



# MICROWAVE DRYING OF ALOE VERA (ALOE BARBADENSIS MILLER): MATHEMATICAL MODELING, KINETICS AND MASS TRANSFER ASPECTS

G. Srinivasan<sup>1</sup>, R. Baskar<sup>2</sup>

<sup>1</sup>Assistant Professor (Sr.Gr.), Department of Chemical Engineering, Erode Sengunthar Engineering College, Erode, Tamil Nadu, India

[gsrinivasanchem@gmail.com](mailto:gsrinivasanchem@gmail.com)

<sup>2</sup>Professor and Head, Department of Food Technology, Kongu Engineering College, Perundurai, Tamil Nadu, India

[naturebaskar@gmail.com](mailto:naturebaskar@gmail.com)

## ABSTRACT

Aloe vera has extensive application in food and pharmaceutical industry in fact contains 97 percent of water. It's perishable in nature and poor shelf life makes it essential to study the drying characteristics of aloe vera. The objective of this present study is to investigate the effect of different microwave (MW) respective power levels (180, 360, 540, 720 and 900 Watts) regarding the moisture ratio (MR), drying rate (DR), effective moisture diffusivity (EMD), specific energy consumption (SEC) and drying efficiency (DE) of aloe vera. The drying process took 70 - 26.5 minutes for attainment of equilibrium moisture content. A mathematical model done by Midilli et al. is considered to be the best and most suitable for a drying conditions among the various thin layer models. The effective moisture diffusivity value at 180 Watts (W) of MW power was found as  $4.5 \times 10^{-8}$  m<sup>2</sup>/sec. while it was raised to  $9.45 \times 10^{-7}$  m<sup>2</sup>/sec at 900 W in this study. Lowest energy consumption 1.4 MJ/Kg water and maximum drying efficiency occurred at higher microwave power level 900 Watts due to less drying duration (time).

**Keywords:** Microwave; Drying, Aloe vera ; Moisture ; energy.

## 1. INTRODUCTION

Aloe Vera (*Aloe barbadensis miller*) is a shrubby or arborescent, perennial, xerophytic, pea-green color plant which grows is being cultivated in many parts of the country. An adult aloe vera plant reaches the height of 30 inches within 1-2 years and having up to 19 to 21 leaves. The leaves are thick, fleshy and green to grey-green in color. The fleshy portion of aloe vera leaves contains different phytochemicals, which are used in the production of various commodity products such as shampoo, gel, body wash, body lotion, sun screen, soothing night cream, face cream, shaving creams, face wash, hair cleanser, soap, juice, tea and powder. Due to its potential health benefits it was reported by many researchers [1-3]. So large scale agricultural production of aloe vera in large quantity is undertaken in several countries such as Australia, Bangladesh, Cuba, Dominican Republic, China, Mexico, Jamaica, Kenya, Tanzania, South Africa, and United States of America. The shelf life of fleshy portion of aloe vera leaves is very limited because of its higher moisture content, it was too difficult to store for a longer period. Hence, increasing shelf life of aloe vera pulp without affecting both its nutritional and chemical composition has become necessary to meet the global demands.

Drying is one of the preservation method used to increase the shelf-life and maintains the nutritional value of the materials. Different drying methods such as, sun drying [4], solar drying [5], vacuum drying [6], rotary drum drying [7], hot air drying [8], vacuum drying [9] these have been used to preserve various plant based materials. Among the various drying methods, microwave drying has a lot of advantages such as shorter drying time, less energy consumption, utilize minimum space, uniform energy distribution and easy to operate [10]. Hence this method was adapted by several researchers to enhance the shelf life of different materials such as grape [11], potato [12], mint leaves [13], mushroom [14], banana [15], garlic [16], chili [17], asparagus [18], parsley [19], garlic cloves [20], white mulberry [21], okra [22], red chili [23], spinach [24], onion [25].

From the literature analysis, it is found that, microwave drying technique not only reduces drying time but also enhances the shelf-life and quality of end products without affecting its chemical and nutritional composition. Therefore an attempt has been made in the present study to examine the feasibility of using microwave drying method to produce high quality of the dried aloe vera product which has not been reported in the technical literature. Therefore, the objective of this present work is carried out to investigate the effect of various microwave power levels on drying characteristics such as moisture ratio (MR), drying rate (DR), effective moisture diffusivity (EMD), specific energy consumption (SEC) and drying efficiency (DE) of aloe vera pulp sample.

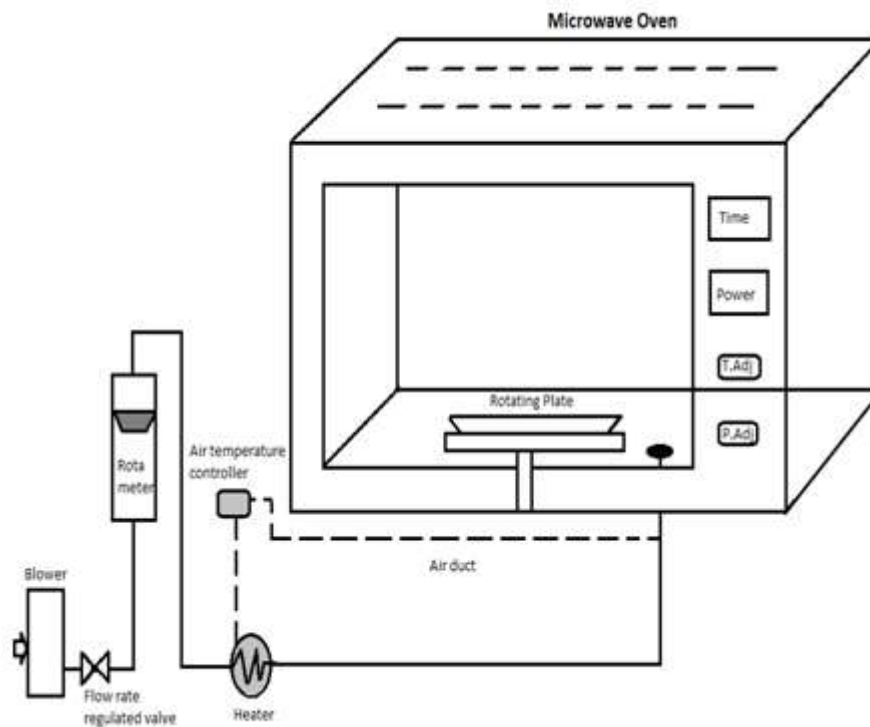
## 2. MATERIALS AND METHODS

### 2.1. Materials

Aloe Vera was purchased from local vendors, in and around Perundurai, Erode, Tamil Nadu, India. The aloe vera was cleaned with running tap water in order to remove the debris present on the surface. It was manually peeled off pulp was taken out from the aloe vera and stored at 4 °C prior to drying experiments. The initial moisture content of aloe vera sample was determined by gravimetric method.

## 2.2. Experimental setup

A programmable multifunctional microwave dryer was fabricated (Fig.1) with digital control facility to adjust the microwave power levels and duration (time). The dimensions of the microwave cavity of the fabricated dryer were 327 X 370 X 207 mm and air flow inside the dryer was regulated with the help of a fan which was inside the microwave cavity. Ventilation holes made at the top of the dryer so as to exhaust the moisture removed from the samples. A digital weighing balance with an accuracy of 0.01g was fitted in the microwave dryer in order to weigh the sample bereft of interrupting the drying process any time.



**Fig 1. Schematic illustration of the microwave drying set-up**

A turnable glass plate was fixed in the bottom of the dryer with the purpose of obtaining homogeneous microwave powers on drying of samples and also to decreasing the level of reflected microwaves from the magnetrons.

## 2.3. Experimental Procedure

A certain amount of aloe vera pulp sample was taken and placed as a single layer on the glass plate. Different microwave power levels (180, 360, 540, 720 and 900 Watts) were used to study the effect of microwave power on the drying characteristics of the samples. Moisture loss of the samples was observed and recorded by means of a digital weighing balance at 60 sec intervals until the weight of the samples reaches a constant value which is an indication of attainment of equilibrium moisture level. During the experimentation, it is observed that the sample is not charred. Triplicate experiments were carried out at the different microwave power levels respectively and the average value was used to evaluate the drying characteristics of the samples.

## 2.4. Moisture Ratio

The Moisture content (MC) is a measure of the amount of water found within a material at fixed duration. Moisture content is expressed as the percentage of the mass of the material that is contributed by the mass of contained water. The moisture content of dried sample at any time (t) could be related to moisture ratio (MR) which was calculated by the method described by [26].

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

Where, MR is the moisture ratio (dimensionless);  $M_t$  is the moisture content at t (kg water/kg dry matter);  $M_e$  is the equilibrium moisture content (kg water/kg dry matter); and  $M_0$  is the initial moisture content (kg water/kg dry matter).



## 2.5. Drying Rate

Drying rate can be defined as the moisture content variation with time and calculated by using the following equation [26].

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (2)$$

Where, DR is the drying rate (kg water/kg dry matter);  $M_t + dt$  is the moisture content at  $t+dt$  (kg water/kg dry matter) and  $t$  is drying time (min).

## 2.6. Mathematical modeling of experimental data

Mathematical modeling of drying data is considered to be an important aspect of any drying process in order to investigate the drying characteristics. Numerous thin layer drying models have been proposed to assess the rate of moisture loss during thin layer drying of materials. These models possess significant practical value to the engineers and researcher for the preliminary evaluation of potential microwave drying operations. The correlations are mathematically simple with the characteristic parameters such as drying constant, providing a combined, but it is sufficiently informative and measures the transport properties (moisture diffusivity, thermal diffusivity, heat and mass transfer coefficients). In this study, the microwave experimental drying data obtained at different power level were fitted to following mathematical models (Table.1).

**Table 1. Thin layer drying models utilized for the determination of MR**

Model No	Model Name	Model	References
1.	Page	$MR = \exp(-kt^n)$	Sarimeseli (2011)
2.	Newton	$MR = \exp(-kt)$	O'Callaghan et al. (1971)
3.	Handerson and Pabis	$MR = a \exp(-kt)$	Roberts et al.(2008)
4.	Midilli.et.all	$MR = a \cdot \exp(-kt^n) + bt$	Midilli et al. (2002)
5.	Logarithmic	$MR = a \exp(-kt) + c$	Akpinar (2008)
6.	Modified Page	$MR = \exp(-(kt)^n)$	Yaldiz et.al(2005)
7.	Wang and Singh	$MR = 1 + at + bt^2$	Arslan and Ozcan (2010)

Three statistical criteria determination co-efficient ( $R^2$ ), sum of squared errors (SSE) and root mean square error (RMSE) were used in this study to evaluate the goodness of fit of the selected models. The following equations were used to compute the statistical parameters.

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N}} \quad (3)$$

$$SSE = 1/N \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \quad (4)$$

Where  $MR_{exp,i}$  is the  $i$ th experimental average moisture ratio.  $MR_{pre,i}$  is the  $i$ th predicted moisture ratio.  $N$  is the number of data values and  $z$  is the number of constant parameters in the thin layer drying models.

## 2.7. Effective moisture diffusivity

The effective moisture diffusivity of a food material characterizes the intrinsic mass transfer property of moisture. During drying, it is assumed that diffusivity, which is explained as much as Fick's diffusion equation, is a physical mechanism to transfer the water to the surface [27]. Effective moisture diffusivity, which is affected by composition, moisture content, temperature, and porosity of the material, is used due to the limited information on the mechanism of moisture movement during drying and the complexity of the process. The effective moisture diffusivity was found from the slope of the normalized plot of the unaccomplished moisture ratio using the following equation [28]:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t \quad (5)$$

Where, MR is the moisture ratio;  $D_{eff}$  is the moisture diffusivity in  $m^2/sec$ , L is the thickness of the sample in meter (m) and t is the drying time (s). The effective moisture diffusivities were typically determined by plotting experimental drying data in terms of  $\ln(MR)$  versus time.

## 2.8. Energy consumption

The Specific energy consumption ( $Q_s$ ) of the drying process was determined as follows [28]:

$$Q_s = \left[ \frac{t_{on} * P * 10^{-6}}{m_w} \right] \quad (6)$$

Where,  $m_w$  is the mass of water evaporated (kg),  $t_{on}$  is the total drying time (s) and P is the power (Watts).

## 2.9. Drying Efficiency

The effect of the moisture content and the drying time on microwave efficiency was calculated using following equation [28]:

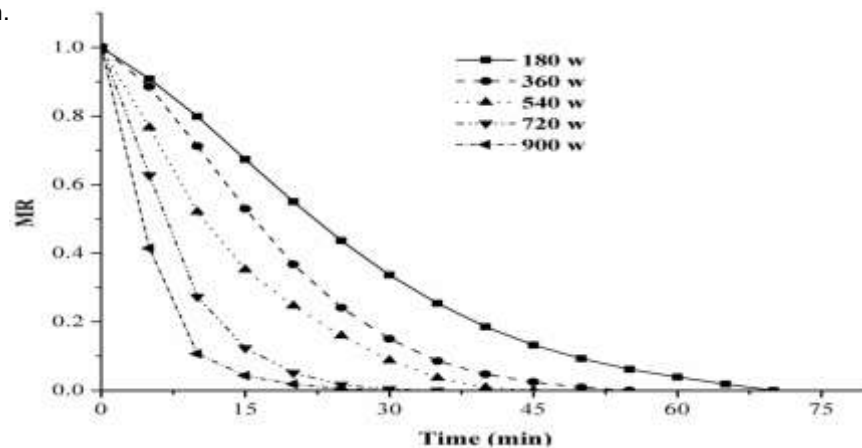
$$\eta_d = \left[ \frac{m_w \lambda_w}{P \Delta t_{on}} \right] * 100 \quad (7)$$

Where,  $m_w$  is the mass of water evaporated (kg),  $\lambda_w$  represents the latent heat of vaporization of  $H_2O$  (2260 KJ Kg<sup>-1</sup>), P is the power (W),  $t_{on}$  is the total drying time and  $\eta_d$  is the Microwave drying efficiency.

## 3. RESULT AND DISCUSSION

### 3.1. Drying kinetics and modeling

Microwave output power is found to have a significant role on the drying process. In order to observe the effect of microwave power level on the moisture ratio, five different MW power levels (180,360,540,720 and 900 Watts) are executed in this research.



**Fig.2.a.Moisture ratio curve of aloe vera at different microwave power**

From the Fig. 2a, it was observed that changes in moisture ratio were possible and greater during the preliminary phase of MW drying process which is, due to the fact that, water being dipolar in nature absorbs the microwave instantly, leads to high moisture diffusion from inner core to outer surface of aloe vera within minimum drying time. Later, the loss of moisture in the sample as the drying progressed, causes decrease in the absorption of microwave power which resulted in decline in the drying rate. Similar research findings were observed and reported in some of the previous studies [29, 30] and [31]. The results have also indicated that mass transfer within the sample was more rapid while increasing the MW output power levels from 180 - 900 Watts, which leads to create a large vapour pressure difference between the centre and surface of the product due to characteristic microwave volumetric heating. The drying rates were calculated from the changes in moisture content in each consecutive time intervals which are identified revealed in (Fig. 3). The presence of higher initial moisture content in aloe vera is responded to microwave drying which has resulted in immediate and complete drying of the sample.

### 3.2. Drying Rate

The drying rate of aloe vera sample gets increased in the initial stage and then slowly decreases as the drying process progresses. The initial moisture content of aloe vera sample was very high which resulted in a higher absorption of microwave power and increased the drying rate of the samples during early stages of drying at different MW output power level (Fig.2b) due to higher moisture diffusion.

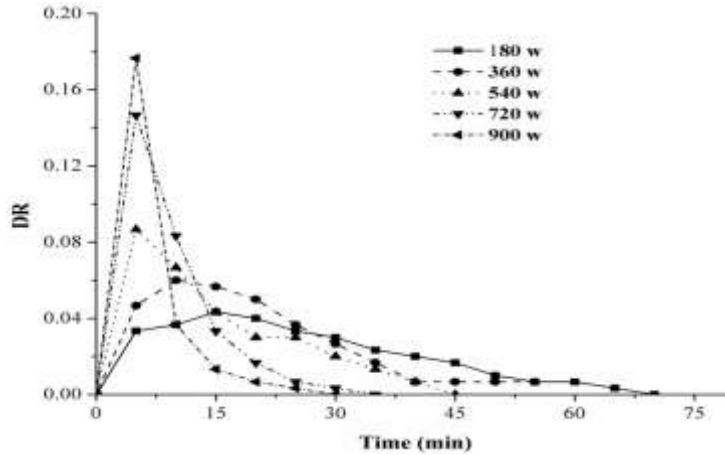


Fig 2.b. Drying rate curve of aloe vera at different microwave power

As the drying progressed, there was a decrease in the absorption of microwave power due to the loss of moisture in the product and decreased the drying rate. It is generally observed that microwave output power had a crucial effect on the drying nature of aloe vera which reduces not only the drying time but also the moisture content of the samples. It is concluded that, higher drying rates were obtained from higher microwave power output power levels. Similar observations were reported in previous studies [32].

### 3.3. Mathematical Modeling of drying data

Mathematical modeling of drying behavior is one of the important parameter to investigate the drying characteristics of any sample. Least square curve fitting method was employed in this study to find out the best thin layer drying model among eight different thin layer models (Table.1) to assess and assure the drying data in a precise and accurate manner. The results of experimental and predicted drying data were analyzed statistically and the best thin layer model which has the capability to predict the drying data was chosen based on the high value of determination co-efficient ( $R^2$ ), lowest sum of squared errors of prediction (SSE) and root mean square error (RMSE) values. The results of statistical analysis for all the experimental conditions reveal that Midilli et al. model furnish the high magnitudes of  $R^2$  values, low magnitudes of SSE and RMSE values (Table 2).

Table 2. Comparison and statistical evaluation of different thin layer drying models

Model	MW Power (Watts)	Estimated Parameter	$R^2$	SSE	RMSE
Page	180	$K=0.00692; n=1.49$	0.9993	0.00109	0.00917
	360	$K=0.00908; n=1.572$	0.9999	0.00016	0.00409
	540	$K=0.03656; n=1.235$	0.9982	0.0019	0.01543
	720	$K=0.05382; n=1.362$	0.9994	0.00055	0.00961
	900	$K=0.11713; n=1.259$	0.9993	0.00054	0.01041
Newton	180	$K=0.03724$	0.9608	0.06452	0.06789
	360	$K=0.05311$	0.9576	0.06047	0.07414
	540	$K=0.07128$	0.9881	0.01267	0.03752
	720	$K=0.12367$	0.9876	0.01157	0.04066
	900	$K=0.19345$	0.9966	0.00278	0.02155
Handerson and Pabis	180	$K=0.04061; n=1.099$	0.9723	0.0455	0.0592
	360	$K=0.05764; n=1.04$	0.9652	0.0452	0.0673
	540	$K=0.07383; n=1.029$	0.9901	0.0106	0.0364



	720	$K=0.12642;n=1.007$	0.9886	0.0106	0.0421
	900	$K=0.19436;n=1.004$	0.9967	0.0027	0.0234
	180	$K=0.00769;n=1.4453; a=0.9945; b=-0.00036$	0.99999	0.00018	0.00411
	360	$K=0.00938;n=1.5555; a=0.9987; b=-0.00015$	0.9989	0.00034	0.00208
Middili.et.al	540	$K=0.00956;n=1.2173; a=0.6972; b=-0.05684$	0.9878	0.00086	0.03804
	720	$K=0.0533;n=1.3694; a=1.0021; b=0.00010$	0.9999	0.00052	0.01147
	900	$K=0.112;n=1.2871;a=1.0000; b=0.00025$	0.9995	0.00042	0.0119
	180	$K=0.02591;a=1.2941;c=-0.2421$	0.9931	0.0113	0.0307
	360	$K=0.04008;a=1.2433;c=-0.1812$	0.9873	0.0181	0.0448
Logarithmic	540	$K=0.0587;a=1.1135;c=-0.0964$	0.9981	0.0019	0.0168
	720	$K=0.1129;a=1.0642;c=-0.0429$	0.9923	0.0072	0.0378
	900	$K=0.1883;a=1.0163;c=-0.0107$	0.9971	0.0024	0.0246
	180	$K=0.5822;n=0.6392$	0.9608	0.0645	0.0704
	360	$K=0.0235;n=0.5843$	0.9561	0.0629	0.0834
	540	$K=0.0268;n=0.5043$	0.9757	0.0259	0.0608
Modified Page	720	$K=0.9806;n=0.1262$	0.9876	0.0115	0.0439
	900	$K= 0.9756 ;n = 0.0946$	0.9764	0.0182	0.0563
	180	$a=-0.0269;b=0.00018$	0.9953	0.0078	0.0245
	360	$a=-0.0384;b=0.00036$	0.9923	0.0109	0.0331
Wang and Singh	540	$a= -0.0504;b=0.00064$	0.9949	0.0048	0.0246
	720	$a=-0.0789;b=0.00148$	0.9808	0.0181	0.0547
	900	$a=-0.0102;b=0.00239$	0.9339	0.0545	0.1044

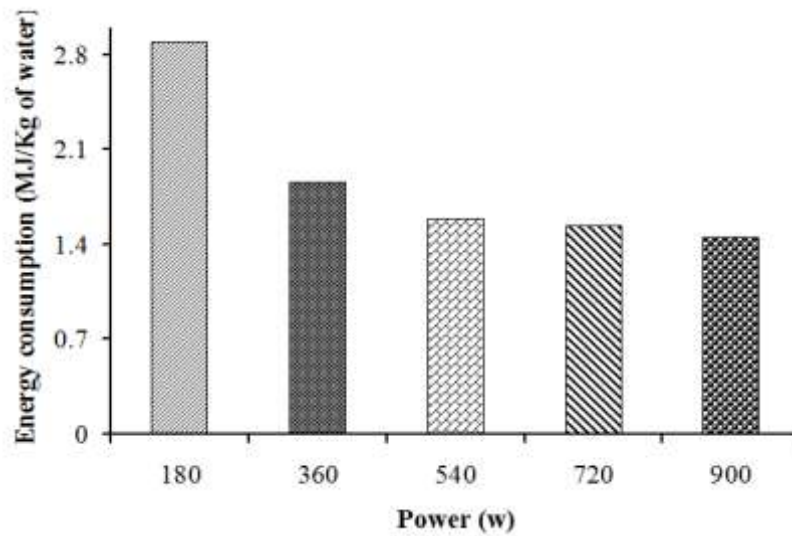
The suitability of Midilli et al. model was validated in comparing with the experimental and predicted moisture ratio under any operating conditions. But, this equation is mathematically simple with the characteristic coefficients; drying constant, providing a combined, but sufficiently informative, measure of the transport properties (moisture and thermal diffusivity, and heat and mass transfer coefficients) of the drying process.

### 3.4. Effective Moisture Diffusivity

Investigation on the moisture diffusion during drying process is commonly accepted and used to study the mechanism during the transport of moisture to the surface and to be evaporated. No documentary evidence was found about investigation on effective moisture diffusivity for aloe vera undergoing microwave treatment. Hence, in this present study effective moisture diffusivity was examined and the results showed that the effective moisture diffusivity value at 180 Watts of MW power was found as  $4.5 \times 10^{-8}$  m<sup>2</sup>/s while it was raised to  $9.45 \times 10^{-7}$  m<sup>2</sup>/s at 900 Watts. This indicated that higher absorption of microwave at higher microwave power level rapidly raised the temperature of the product in the initial stages of drying, increased the evaporation of water molecules of the samples and results in higher moisture diffusivity when samples were dried at higher microwave power levels. In addition, higher moisture content of sample in the initial stage of drying got increased the permeability of water to vapor, induced the sample in an open pore structure and increased the moisture diffusivity of sample during drying process.

### 3.5. Specific energy consumption

The specific energy consumption is one of the prime parameters to analyze the drying process. In this study, specific energy consumption was determined at all sorts of the microwave power levels (180,360,540,720 and 900 Watts) and the results were shown in Fig.3.

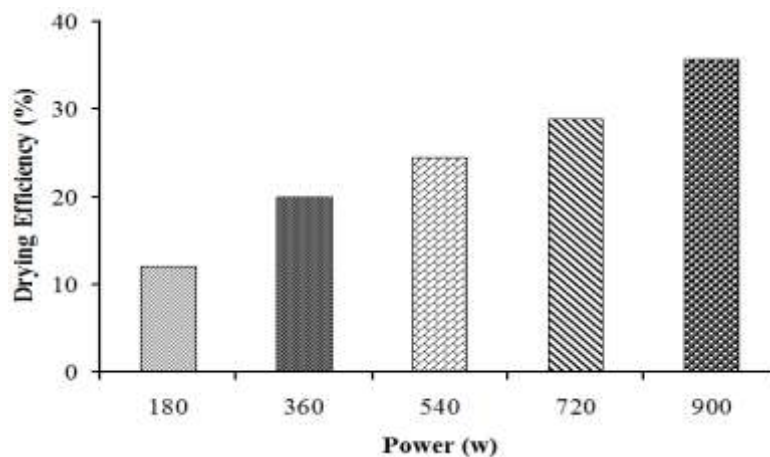


**Fig 3. Specific energy consumption for microwave drying of Aloe vera**

The results exhibited that, lowest energy consumption (1.4 MJ/Kg water) occurred at high microwave power level 900 Watts due to the lowest drying time when compared with other power level. Similar results narrated about less energy consumption due to short drying time were reported in several research works [33].

### 3.6. Energy efficiency of microwave drying

The drying efficiency at different microwave power level was evaluated and the results were illustrated in Figure.4.



**Fig 4. Drying efficiency of Aloe vera at different microwave power**

From the results, it was observed that drying efficiency was increased with increasing microwave power level. Intensity of heat generation or the ability of the product to absorb microwave energy decreased due to the reduction of moisture during the microwave drying process [34, 35]. Hence, the drying efficiency increased rapidly at higher microwave power level 900 W.

## 4. CONCLUSION

Drying characteristics of aloe vera were studied under different microwave power levels (180,360,540,720 and 900 Watts). The results showed that drying time decreased drastically with the increase of microwave output power due to the absorption of microwave which reduces the moisture content of the samples in the initial stage of drying and gives rise to



an accelerating peak on the drying rate curves. The variations of moisture content, drying rate and moisture ratio are found to be greatly affected by the microwave power density. The results also showed that the effective moisture diffusivity increased with the increase in microwave output power. Minimum specific consumption and maximum drying efficiency values are obtained at 900 Watts of microwave power level. It is concluded that this study demonstrates the methodology and guidance for the use of microwave as an ideal tool for drying of aloe vera.

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G. Srinivasan received his B.Tech. degree in Chemical Engineering from Adhiyamaan College of Engineering, Hosur, Tamil Nadu, India in the year 1997 and received his M.Tech. degree in Biotechnology from the Annamalai University, Chidambaram, Tamil Nadu, India in the year 2008. Currently he is working as Assistant Professor (Senior Grade) in the department of Chemical Engineering at Erode Sengunthar Engineering College, Perundurai, Erode, Tamil Nadu, India. He has received a grant of Rs.80, 000/- from the Ministry of Earth Sciences (MoES), New Delhi, for the two days National Workshop on “Green Technology”-an awareness programme for farmers in rural area



Dr. R. Baskar is working as Professor and Head in the department of Food Technology at Kongu Engineering College, Perundurai, Erode, India. He has published 7 papers in the national journals and more than 20 papers in the various international journals. He has received fund of Rs. 50,70,400/- from the Department of Science & Technology, New Delhi for the project titled “Treatability studies for Textile waste water treatment”.