwave power level, only warming up and falling rate period are visible with decreased drying time. Alike trend can be seen in the microwave drying of soybean, spinach, parsley leaves [16, 29, 30].

3.3 Kinetic Analysis

There are various models which are being used to predict thin layer drying kinetics [31].

In this study, the model fitness was tested by performing nonlinear regression analysis and with Origin 2021b software. Models used to evaluate kinetic parameters of microwave-based star fruit drying process are proposed by Newton Wang and Singh, and Henderson. Using the kinetic parameters assessed from the above models, the moisture ratio was predicted to validate the fitness of the model. By using ANOVA, statistical parameters like RMSE (root mean square error), R^2 (coefficient of determination) and X^2 (chi-square) were calculated between the experimental and predicted moisture ratio. These values are shown in Table 2. The value of R^2 varies from 0.929 to 0.999, chi-square X^2 value from 0 to 0.008, and RSME from 0 to 0.012. The best-fit model can be found by the highest R^2 value and lowest chi-square (X^2) and root mean square error (RMSE) values. It is clear from the models that the value of drying constant (k) increases with enhanced microwave power and due to volumetric heat generation.

It is found that Wang and Singh model is the best fit for microwave drying of star fruit. Though in many studies, Page model and Midilli model have reported as

Table 2 Drying kinetic parameters and associated statistical parameters of the star fruit microwave drying process

Model	Power	a	b	k	R^2	Chi-square X^2	RMSE
Newton model	150			0.064	0.966	0.003	0.003
	300			0.253	0.989	0.001	0.001
	450			0.327	0.960	0.003	0.003
	525			0.480	0.999	0.000	0.000
Henderson model	150	1.135		0.075	0.929	0.006	0.005
	300	1.099		0.282	0.982	0.002	0.001
	450	1.022		0.374	0.963	0.004	0.003
	525	1.009		0.485	0.965	0.008	0.005
Wang and Singh model	150	−0.037	−0.000		0.987	0.002	0.012
	300	−0.186	0.008		0.992	0.002	0.005
	450	−0.233	0.013		0.998	0.000	0.002
	525	−0.255	0.011		0.999	0.000	0.000

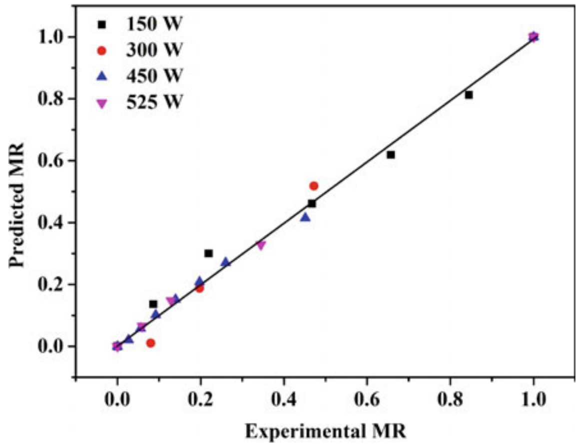

Fig. 6 Plot between predicted and experimental moisture ratio using Wang and Singh model

the best fit, Wang and Singh model also affirmed significantly good fit to the experimental results. Figure 6 shows the fitness of the Wang and Singh model plotted with experimental and predicted moisture ratio at various input microwave power levels. A straight line of the plot showed that the model is quite stable for the microwave drying of star fruit. This model also showed significantly good fit for microwave drying of other foods species such as soybean [29], pepper [17], fresh turmeric fingers and cured turmeric fingers [32].

3.4 *Effective Moisture Diffusivity*

Effective moisture diffusivity is the rate of diffusion of the moisture in the fruit. Figure 7 shows the increase in effective moisture diffusivity with input microwave power level alteration from 150 to 525 W. It is found to alter as 1.83×10^{-8} to 9.74×10^{-8} m^2/s at various microwave power levels. The effective moisture diffusivity increased by 5 times at 525 W in comparison to that at 150 W. The higher moisture diffusivity at 525 W significantly reduced the constant rate period in comparison to that at 150 W input microwave power level.

The effective moisture diffusivity of various selected food specimen was found to alter as 10^{-6} to 10^{-11} m^2/s. The reported mean effective moisture diffusivity for white mulberry was found to alter as 1.06×10^{-8} to 3.45×10^{-8} m^2/s for input microwave power alteration from 100 to 500 W [25]. Incidentally, for soybean, the reported effective moisture diffusivity altered from 1.99×10^{-9} to 12.25×10^{-9} m^2/s for input microwave power variation from 200 to 600 W [29]. Hence, the outcomes obtained in this study showed a similar trend as in the literature.

In conventional air drying of star fruit, effective moisture diffusivity was reported to be about 3.10×10^{-10} and 3.45×10^{-10} m^2/s at 60 and 70 °C respectively for fresh samples [33]. It is quite evident that the moisture diffusivity for microwave drying

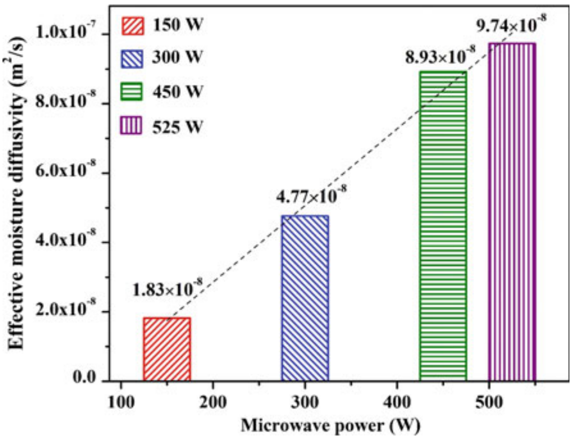

Fig. 7 Plot depicting the variation of effective moisture diffusivity (m^2/s) with input microwave power level (W)

of star fruit is higher by 50 to 250 times than the reported value for the conventional drying process.

3.5 Activation Energy

The lowest amount of energy needed to commence the diffusion of moisture in the fruit is known as activation energy. It is estimated using the Arrhenius plot depicted in Fig. 8. The D_0 is estimated as 2.22×10^{-7} m^2/s and the activation energy ($E_{a.}$) of microwave-dried star fruit is found as 16.92 W/g.

Incidentally activation energy values for the microwave drying of Pandanus leaves (13.6 W/g) and mint leaves (12.3 W/g) were similar [34, 35]. The reported activation

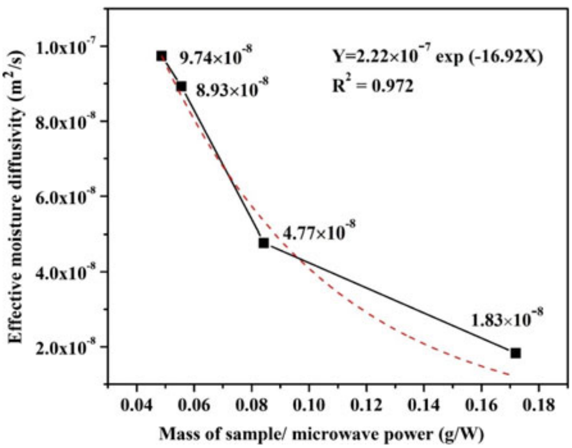

Fig. 8 Plot depicting the variation of effective moisture diffusivity (D_{eff}) with mass of specimen/microwave power (m/p)

energy values for microwave drying of kiwi slices were 17.9, 20.1, 21.4 W/g at alternate sample thickness of 3, 6 and 9 mm respectively [36]. For pepper drying, the activation energy was found to be 14.194 W/g [17].

3.6 Energy Analysis

Energy efficiency (shown in Fig. 9), specific energy consumption (shown in Fig. 10) and specific energy losses (shown in Fig. 11) at various input microwave power levels have been assessed.

Figure 9 shows that the energy efficiency of drying has a proportional relationship with the microwave power level. Energy efficiency varied from 16.74 to 26% for an input microwave power variation from 150 to 525 W. At a low microwave power level, the quantity of water evaporated was comparatively low and drying time was comparatively high. This leads to lower energy efficiency. However, with

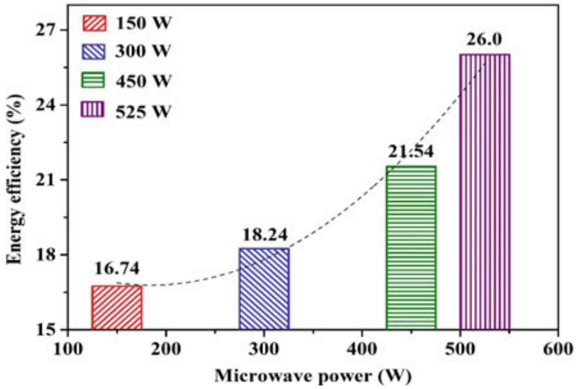

Fig. 9 Variation of microwave energy efficiencies (%) with microwave power (W) levels

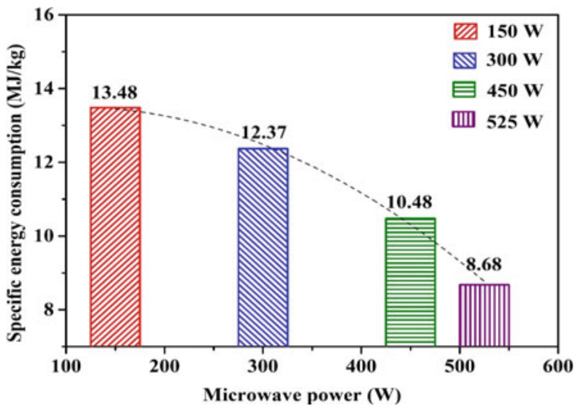

Fig. 10 Variation of specific energy consumption (MJ/kg) of star fruit with input microwave power levels (W)

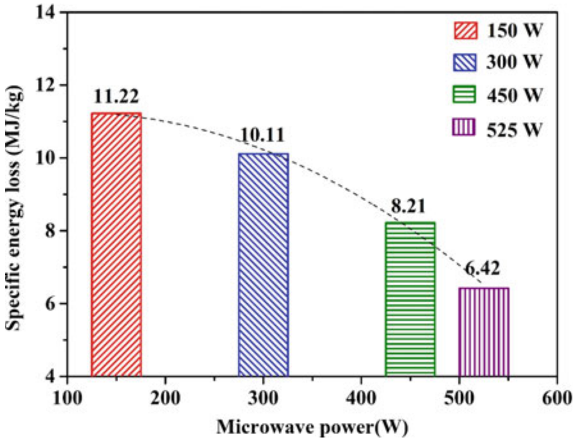

Fig. 11 Plot depicting specific energy loss (MJ/kg) of star fruit at various microwave power levels (W)

increased microwave power, the mass of evaporated water enhanced and leads to energy efficiency. Similarly, for microwave drying of turmeric slices, the energy efficiency values for fresh samples were revealed to be about 10.12 to 24.78%, and for cured samples were about 9.24 to 23.07% for an input microwave power range of 270–900 W [32]. For microwave drying of kiwi slices, the energy efficiency altered from 15.15 to 26.16% for a slice thickness of 9 mm for similar microwave power alteration [36].

As the energy efficiency increased with microwave power, the specific energy consumption (SEC) and specific energy loss were consequently reduced. This can be seen in Figs. 10 and 11. Specific energy consumption (SEC) and specific energy loss reduced from 13.48 to 8.68 MJ/kg and 11.22 to 6.42 MJ/kg, respectively for the microwave drying of star fruit. There is a relative reduction in the specific energy consumption (SEC) of 35.62% at 525 W in comparison to that at 150 W microwave power level. The reported SEC value for microwave drying of apple slices was 6.2 MJ/kg at 360 W [37]. In the case of microwave drying of soybean, the reported SEC and specific energy loss were reduced from 9.12 to 4.91 MJ/kg and 6.04 to 1.67 MJ/kg, respectively, for a surge in microwave power from 200 to 600 W [29].

3.7 Exergy Analyses

The consequence of altered microwave power on exergy efficiency and specific exergy loss can be seen from Figs. 12 and 13 respectively. With an increase in microwave power, the exergy efficiency enhanced and specific exergy loss reduced. Exergy efficiency is 3.93, 6.04, 8.74, and 11.99% at various input microwave power levels of 150, 300, 450, and 525 W, respectively. While comparing with the energy efficiency, the exergy efficiency is found to be lower by 12–14% for all microwave power levels. This is due to entropy generation. Similar trends and results have been revealed in microwave-dried turmeric slices. In this study, the exergy efficiency for fresh samples in the range of 2.18–12.77% for a surge in input microwave power from 270 to 900 W [32].

The specific exergy loss is found to reduce from 12.95 to 7.64 MJ/kg for a surge in input microwave power level from 150 to 525 W. Although exposure of microwave at high power levels leads to high-temperature regimes in the fruit affirming higher exergy loss, a reverse trend is observed with the reduction in the exergy loss at elevated input microwave power level. This may be due to elevated drying time during the low microwave power input leading to higher entropy generation in the system.

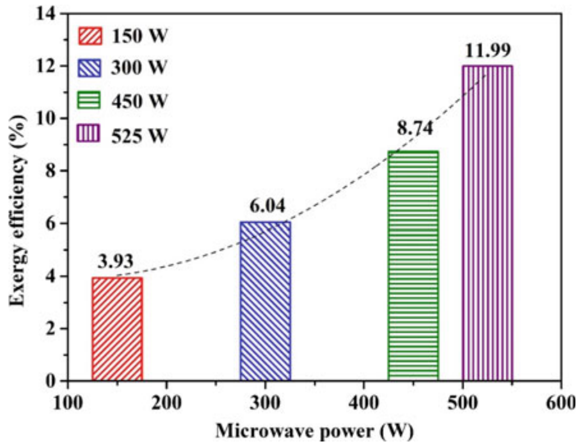

Fig. 12 Exergy efficiencies (%) of star fruit at various levels of microwave power (W)

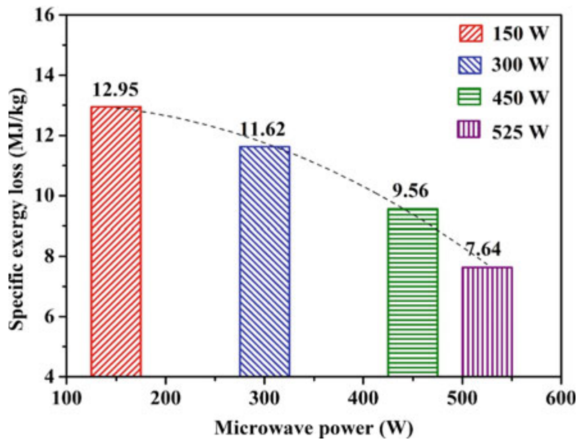

Fig. 13 Specific exergy loss (MJ/kg) of star fruit at various levels of microwave power (W)

3.8 Fourier Transform Infrared Spectroscopic Analyses

The functional groups alteration in the star fruit after microwave drying is analysed by FTIR from 4000 to 500 cm^{-1}. FTIR analysis of the fresh star fruit and dried star fruit at various input microwave power levels (150, 300, 450, and 525 W) is shown in Fig. 14. The fresh star fruit indicated a broader peak at 3315 cm^{-1}. This is recognised as O–H stretching due to the inherent moisture. The dried star fruit demonstrated different functional groups in comparison with the raw fruit [38]. The peak around 1640 and 1066 cm^{-1} can be recognised as C=O and C–O stretching respectively. C=O stretching represents ketones, aldehydes, carboxylic acids and C-O represents primary, secondary, and tertiary alcohols [39]. For dried star fruit, the peaks at the wave numbers 2924 and 2850 cm^{-1} can be recognised as C–H and CH_3. Around the wavenumbers 1460 and 1033 cm^{-1}, the peaks were recognised as C–H and C–O and thereby affirmed on the presence of ketones, aldehydes, carboxylic acids and primary, secondary and tertiary alcohols. Hence, this analyses showed the retention of various acids, primary, secondary and tertiary alcohols in dried sample due to water removal. The functional groups in dried fruits are found to be identical at all microwave power levels. This showed that the fruit sample is able to retain all its chemical constituents at a higher micro wave power level of 525 W and without any deterioration.

3.9 Economic Analysis

The economic analysis is executed to calculate the cost of dried fruit by microwave drying and in terms of payback period. Table 3 shows the economic parameters considered in the present study.

The payback period for the microwave drying of star fruit is estimated as 6.13 years and the life period of the equipment as 20 years. It is found similarly in the literature that confirmed payback period of a greenhouse dryer to be about as 3.2 years for a service life period of about 10 years [27].

Figure 15 shows the price of drying per kg of the final product obtained for altered microwave power and plant capacity. It can be seen that the cost of drying reduced with enhanced with capacity and microwave power level. The cost of drying with 0.6 kg plant capacity at 525, 450, 300 and 150 W is found as 4.63, 6.36, 8.64, and 15.27 INR respectively. At 1000 kg capacity, the cost of drying is reduced below 1 INR at 525, 450, 300 and 150 W microwave power levels.

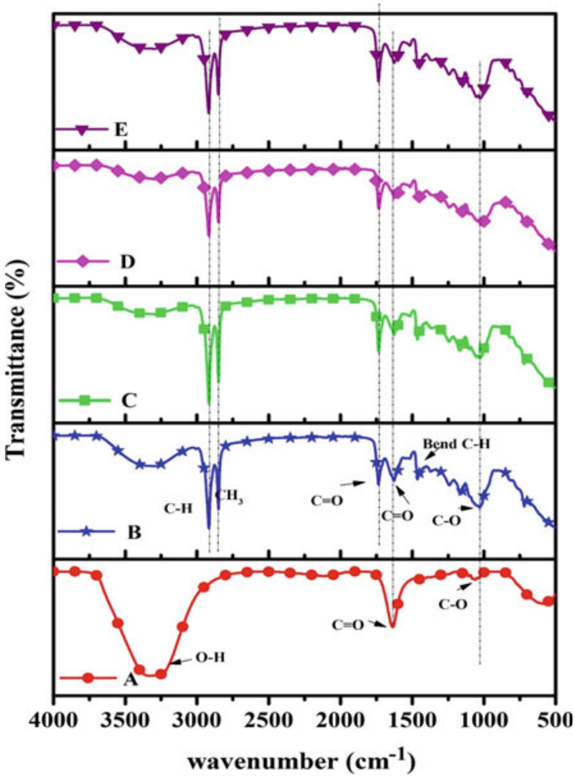

Fig. 14 FTIR analysis of starfruit (A represents fresh starfruit and B, C, D, E represent dried starfruit at 150, 300, 450, and 525 W respectively)

Table 3 Economic parameters for the estimation of cost of the dried products

Economic parameters	Values
Capital cost of microwave dryer	450,000 INR
Annual depreciation	10%
Service life of microwave	20 years
Salvage value	54,709.5 INR
Rate of interest	5%
Rate of inflation	3%
Rate of discount	8%
Electricity charge	7.4 INR/kwh
Number of hours microwave run	7200 h/year

4 Conclusions

This study reveals the drying characteristics of microwave-dried star fruit. Activation energy, effective moisture diffusivity and drying kinetics are estimated. A 3E analysis

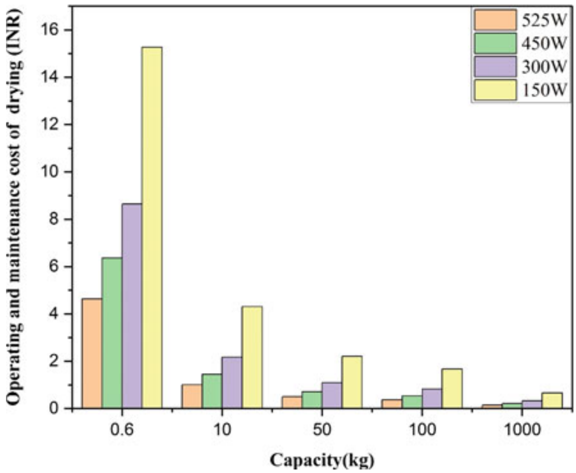

Fig. 15 Variation of operating and maintenance cost (in INR) with capacity

(energy, exergy and economic) is performed to assess the feasibility of commercial implementation.

- The drying time under microwave condition at 150 W is reduced significantly by 11–16 times in conjunction with the conventional drying method. FTIR analyses confirmed that the microwave drying up to a certain input microwave power level of 525 W did not deteriorate the chemical constituents of star fruit.
- A predominant falling rate period is observed at elevated input microwave power levels (300–525 W). However, a constant drying rate period is prevailed at low input microwave power levels at 150 W. The microwave drying enhanced the moisture diffusivity by 50–250 times in comparison to the conventional air drying method.
- Wang and Singh model is the best-fit model for the obtained experimental drying rate characteristics of the microwave drying of star fruit.
- With increased input microwave power, the energy efficiency of the microwave drier enhanced from 16 to 26%. Hence, both specific energy consumption, specific energy loss got reduced. The exergy efficiency is obtained as high as 12% at 525 W due to the entropy generation.
- At a higher capacity of 1000 kg drier, the operating cost of drying reduced to reach below 1 INR for all microwave power levels.

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