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Influence of Temperature on Drying Kinetics of *Aloe vera* and Its Mathematical Modeling

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

The drying characteristics and the effect of drying air temperature on hot air drying of *aloe vera* (*Aloe barbadensis Miller*) were investigated at 50, 60, 70 and 80°C. Five thin layer drying mathematical models (*viz.* Logarithmic, Newton, Henderson–Pabis, Page and Modified Page) were fit into the experimental moisture ratio for the kinetic study of *aloe vera*. Fick's diffusional model and Arrhenius type of relationship were used to calculate the moisture diffusivity and activation energy respectively. The diffusivity coefficient increased from 1.03 x 10^{-09} to 1.55 x 10^{-09} m^2 s^{-1} with the increase in temperature from 50 to 80°C with estimated activation energy and Arrhenius factor of 19.83 kJ mol^{-1} and 1.98 x 10^{-07} respectively. Henderson-Pabis model provided the best fit data and can be epitomized as an excellent tool for accessing the drying kinetics of *Aloe vera*.

Keywords: Convective drying; Moisture diffusivity; Activation energy; Mathematical modeling.

1. INTRODUCTION

Aloe vera (*Aloe barbadensis* Miller), largely used in the food and cosmetic industry, is a semi-tropical perennial plant. The etymology of 'Aloe' comes from "alloeh (k)" (Arabic) or "allal" (Hebrew) or "alsos" (Greek); which means 'bitter' [1,2]; "vera" means 'truly veritable'. There are

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about 400 different species found under the genus '*Aloe*' among which *Aloe barbadensis* Miller is the most biologically active one and is being used extensively [3].

Aloe vera gel, due to its antioxidant property, is being widely used in cosmetic and toiletry industry, where it acts as a base ingredient for the preparation of lotions, creams, shampoos, soaps and facial cleaners [4,5]. Nowadays, *aloe vera* is also being promoted as a food and pharmaceutical product due to its anti-inflammatory, anti-allergic, antibacterial and healing properties [6,7,8]. Aloe gel is a very good source of carbohydrate, protein, fiber, vitamin C and vitamin E etc. Health drinks, juices, yogurts, marmalades, biscuits of *aloe vera* are now commercially available and are on increasing demand. However, aloe products are vulnerable to spoilage because of its high water activity. Unfortunately, due to the unavailability of proper processing techniques, many of these products spoil even before reaching the consumers causing a huge loss to the cultivator and processor. Thus it has become vital to develop better methods of preservation for enhancing the shelf life while maintaining the quality. The same can be achieved by drying, dehydration and different other thermal treatments.

Drying is one of the best methods for preserving the food materials for longer duration. It increases the shelf life by decreasing the water activity in the product which inhibits the growth of microorganisms and ultimately decreases the spoilage reaction. Another important advantage of the dried product is the reduction in the cost of packaging, storage and transportation due to their comparatively smaller volume and mass [9]. However, the main constraint during drying of *aloe vera* is retention of its antioxidant and other temperature sensitive nutrients while reducing the moisture content to a safer level in order to prevent spoilage.

The drying kinetics of food is a complex phenomenon to be monitored. Thus, it requires simple representations for predicting the overall drying behavior and optimizing the drying parameters. Studies had been carried out on drying kinetics of fruits and vegetables by [10,11,12,13,14,15,16].

Mathematical modeling and simulation are regularly used to study the process of drying, to endorse mechanisms and to optimize the operating parameters and conditions. The main objective to recommend a mathematical model is to simulate the drying curves and assess the effect of air-drying temperature on physical, biochemical and functional properties exhibited by the dehydrated products. A well understood mathematical modeling for any drying process helps in preventing product deterioration, excessive energy consumption, equipment stress and a decrease in product yield [17]. Numerous empirical equations are there to simulate the drying process and are useful in modeling the drying kinetics as well as in designing of different drying systems [18]. The mathematical models generally demonstrate a direct relationship between the moisture content and drying time; and also strongly obey Fick's second law for diffusion model [19]. This experiment was carried out to study drying characteristics of *aloe vera* slabs and different thin layer mathematical models were fit to describe the drying process.

2. MATERIALS AND METHODS

2.1 Collection and preparation of the sample

Fresh, healthy and matured *aloe vera* leaves were obtained from Instructional Herbal Garden, IGKV, Raipur. The procured *aloe vera* leaves were washed under tap water to remove the foreign materials and dirt sticking to it. The spikes and the thick dark green outer skin (epidermis) were peeled out manually from the thick colorless parenchyma (or gel fillet) using a stainless steel knife. The fillets were cut into 50 × 30 × 10 mm slabs with the help of stainless steel cutter and stored in an airtight container, till the experiment was started, to avoid moisture loss and contamination.

2.2 Experimental set-up

A laboratory model convective tray dryer was used for drying experiment. The temperature of the drying chamber was pre-set through a temperature indicator cum controller provided on the control panel of the dryer. The dryer was first switched on and left till the preset temperature is attained, then the sample was kept inside.

The *aloe vera* samples were dried in a laboratory tray dryer at 50, 60, 70 and 80°C drying air temperatures. The drying process is ceased when no weight reduction is observed. Data were recorded at an interval of 1 h until completion of the experiment which was later used to analyze the moisture movement characteristics viz. moisture ratio, drying rate, moisture diffusivity and activation energy etc.

2.3 Equilibrium moisture content

Based on the author's best knowledge, very little information is available on the equilibrium moisture content (EMC) of air-dried *aloe vera* gel samples, at the air temperature range of 50 to 80°C, in any literature. Therefore a separate set of experiments on convective drying was conducted to determine the EMC values by dynamic method [20]. The EMC values were determined by drying the *aloe vera* fillets for 24 hours in the convective dryer at all temperature as mentioned above.

2.4 Drying characteristics

The drying behavior of the fresh cut *aloe vera* slabs was investigated. The variation in moisture content of *aloe vera* slabs with drying time, drying rate and effective moisture diffusivities were calculated and presented in subsequent sections.

2.4.1 Drying rate

The drying rate of aloe leaves was calculated using the following equation [12].

$$\frac{\mathrm{dM}}{\mathrm{dt}}=\frac{\mathrm{M_t}-\mathrm{M_{(t+\Delta t)}}}{\Delta \mathrm{t}} \qquad (1)$$

Where,

M_t -moisture content at t (g water/ g dry matter)
$M_{t+\Delta t}$ -moisture content at t+Δt (g water/ g dry matter)
t - time (min).

2.4.2 Moisture ratio

The moisture ratio (MR) at each moisture content level was determined by the following equation.

$$MR=\frac{\mathrm{M_t}-\mathrm{M_e}}{\mathrm{M_i}-\mathrm{M_e}} \qquad (2)$$

Where,

MR - Moisture ratio
MC - Moisture content at any time (d.b.)
MC_i - Initial moisture content (d.b.)
MC_f - Equilibrium moisture content (d.b.)

2.5 Modeling of convective drying of *aloe vera*

To determine the kinetics of drying, the moisture ratio data of *aloe vera* sample dried at different temperature were fitted to five thin layer drying models as given in Table 1. The constants (*viz.* k, a, n etc.) were calculated using Microsoft Excel Solver tool.

2.6 Moisture diffusivity and activation energy

During drying, moisture diffusivity is the principle phenomena that results in weight reduction decreasing the product's water activity. Since here, the drying occurred in falling rate period; the moisture transfer is mainly by molecular diffusion which is influenced by temperature, air velocity, shrinkage, case hardening and initial moisture content of the product. Conventionally, Fick's second diffusion model is used to estimate the moisture diffusivity of any product with assumptions like negligible shrinkage, constant diffusion rate and moisture migration is through diffusion only [21]. For infinite slab (*aloe vera* slabs were assumed as an infinite slab), the mathematical model of Fick's law is given by:

$$\mathrm{MR}=\frac{\mathrm{M_t}-\mathrm{M_e}}{\mathrm{M_i}-\mathrm{M_e}}=\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left[\frac{-(2n+1)^2\pi^2 D_{eff}}{4H^2}t\right] \qquad (3)$$

Table 1. Mathematical models used for drying study

Model equation	Name	Reference
MR = exp (-kt)	Exponential	Liu and Bakker-Arkema [43]
MR = a + b ln(t)	Logarithmic	Chandra and Singh [44]
MR = a exp (-kt)	Henderson and Pabis	Henderson and Pabis [45]
MR = exp (-kt^n)	Page	Zhang and Litchfield [46]
MR = exp (-kt)^n	Modified page	Overhult et al. [47]

However, for long drying periods, Eq. 3 can be further simplified to only the first term of the series.

$$ln\frac{M-M_e}{M_i-M_e} = ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4H^2} \quad (4)$$

Where,

MR - Moisture ratio (Dimensionless)
M_t - Moisture content at any time (d.b.)
M_i- Initial moisture content (d.b.)
M_e- Equilibrium moisture content (d.b.)
D_{eff}- Effective diffusivity (m^2/s)
H - Half thickness of slab in sample (m)
n- Positive integer
t- Time (sec)

A general form of Eq. 4 could be written in general semi-logarithmic form as follows [22].

$$\ln MR = A + Bt \quad (5)$$

The effective diffusivity can be calculated graphically (ln MR versus t) with slope B

$$slope = \frac{\pi^2 D_{eff}}{4H^2} \quad (6)$$

The activation energy of *aloe vera* during convective drying has been estimated from the Arrhenius type of relationship as given below:

$$D_{eff} = D_o \exp\left(\frac{-E_a}{RT_{abs}}\right) \quad (7)$$

Where,

D_{eff} - Effective diffusion coefficient, m^2/s
D_o-Constant equivalent to effective diffusion coefficient at infinite temperature, m^2/s
E_a- Activation energy, kJ/mol
R - Universal gas constant, 8.314 kJ/mol K
T_{abs}-Absolute temperature, K

2.7 Statistical analysis

For selecting the best fit model, coefficient of determination (R^2) was the main criteria, whereas the goodness of fit was also determined by various statistical parameters like reduced mean square of the deviation i.e. chi-square (χ^2) and root mean square error (RMSE). For quality fit, the R^2 value should be higher and closer to one; however, χ^2 and RMSE values should be lower approaching zero [10,23,24,25]. The above parameters were calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp} - MR_{pre}\right)^2}{N-Z} \quad (8)$$

$$E_{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre} - MR_{\exp}\right)^2\right]^{1/2} \quad (9)$$

Where,

MR_{exp}– experimental moisture ratio
MR_{pre}– predicted moisture ratio
N – Number of observations and
Z – Number of drying constants.

3. RESULTS AND DISCUSSION

3.1 Variation in moisture content with time

Aloe vera is dried from initial moisture content of 7042.85 per cent (d.b.) to the final moisture content of 15.20, 14.81, 13.55 and 12.06 per cent for the temperature of 50, 60, 70 and 80°C respectively. It has been observed from Fig 1 and 2 that the convective drying of *aloe vera* gel slabs followed a typical trend. The entire drying process occurred during the falling rate period [26] and no constant rate period was found. The drying curve exhibited steeper slope with an increase in drying air temperature. This indicates that the drying rate increased with an increase in drying air temperature, resulting in a substantial decrease in the drying time; which is a well-established fact for drying of biological materials. Similar behavior was observed by Vergara, et al. [27] for osmotically dehydrated apple, Maskan and Gogus [28] for mulberry, Pokharkar [29] for pineapple, Jain [30] for papaya and Pisalkar et al. [22] for *aloe vera*.

3.2 Effective moisture diffusivity

The natural logarithms of moisture ratio (ln MR) were plotted against average drying time (t) for different drying air temperatures, and are shown in Fig. 3. It was observed from the figure that the relationship is non-linear in nature. This non-linearity in the relationship might be due to reasons like shrinkage in the product, variation in moisture diffusivity with moisture content and change in product temperature during drying [31,32].

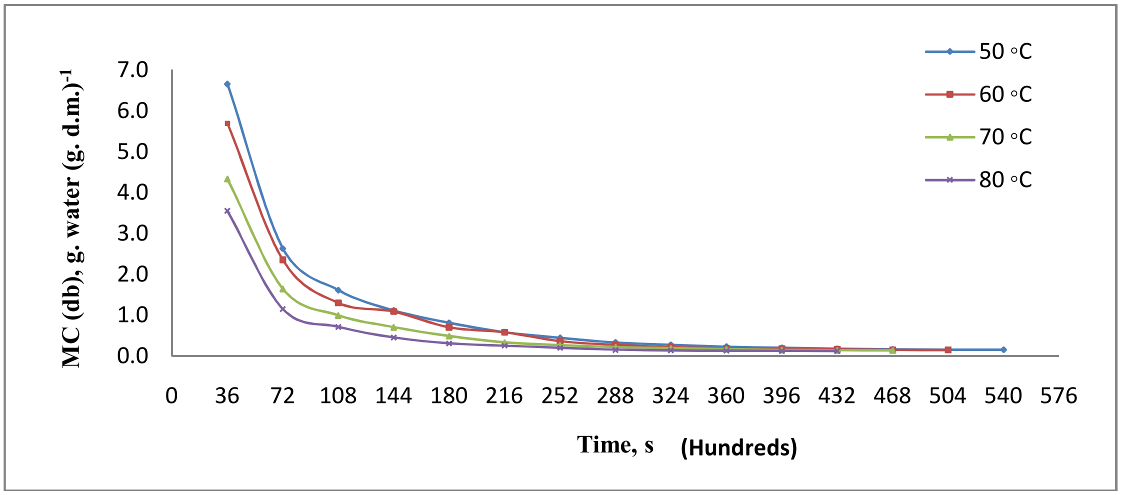

Fig. 1. Variation in moisture content with drying time for different temperatures

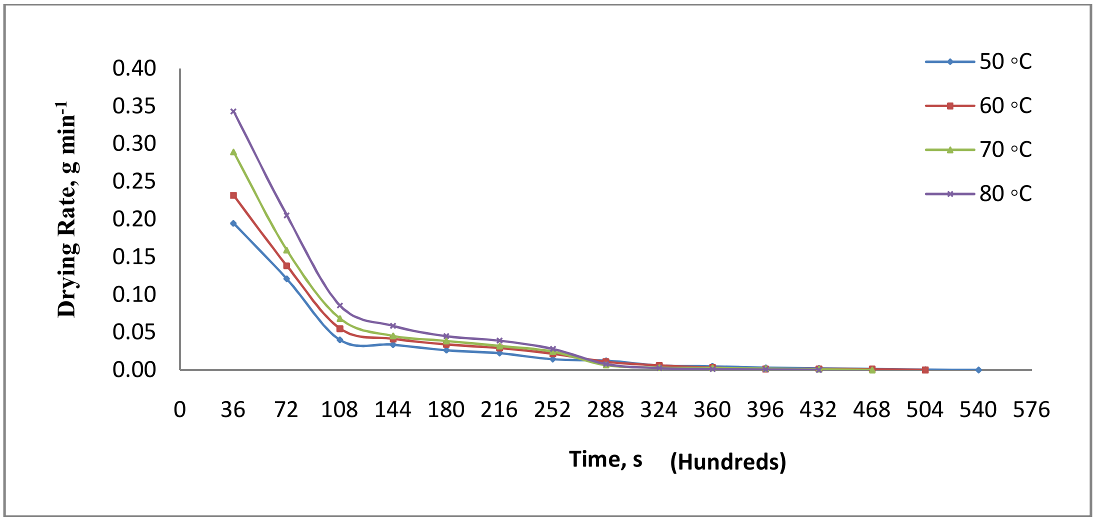

Fig. 2. Variation in drying rate with drying time for different drying temperatures

The effective diffusivity coefficient of samples dried at 50, 60, 70 and 80°C is observed to be 1.03 x 10^{-09}, 1.10 x 10^{-09}, 1.27 x 10^{-09} and 1.55 x 10^{-09} m^2 s^{-1} respectively. It is evident that D_{eff} values increased with increase in drying temperature. It has been reported by Prabhanjan et al. [33] that the higher temperature provides a larger water vapor pressure deficit, which is one of the driving forces for the outward moisture diffusion process. Several authors have also shown a similar behavior of D_{eff} when working with apricots [10]; okra [12]; *aloe vera* [34] and kale [35].

However, with a decrease in moisture content, the D_{eff} value increased. Ironically it has also been observed that the D_{eff} started decreasing as the moisture content decreased further below at the end of drying. This might be attributed to the loss of moisture which resulted in collapsing and overlapping of the cell structure thus reducing porosity and diffusion. Similar results were found by Khodke [36] for drying of potato cubes. McMinn and Magee [37] also reported that the variation of effective moisture diffusivity with moisture content is a complex function, dependant on the variation of physical parameters, i.e. porosity and density during the process and interaction of the food components like starch, cellulose or protein with water.

3.3 Activation energy

The temperature dependence of average effective moisture diffusivity $(D_{eff})_{avg}$ during convective drying can be expressed as Arrhenius type relationship (Fig. 4). The Activation energy and Arrhenius factor were found to be 19.83 kJ mol^{-1} and 1.98 x 10^{-07} respectively. It is implied from the figure that moisture diffusivity of *aloe vera* sample decreased linearly with increase in $1/T_{abs}$.

These results for the activation energy agree with those obtained by other researchers, for example; 13.9–30.5 kJ mol^{-1} in gelatinized starches [38]; 12.30 and 39.47 kJ mol^{-1} in potatoes and beans, respectively [39]; 36.11 kJ mol^{-1} for kale [35]; 51.26 kJ mol^{-1} [12] for okra; 82.93 kJ mol^{-1} [40] for mint, 30.37 kJ mol^{-1} and 24.4 kJ mol^{-1} for fresh *aloe vera* [34,41] respectively.

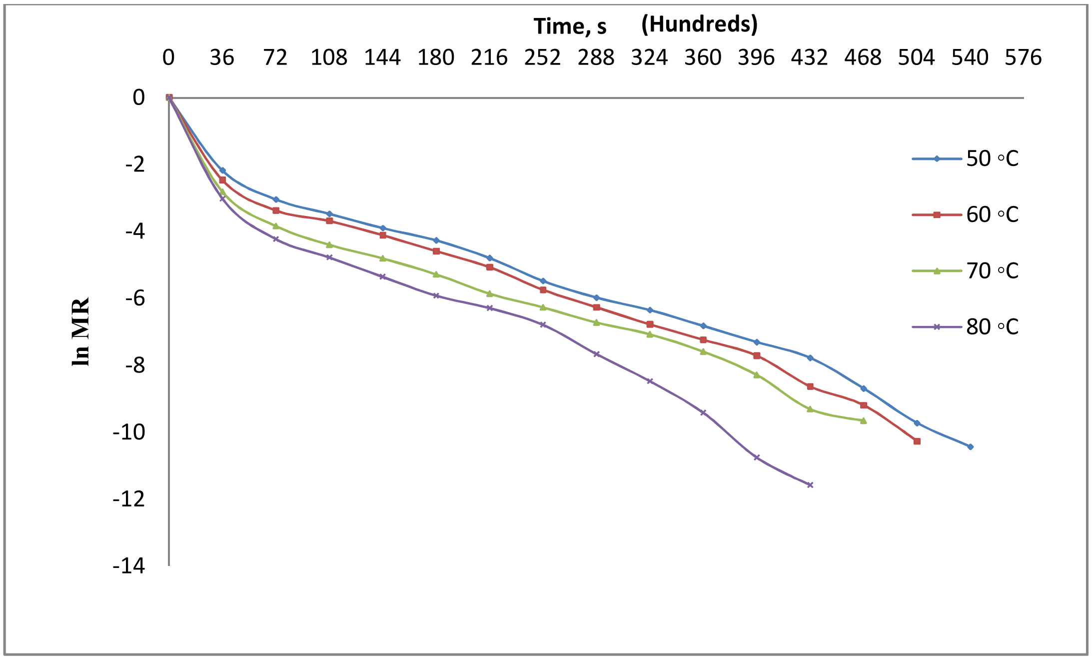

Fig. 3. Variation in ln (MR) versus time for convective drying *aloe vera* samples

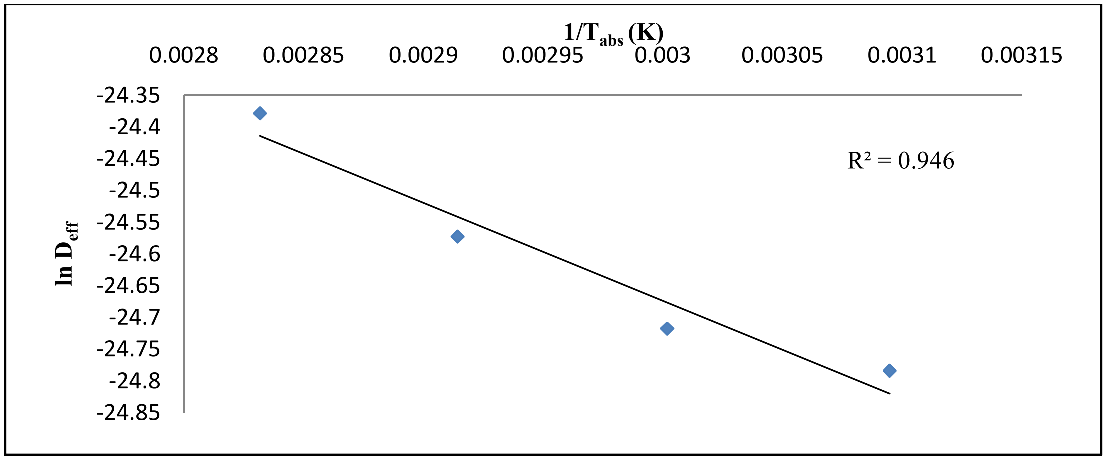

Fig. 4. Relationship between moisture diffusivity with reciprocal of absolute temperature

Table 2. Values for model constants and statistical parameters used in convective drying of *aloe vera* sample

Name of model	Air temp.	Drying constant				Statistical parameters		
		k	n	a	b	R^2	χ^2	E_{RMS}
Exponential	50	0.0002204	-	-	-	0.994	0.0009	0.030
	60	0.0002360	-	-	-	0.982	0.0026	0.050
	70	0.0002798	-	-	-	0.988	0.0016	0.039
	80	0.0003305	-	-	-	0.995	0.0010	0.022
Henderson and Pabis	50	0.005	-	1.004	-	0.994	0.0010	0.030
	60	0.008	-	1.055	-	0.986	0.0022	0.044
	70	0.011	-	1.057	-	0.992	0.0013	0.034
	80	0.020	-	1.029	-	0.996	0.0005	0.021
Page	50	0.005	1.032	-	-	0.883	0.0012	0.034
	60	0.004	1.184	-	-	0.976	0.0040	0.060
	70	0.004	1.223	-	-	0.986	0.0005	0.021
	80	0.012	1.162	-	-	0.989	0.0014	0.035
Modified page	50	0.006	1.032	-	-	0.983	0.0020	0.028
	60	0.009	1.184	-	-	0.976	0.0097	0.094
	70	0.012	1.223	-	-	0.986	0.0101	0.095
	80	0.022	1.162	-	-	0.989	0.0312	0.165
Logarithmic	50	-	-	1.610	-0.244	0.945	0.0187	0.133
	60	-	-	1.663	-0.272	0.927	0.0317	0.170
	70	-	-	1.632	-0.280	0.947	0.0297	0.163
	80	-	-	2.594	-0.544	0.820	0.0964	0.289

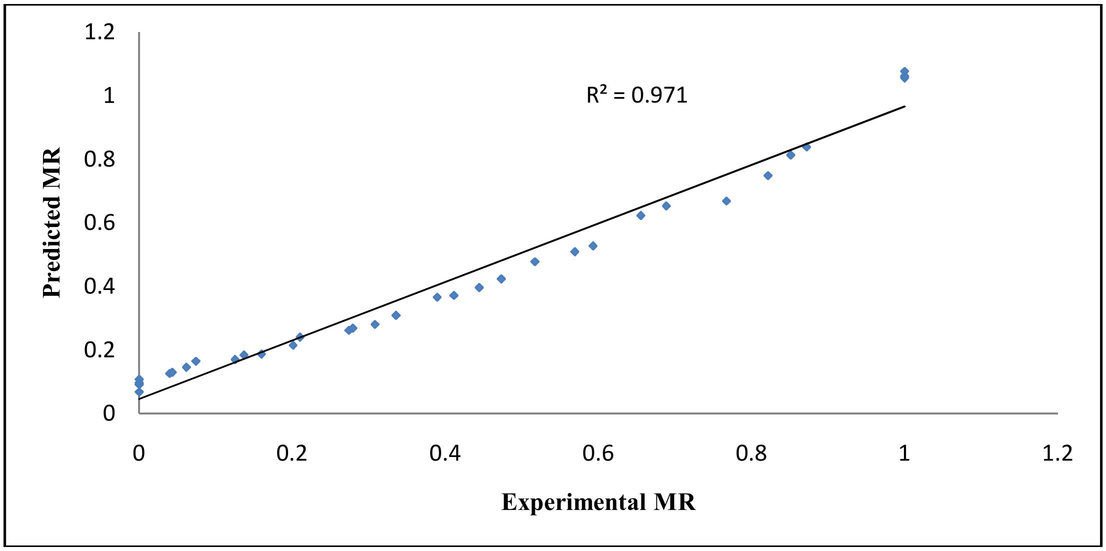

Fig. 5. Experimental and predicted values of moisture ratio by Henderson and Pabis model at various temperatures

3.4 Modeling of drying curve

Table 2 showed the constant values of different models calculated using Microsoft Excel Solver Tool. It also depicted overall statistical parameters for the models. Henderson and Pabis model showed the highest values of coefficient of determination (R^2) and the lowest values for root mean square error (RMSE) and reduced mean square of the deviation (χ^2) making it the most satisfactory among the models to represent the thin-layer drying of *aloe vera* samples. This was another confirmation of the suitability of Henderson and Pabis model to thin layer drying of high moisture products. The same has been reported by Jain [30] for air drying of papaya and Koua et al. [42] for thin layer solar drying of mango, banana and cassava etc.

The best fit model (Henderson and Pabis model) for convective drying studies was validated by comparing the predicted and observed values of moisture ratio in all drying experiment. The predicted and observed values of moisture ratio were plotted as shown in Fig. 5.

4. CONCLUSION

It can be observed that as the drying temperature increased from 50-80°C; the drying time reduced from 54,000 s to 43,200 s. Henderson-Pebis model was found to be the best fit model when fitted with the experimental moisture ratio with the regression coefficient of 0.992 and least χ^2 and RMSE value of 0.0012 and 0.032 respectively.

The mathematical model for air drying based on the Fick's law of diffusion was found quite adequate to predict the mass transport data during the drying process. The effective diffusivity coefficient of samples dried at 50-80°C varied within a range of 1.03×10^{-09} – 1.55×10^{-09} m^2 s^{-1}. It is observed that moisture diffusivity values increased with drying air temperature. The activation energy and Arrhenius factor was found to be 19.83 kJ mol^{-1} and 1.98×10^{-07} respectively.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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