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# Mathematical Modelling, Energy and Exergy Analysis of Tomato Slices in a Mixed Mode Natural Convection Solar Dryer

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### *Authors' contributions*

*This work was carried out in collaboration between all authors. Authors DA and SRR designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author GKM managed the analyses of the study. Author VRK managed the literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

This paper reports the drying kinetics of tomato (*Lycopersicon esculentum*) with different drying loads in a fabricated mixed mode natural convection solar dryer. The energy utilization ratio (EUR) and exergetic efficiency ($\eta_{Ex}$) was also estimated. Tomato slices were dried to reach the final moisture content of below 8% (w.b) from 93.67% (w.b) in a period of 20 h, 23 h and 30 h for a load of 2 kg/$m^2$, 4 kg/$m^2$ and 6 kg/$m^2$, respectively. Different thin layer mathematical models were selected to fit the experimental data. According to the statistical results, the approximation of Two-term was shown a better fit to the experimental drying for the load of 2 kg/$m^2$ and 4 kg/$m^2$ whereas the Logarithmic model was shown a better fit for a 6 kg/$m^2$. The maximum value of $D_{eff}$ was obtained

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as $1.14\times10^{-10}$ $m^2/s$ for a loading rate of 2 $kg/m^2$.The EUR was found to be 24.21%, 41.42% and 58.03% for the load of 2 $kg/m^2$, 4 $kg/m^2$ and 6 $kg/m^2$, respectively, and $\eta_{Ex}$ was 59%, 54% and 50% for the three load conditions of 2 $kg/m^2$, 4 $kg/m^2$ and 6 $kg/m^2$, respectively. The dryer efficiency increased from 17.33% to 35% with increased in load from 2 $kg/m^2$ to 6 $kg/m^2$.

*Keywords: Moisture diffusivity; mathematical modelling; exergy efficiency; tomato slice; dryer efficiency.*

## ABBREVIATIONS

| | |
|---|---|
| *DR* | *Drying rate, kg water/(kg dry matter. h)* |
| $\Delta M$ | *Loss of the mass of the crop, kg water/kg dry matter* |
| $\Delta t$ | *Interval of time, min* |
| $\eta_s$ | *Dryer efficiency* |
| $m_w$ | *Mass of water evaporated during drying, kg/s* |
| $h_{fg}$ | *Latent heat of vaporization of water, kJ/kg* |
| $I$ | *Solar intensity, W/$m^2$* |
| $A$ | *Solar collector area+ surface area of glass at the top, $m^2$* |
| $t$ | *Drying time, h* |
| *MR* | *Moisture ratio* |
| $M_t$ | *Moisture content at any time t, kg water/kg solid* |
| $M_e$ | *Equilibrium moisture content, kg water/kg solids* |
| $M_o$ | *Initial moisture content* |
| $D_{eff}$ | *Effective moisture diffusivity, $m^2/s$* |
| $L$ | *Half the thickness of slice of the sample, m* |
| $M$ | *Moisture content, kg of water/kg of dry matter* |
| $MR_{pred,i}$ | *Predicted moisture ratio* |
| *EMC* | *Equilibrium moisture content* |
| $MR_{expt,i}$ | *Experimental moisture ratio* |
| *EUR* | *Energy utilization ratio* |
| $Cp_{da}$ | *Specific heat of drying air, kJ/kg.K* |
| $E_{dco}$ | *Outlet enthalpy of drying chamber, kJ/kg* |
| $\dot{E}X$ | *Exergy, kJ/kg* |
| $T_\infty$ | *Temperature of ambient or surrounding* |
| $T_{dc0}$ | *Outlet temperature of drying chamber, °C* |
| $\eta_{EX}$ | *Exergetic efficiency* |
| $m$ | *Moisture content at a given time, kg water/kg dry matter* |
| $\dot{m}_{dai}$ | *Mass flow rate of inlet drying air, kg/s* |
| $\dot{m}_{da0}$ | *Mass flow rate of outlet drying air, kg/s* |
| $s_i$ | *Inlet specific humidity, kg/kg* |
| $s_0$ | *Outlet specific humidity, kg/kg* |
| $\dot{m}_p$ | *Moisture content of product* |
| $\dot{Q}$ | *Net heat, kJ/s* |
| $\dot{W}$ | *Energy utilization, J/s* |
| $\dot{m}_0$ | *Mass flow rate of outlet air, kg/s* |
| $\dot{m}_i$ | *Mass flow rate of inlet air, kg/s* |
| $E_i$ | *Inlet enthalpy, kJ/kg* |
| $E_0$ | *Outlet enthalpy, kJ/kg* |
| $V_i$ | *Inflow velocity, m/s* |
| $V_o$ | *Outflow velocity, m/s* |
| $T$ | *Temperature, K* |
| *Cp* | *Specific heat, kJ/(kg. K)* |
| $E$ | *Enthalpy, kJ/kg* |
| $N$ | *Number of observations* |
| $s$ | *Number of model constants* |
| $\dot{m}_{da}$ | *Mass flow rate of drying air, kg/s* |
| $E_{dci}$ | *Inlet enthalpy of drying chamber, kJ/kg* |
| $T_{clo}$ | *Outlet temperature of collector, °C* |
| $T_{cli}$ | *Inlet temperature of collector, °C* |
| $\dot{E}X_{dci}$ | *Exergy inflow of drying chamber, kJ/kg* |
| $T_{dci}$ | *Inlet temperature of drying chamber, °C* |

## 1. INTRODUCTION

Agricultural products, especially fruits and vegetables are highly perishable nature and are seasonal. Most of produced fruits and vegetables are being lost after harvesting at the market and field level. Tomato (*Lycopersicon esculentum*) is considered as one of the most important vegetables occupying second position amongst the vegetable crops in terms of production [1]. Tomato is a perishable fruit that contains high moisture content and cannot be stored for longer period. Therefore, it is necessary to dehydrate it without changing the nutritional and sensory characteristics.

Drying process is one of the most preservation techniques used which extends the shelf life of the products by reducing the water content to a safe level. It also makes the seasonal food available throughout the year. Drying process reduces transportation cost by lowering the weight and volume, packing size and storage space [2]. There are different drying methods: open sun drying, solar drying and mechanical drying (Tray drying, drum drying and spray drying etc.). Among all these methods, open sun drying is mostly practiced by humans by directly drying the food in the hot sun. The major drawbacks of sun drying are: it occupies more space or area, thus results in uneven control of drying; it involves high labour cost and also low product quality because of more drying time, dust, insects, birds and other foreign matter [3]. To alleviate all these problems, different drying methods have been developed to prevent the deterioration of the food materials. Improvement of sun drying has led to the evolution of solar drying protecting the food from contamination and weather conditions while retaining the product qualities as such [4]. Therefore, the introduction of solar dryer systems become popular to reduce the losses of agricultural food material and to improve the quality of the dried product significantly when compared to traditional method [5,6] and also they are cheaper and more practical when compared to mechanical dryers [7,8]. However, solar dryers must be properly designed in order to meet the particular drying requirements of specific crop and to give satisfactory performance with respect to the energy requirement [9].

The direct solar dryers involve the thin layer of product spread over large space to expose to solar radiation. In indirect solar dryers or convective solar dryers, the atmospheric air is heated in flat plate collector or concentrated type solar collector in which the hot air or the heated air flow in the cabin where products are dried. Moisture from the food material is lost by convection and diffusion. This method of drying is used to avoid direct exposure to the solar radiation. In this kind of drying process, the chamber temperature and thickness of drying samples are the main factors taken into consideration [10]. In mixed mode type, the product is dried with both direct exposure to solar radiation and hot air supplier on it. In this process, the product is dried according to convective moisture loss. A cheap and simple mixed mode solar dryer was introduced [11] for farmers. This type of dryer is often used for drying of agricultural crops in the wet season [12]. Among the three different types of dryers, the mixed-mode dryer is the best because it has the highest drying rate [13].

The mathematical models are useful to design any new equipment, to modify existing system and to optimize the drying times, and to promote the better understanding of the drying mechanisms [3,14]. For the optimization of drying processes, less energy is used for maximum moisture removal. As a consequence, energy quantity and quality as well as heat and mass transfer should be investigated throughout the drying process [15]. Therefore a rigorous analysis of the convective drying process should be based on the mass and energy conservation principles as well as on the exergetic balance of the process. The energy and exergy analyses of drying process should be performed by employing the first and second laws of thermodynamics [16]. Exergy is defined as the amount of work obtained from a stream of matter, heat or work as it comes to equilibrium with a reference environment, and is a measure of the potential of a stream to cause change, as a result of not being completely stable relative to the reference environment. It is the combination of the property of a system and its environment because it depends on the system and its environment [17].

Extensive work has been carried out on mathematical modelling of thin layer drying of different agricultural food materials such as apple [18], red chilli [19], organic apple [20], apricot [21,6], grape [5]. Information on the energy and exergy analyses of solar drying of Tomato appears to be scanty in the scientific literature to the best of our knowledge. But the literature about the variation of energy and exergy efficiency under different load conditions of tomato in a mixed mode natural convection solar dryer has not been yet studied according to the author's knowledge. Therefore, the study has been undertaken to investigate the thin-layer drying characteristics of tomato in a mixed mode natural convection solar dryer and to study the variation of energy and exergetic efficiency under different load conditions.

## 2. MATERIALS AND METHODS

### 2.1 Drying Procedure

A mixed mode natural convection solar dryer (Fig. 1) was fabricated at College of Agricultural Engineering, Sangareddy, Medak district, Telangana State of India. It is situated on the latitude of 17.6294° N, a longitude of 78.0917° E and at an elevation of 621 m above mean sea level. Tomatoes (*Lycopersicon esculentum*) used for the drying experiment were procured from the local market based on visual assessment of uniform colour and geometry. The drying experiments were conducted during the month of April to May in the year of 2015. During drying process, the moisture loss of samples was measured by means of a digital electronic balance (Testing Instrument Pvt. Ltd., India) having an accuracy of ±0.001 g. The initial moisture content of the tomatoes was determined according to [22] as 93.67% (w.b.). The two trays were loaded with equal amount of tomato slices of thickness 6±1 mm. During the experiments, temperatures were measured for every 10 min interval using a digital thermometer. The moisture content ($M_{wb}$) is expressed on wet basis (w.b). The drying rate was calculated using the following equation. The drying curves are then plotted against the moisture content.

$$\mathrm{DR} = \frac{\Delta \mathrm{M}}{\Delta \mathrm{t}} \quad (1)$$

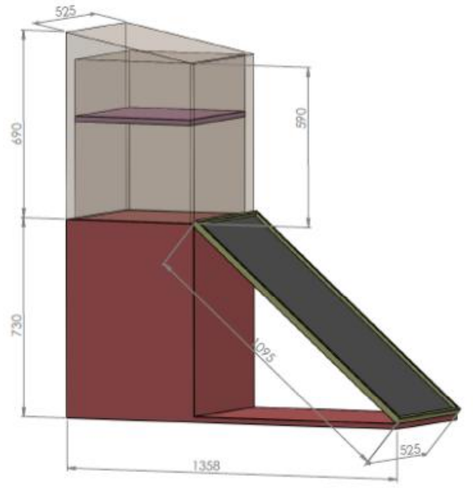


**Fig. 1. Mixed mode natural convection solar dryer**

## 2.2 Dryer Efficiency

The efficiency of the dryer for mixed mode type was estimated using the following equation:

$$\eta_s = \frac{m_w h_{fg}}{IAt} \quad (2)$$

## 2.3 Mathematical Modelling

The drying kinetics of tomato slices was expressed in terms of empirical models, where the experimental data were plotted in the form of dimensionless moisture ratio (MR) against drying time (expressed in min) for infinite slab [23,24] is

$$\mathrm{MR} = \frac{\mathrm{M(t)} - \mathrm{M}_e}{\mathrm{M}_o - \mathrm{M}_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left( -(2n+1)^2 \pi^2 \frac{\mathrm{D_{eff}} t}{4L^2} \right) \quad (3)$$

For longer drying periods for infinite slab, the above equation is simplified, without much affecting the accuracy of the prediction [25].

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} = \frac{8}{\pi^2} \exp\left[ -\pi^2 \frac{\mathrm{D_{eff}\, t}}{4\mathrm{L}^2} \right] \quad (4)$$

During the drying of tomato, value of EMC is relatively small compared to M or $M_o$ [24], therefore, the EMC was assumed to be zero. Hence, the above expression is simplified to following equation to compute the moisture ratio:

$$\mathrm{MR} = \frac{\mathrm{M}}{\mathrm{M_0}} \quad (5)$$

The experimental data of moisture ratio and drying time was fitted to different empirical models shown in Table 1 to analyze the behaviour of thin layer drying of tomato slices. The following statistical equations [26] are used to describe the goodness of fit of the dried tomato slices:

$$\mathrm{R}^2 = \frac{\mathrm{N} \sum_{i=1}^{N} \mathrm{MR_{pred,i}} \mathrm{MR_{exp,i}} - \sum_{i=1}^{N} \mathrm{MR_{pred,i}} \sum_{i=1}^{N} \mathrm{MR_{exp,i}}}{\sqrt{\left(\mathrm{N} \sum_{i=1}^{N} \mathrm{MR^2_{pred,i}} - \left(\sum_{i=1}^{N} \mathrm{MR^2_{pred,i}}\right)^2\right)\left(\mathrm{N} \sum_{i=1}^{N} \mathrm{MR^2_{exp,i}} - \left(\sum_{i=1}^{N} \mathrm{MR^2_{exp,i}}\right)^2\right)}} \quad (6)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}} \sum_{i=1}^{N} \left( \mathrm{MR_{exp,i}} - \mathrm{MR_{pred,i}} \right)^2} \quad (7)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left( \mathrm{MR_{exp,i}} - \mathrm{MR_{pred,i}} \right)^2}{\mathrm{N} - \mathrm{s}} \quad (8)$$

The drying rate constants and coefficients of the model equations were estimated by nonlinear regression analysis using curve fitting tool in the MATLAB software package (R2015a (8.5.0.197613)) and the goodness of fit of the curves was determined by correlation analysis.

## 2.4 Estimation of Effective Moisture Diffusivity

During drying, diffusion is a complex process and it can be defined by Fick's second law as given below:

$$\frac{\partial \mathrm{M}}{\partial \mathrm{t}} = \mathrm{D_{eff}} \nabla^2 \mathrm{M} \quad (9)$$

The falling rate period of biological materials is best described by Fick's second law of diffusion [23,26]. The effective moisture diffusivity was estimated by using analytical solutions of Fick's second law for unsteady state diffusion. This analytical solution of the above equation is solved by considering tomato slice as infinite slab geometry. For the mathematical modelling, the following assumptions

**Table 1. Mathematical models applied to the drying curves**

| Sl. no. | Model | Expression | References |
|---|---|---|---|
| 1 | Aghabashlo model | $\exp(-k_1t/(1+k_2t))$ | [33] |
| 2 | Demir et al. | $a \exp(-kt)^n+b$ | [34] |
| 3 | Hii et al. | $a \exp(-k_1t^n) + b \exp(-k_2t^n)$ | [35] |
| 4 | Logarithmic | $a \exp(-bt)+c$ | [25] |
| 5 | Modified Midilli et al. | $a \exp(-kt)+b$ | [36] |
| 6 | Modified Page III | $k \exp(-t/d^2)^n$ | [37] |
| 7 | Two term model | $a \exp(-k_1t) + b \exp(-k_2t)$ | [38] |
| 8 | Wang and Singh | $1+at+bt^2$ | [39] |

[23,24] are taken into account; a) Initial Moisture content is uniform through the product, b)temperature and diffusivity coefficient is constant, and c) external mass transfer resistance was neglected. Effective moisture diffusivity ($D_{eff}$) was obtained from the slope (m) of the plot of ln (MR) against the drying time. Moisture diffusivity ($D_{eff}$) is estimated with the following expression:

$$m = \frac{\pi^2 D_{eff}}{4L^2} \tag{10}$$

## 2.5 Energy and Exergy Analysis

The energy utilization ratio and exergy analysis can be evaluated by using the first and second law of thermodynamics in order to obtain the thermodynamic behaviour of the drying air in the thermal system. For the single layer of drying for energy and exergy analysis, the conservation of mass of drying air and moisture and conservation of energy was performed by using the following expression [27]

Equation for the conservation of mass of drying air:

$$\sum \dot{m}_{dai} = \sum \dot{m}_{da0} \tag{11}$$

Equation for the mass conservation of moisture is

$$\sum\left(\dot{m}_{dai}s_i + \dot{m}_p\right) = \sum \dot{m}_{dai}\, s_0 \tag{12}$$

Equation for the conservation of energy of the system is given by

$$\dot{Q} - \dot{W} = \sum \dot{m}_0 \left[E_0 + \frac{V_0^2}{2}\right] - \sum \dot{m}_i \left(E_i + \frac{V_i^2}{2}\right) \tag{13}$$

During the solar drying process, the energy utilization ratio (%) was found with the ratio of heat utilization by system to the heat energy given from the solar collector by using following expression [27]:

$$EUR = \frac{\dot{m}_{da}(E_{dci} - E_{dco})}{\dot{m}_{da}\, Cp_{da}(T_{clo} - T_{cli})} \tag{14}$$

The exergy analysis is an important tool that can be used in the design of thermal system. This analysis gives useful information to opt the suitable design component and operational procedure [27,28]. The exergy analysis is estimated by employing the second law of thermodynamics. The exergy inflow, outflow and loss can be evaluated based on the thermodynamic law with the general form of given equation [28]:

$$E\dot{X} = Cp_{da}\left[(T - T_\infty) - T_\infty \ln\frac{T}{T_\infty}\right] \tag{15}$$

For exergy inflow of the drying chamber:

$$E\dot{x}_{dci} = Cp_{da}\left[(T_{dci} - T_\infty) - T_\infty \ln\frac{T_{dci}}{T_\infty}\right] \tag{16}$$

For exergy outflow of the drying cabinet:

$$E\dot{x}_{dc0} = Cp_{da}\left[(T_{dc0} - T_\infty) - T_\infty \ln\frac{T_{dc0}}{T_\infty}\right] \tag{17}$$

The exergy losses can be determined with the following equation:

$$\sum E\dot{x}_{Loss} = \sum E\dot{x}_{dci} - \sum E\dot{x}_{dc0} \tag{18}$$

The exergetic efficiency can be defined as the ratio of exergy use (investment) in the drying of the product, to exergy of the drying air supplied to the system. However, it is explained as the ratio of exergy outflow to exergy inflow for the drying cabinet. The general form of exergetic efficiency is written as [27]:

$$\text{Exergetic Efficiency} = \frac{\text{Exergy outflow}}{\text{Exergy Inflow}} \tag{19}$$

$$\eta_{Ex} = \frac{\text{Exergy Inflow} - \text{Exergy loss}}{\text{Exergy Inflow}} \tag{20}$$

## 3. RESULTS AND DISCUSSION

### 3.1 Dryer under No-load Condition

It was observed that the average maximum and minimum temperature inside the dryer was found to be 51°C and 37°C, respectively. Relative humidity for the corresponding temperatures was 52% and 68%. Similarly, outside the dryer, the ambient temperatures of maximum and minimum observed to be 40°C and 30°C. Hence, inside the dryer, there is an increase in temperature of about 11°C as compared to the outside ambient temperature. The average solar radiation was found to be 1084.26 W/m$^2$.

### 3.2 Kinetics under Different Drying Loads

During the experiments, the weather was generally sunny and no rain appeared. The maximum and minimum temperatures inside the solar dryer during the drying periods of 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$ were observed to be 50.5°C and 37°C; 51.5°C and 37°C; 51.7°C and 37°C, respectively. The average solar insolation during drying of these loads in a dryer was observed to be 1097.62 W/m$^2$, 1041.37 W/m$^2$ and 1114.25 W/m$^2$, respectively. Fig. 2 shows the reduction in moisture content from 93.67% to 7.76% (w.b.) in 20 h, 7.65% (w.b.) in 23 h and 7.56% (w.b.) in 30 h of duration for 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$ respectively. The plot of moisture ratio in each of the loading of 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$ against drying time is shown in Fig. 3. This drying curve shows that moisture ratio decreased exponentially with increased in drying time. It was observed that a tray load of 6 kg/m$^2$ was associated with higher moisture ratio followed by 4 kg/m$^2$ and 2 kg/m$^2$. The results are in good agreement with the results of green banana [30]. It can also be observed that the removal of moisture was faster at the beginning of the drying due to the availability of free unbound moisture than immediate following hours.

The Fig. 4 represents the variation of drying rate with respect to drying time. Initially, the rate of drying was more and was found to be decreased as drying time proceeds. The drying rate was significantly affected by all drying loads. It was observed that the drying process occurred in the falling rate period. In the present work, constant drying rate period was not much observed, indicating that the rate of drying is controlled by liquid diffusion from the integral parts of solid to surface [10]. These results were in agreement with the results for sultana grape [5], apricot [9], plum [31] and prickly pear peel [32].

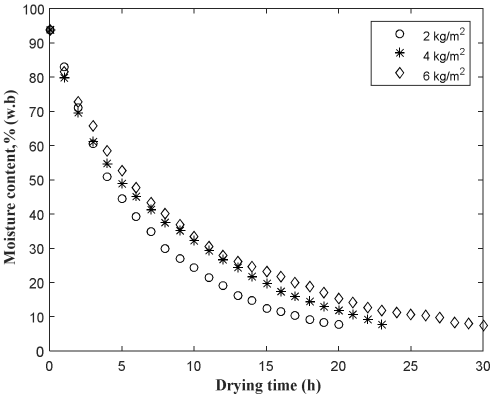


**Fig. 2. Variation of moisture content with drying time for different loading rates**

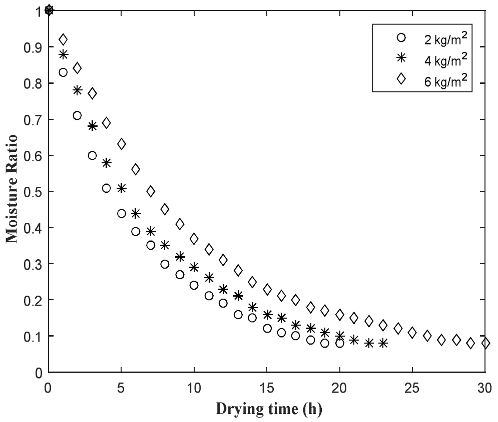


**Fig. 3. Plot of moisture ratio with drying time**

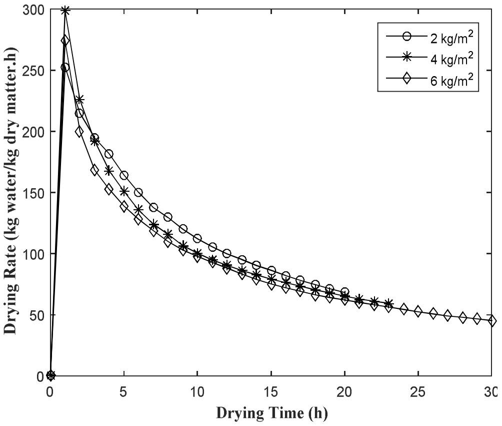


**Fig. 4. Plot of drying rate against drying time for different drying loads**

### 3.3 Model Fitting

The obtained moisture content data from the experiments were fitted to the 8 different drying models (Table 1) in the form of dimensionless MR and drying time. According to the statistical results, the model constants, coefficients and the comparison criteria namely, $R^2$, $\chi^2$ and RSME data are presented in Table 2. The lower value of $\chi^2$, RMSE and higher value of $R^2$ was chosen for the better goodness of the fit. The Two-term was the best fitted model among all mathematical models for the tray load of 2 kg/$m^2$ and 4 kg/$m^2$ with highest $R^2$ as 0.99971 and 0.99943, lower $\chi^2$ as $2.03\times10^{-5}$ and $4.17\times10^{-5}$ and lowest RMSE as 0.0045 and 0.008459, respectively, whereas for a tray load of 6 kg/$m^2$, Logarithmic model was best suited with highest $R^2$ as 0.99935 and lowest $\chi^2$ and RMSE as $4.78\times10^{-5}$and 0.006914, respectively.

Fig. 5 illustrates the comparison between experimental moisture ratio and predicted moisture ratio by Two-term model for a loading of 2 kg/$m^2$ and 4 kg/$m^2$, respectively and by Logarithmic model for 6 kg/$m^2$. The predicted MR from these models was also decreased exponentially as shown in Fig. 5. It is concluded that there is good agreement between calculated and experimental data, which indicates that the Two-term and Logarithmic model could adequately describe the drying behaviour of tomato at different loading rates of 2 kg/$m^2$, 4 kg/$m^2$ and 6 kg/$m^2$ respectively.

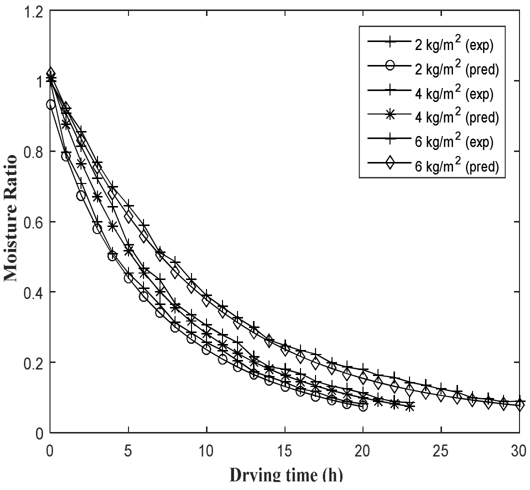


**Fig. 5. Comparison of the experimental and predicted moisture ratio against drying time at different drying loads**

### 3.4 Effective Moisture Diffusivity

The effective moisture diffusivity was computed by using the graph of ln (MR) against time for the different tray loads is shown in Fig. 6. The moisture diffusivity of tomato in natural convection drying were decreased with increased in loads of 2 kg/$m^2$, 4 kg/$m^2$ and 6 kg/$m^2$. The maximum value of $D_{eff}$ was obtained as $1.14\times10^{10}m^2/s$ during the experiment for a loading rate of 2 kg/$m^2$. The minimum value of $D_{eff}$ was found to be $4.91\times10^{-11}$ $m^2/s$ was for 6 kg/$m^2$. According to the [29], the values of effective diffusivity fall within the range of $10^{-11}$ to $10^{-6}$ for all agricultural and food products.

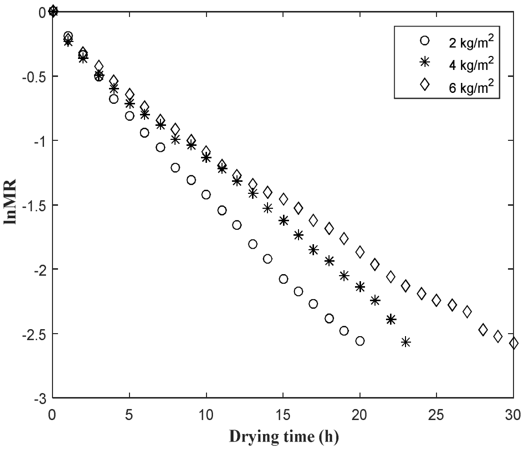


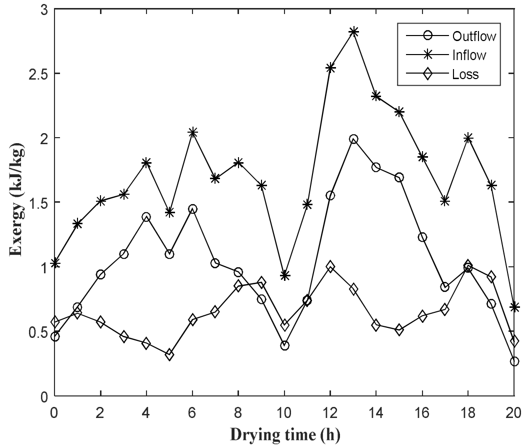
**Fig. 6. Plot of ln(MR) with drying time for different drying loads**

### 3.5 Dryer Overall Efficiency

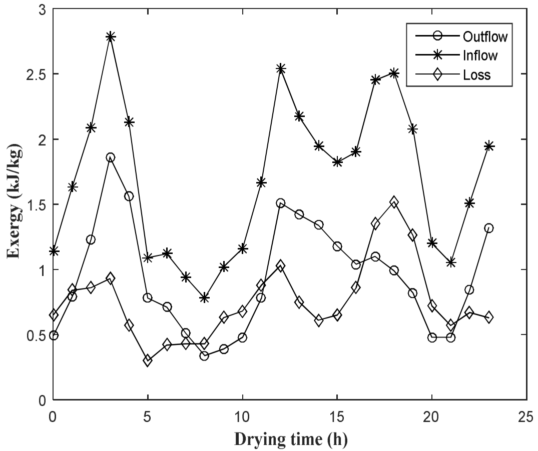
The overall efficiency of the drying is affected by several factors such as drying time, climatic conditions (solar radiation and temperature), the drying characteristics of the dried materials, and structure of the drying devices, etc. In the present research work, the efficiency of mixed mode natural convection solar dryer for three loads of 2 kg/$m^2$, 4 kg/$m^2$ and 6 kg/$m^2$ was found to be 17.33%, 30.37% and 35%, respectively. During drying process, it was observed (graph is not presented here) that higher efficiency was observed at initial stage of drying, later stage this dryer efficiency was decreased due to decrease in moisture content. Moreover, the efficiency was more at a drying load of 6 kg/$m^2$ might be due to highest drying time and more amount of moisture loss in the sample, whereas efficiency was less at 2 kg/$m^2$ might be due to less drying time and least amount of moisture loss.

**Table 2. Statistical parameters for different mathematical models for a drying load of 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$**

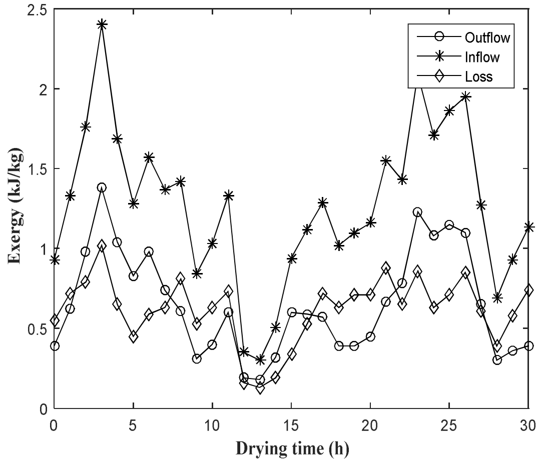
| Sl. no. | Model | Parameters | R-Square | RMSE | Reduced Chi-Square |
|---|---|---|---|---|---|
| | | **2 kg/m$^2$** | | | |
| 1 | Aghabashlo model | k1 = 0.177 ; k2 = 0.02024 | 0.9992 | 0.0078 | 6.14E-05 |
| 2 | Demir et al., | k = 0.3774; a = 0.9276;b = 0.05245; n =0.4445 | 0.9983 | 0.0117 | 1.37E-04 |
| 3 | Hii et al. | k1 = 0.41 ; k2 = 0.324 ;a = -1.511; b = 2.52 ; n =0.774 | 0.9993 | 0.0079 | 6.19E-05 |
| 4 | Logarthamic | a = 0.9276 ;b = 0.1678; c = 0.05243 | 0.9983 | 0.0114 | 1.30E-04 |
| 5 | Modified Midilli et al. | a = 0.9276; b = 0.05244; k = 0.1678 | 0.9983 | 0.0114 | 1.30E-04 |
| 6 | Modified Page III | d = 3.366; k = 0.9554; n = 1.61 | 0.9948 | 0.0201 | 4.03E-04 |
| 7 | Two term model | k1=0.1149; k2=0.3955; a=0.7318; b=0.268 | 0.9998 | 0.0045 | $2.03\times10^{-5}$ |
| 8 | Wang and Singh | a = -0.1156; b =0.003645 | 0.9641 | 0.0515 | 2.65E-03 |
| | | **4 kg/m$^2$** | | | |
| 1 | Aghabashlo model | k1 = 0.1625; k2 = 0.03138 | 0.9899 | 0.0250 | 6.25E-04 |
| 2 | Demir et al., | k= 0.1886; a = 0.8627; b = 0.06527; n =0.6984 | 0.9895 | 0.0266 | 7.10E-04 |
| 3 | Hii et al. | k1 = 0.41; k2 = 0.411; a = 64.29; b = -63.29; n= 0.67 | 0.9977 | 0.0129 | 1.66E-04 |
| 4 | Logarthamic | a = 0.8629; b = 0.1316; c = 0.06503 | 0.9895 | 0.0260 | 6.76E-04 |
| 5 | Modified Midilli et al. | a = 0.8629 ; b = 0.06504; k = 0.1316 | 0.9895 | 0.0260 | 6.76E-04 |
| 6 | Modified Page III | d = 4.277; k = 0.8996; n = 1.955 | 0.9855 | 0.0305 | 9.33E-04 |
| 7 | Two term model | k1=0.07882; k2=0.1809; a=0.399; b=0.6102 | 0.9995 | 0.0065 | $4.17\times10^{-5}$ |
| 8 | Wang and Singh | a = -0.09613; b = 0.002596 | 0.9270 | 0.0670 | 4.49E-03 |
| | | **6 kg/m$^2$** | | | |
| 1 | Aghabashlo model | k1 =0.1439; k2 = 0.02712 | 0.9952 | 0.0169 | 2.86E-04 |
| 2 | Demir et al. | k = 0.195; a = 0.8656; b = 0.07111; n =0.6207 | 0.9942 | 0.0192 | 3.67E-04 |
| 3 | Hii et al. | k1 =0.168; k2= 0.17; a = 44.22; b = -43.07; n = 0.60 | 0.9849 | 0.0316 | 1.00E-03 |
| 4 | Logarithmic | a=0.1059; b=0.9844; c=0.03603 | 0.9994 | 0.0069 | $4.78\times10^{-5}$ |
| 5 | Modified Midilli et al. | a = 0.8656 ; b = 0.07111;k = 0.121 | 0.9942 | 0.0188 | 3.54E-04 |
| 6 | Modified Page III | d =4.702; k = 0.8963; n = 2.074 | 0.9863 | 0.0290 | 8.44E-04 |
| 7 | Two term model | a = 0.7242; b = 0.2629; k1 = 0.07692; k2 = 0.4442 | 0.9987 | 0.0091 | 8.23E-05 |
| 8 | Wang and Singh | a = -0.08066; b =0.001768 | 0.9187 | 0.0694 | 4.82E-03 |



**a) 2 kg/m$^2$**



**b) 4 kg/m$^2$**



**c) 6 kg/m$^2$**

**Fig. 7. Comparison of exergy inflow, outflow and loss with drying time for different drying loads: a) 2 kg/m$^2$, b) 4 kg/m$^2$ and c) 6 kg/m$^2$**

### 3.6 Energetic and Exergetic Analysis

The energy analysis for drying of tomato was performed by using data obtained from the mixed mode natural convection solar dryer. The energy utilization in the drying chamber was calculated using Eq. [14]. The EUR was defined as the ratio of the energy utilization to the energy given from the solar collector. Net heat of collector ($Q_c$) was found to be as 3.42 kJ/s, 3.40 kJ/s and 2.94 kJ/s for a load of 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$, respectively whereas maximum net heat of drying chamber ($Q_{da}$) was observed to be 0.83 kJ/s, 1.40 kJ/s and 1.71 kJ/s for a load of 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$, respectively. The EUR for different loading rates was found to be 24.21%, 41% and 58.03%, respectively showing that energy utilization ratio increased with increased loading rates.

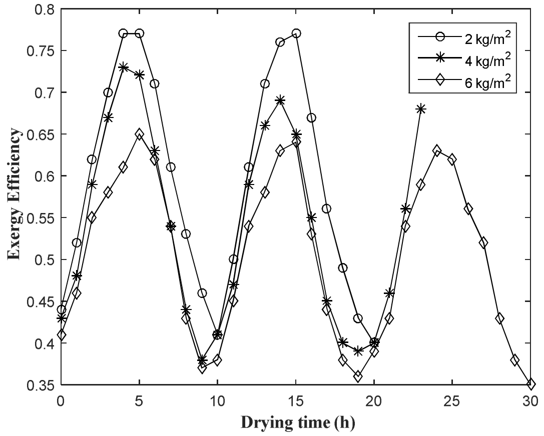


**Fig. 8. Comparison of exergy efficiency with drying time for different drying loads**

Fig. 7(a) shows that maximum exergy outflow on the first day of 9 h was found to be 1.45, 1.86 and 1.38 kJ/kg for a load of 2, 4 and 6kg/m$^2$ respectively. Fig. 7(b) represents the maximum exergy inflow on the first day of 9 h was found to be 2.04, 2.79 and 2.4 kJ/kgfor a load of 2, 4 and 6kg/m$^2$respectively. It is concluded that for the first day exergy inflow, exergy outflow and exergy loss in the drying chamber increased during the first three hours and after that showed a decaying behaviour during evening hours. A variation of the exergy inflow was due to changes in the solar radiation. During the operation, performed on the second day, the time variation of the exergy inflow was similar. In particular, an increasing pattern was observed during the first 4 hours and again a decaying pattern was observed after such interval. The exergetic efficiencies against drying time for the different loads are presented in Fig. 8. Exergetic efficiency for a load of 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$ was found to be 59%, 54% and 50%, respectively.

## 4. CONCLUSIONS

The drying characteristics of the tomato slices were studied in a fabricated mixed mode natural convection solar dryer for the different loads with eight mathematical models to fit the experimental data. The results indicate that the Two-term model was best to fit the drying data for the load of 2 kg/m$^2$ and 4 kg/m$^2$ whereas Logarithmic model for 6 kg/m$^2$. The drying process took place in falling rate period. The moisture diffusivity ranges from $1.14\times10^{-10}$ m$^2$/s to $7.94\times10^{-11}$ m$^2$/s. The drying rate gradually decreased with increased tray load. It was observed that the exergetic efficiency decreased with increased in tray load and moreover, Energy utilization ratio increased with increased in tray load. The efficiency of the mixed mode natural convection solar dryer for a load of 2 kg/m$^2$, 4 kg/m$^2$ and 6 kg/m$^2$ was observed to be 17.33%, 30.37% and 35%, respectively.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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