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Drying Kinetics and Modelling of Mass Transfer in Thin Layer Convective Drying of Pineapple

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Authors' contributions

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

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ABSTRACT

The aim of the investigation was to study the drying characteristics of pineapple at different temperatures of 55, 60, 65, 70 and 75℃ with 1.5 m/ s constant air velocity. In the present study, the best drying model was selected to describe the drying behaviour, and to develop the moisture profile using COMSOL. Based on the best criteria, Verma et al. was chosen as the best fit to the experimental data. The predicted moisture ratio values obtained from COMSOL simulation and Verma et al. were good agreement with the experimental data.

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Keywords: Drying; mass transfer; moisture profile; mathematical modelling.

1. INTRODUCTION

Drying is one of the oldest processes in which heat and mass transfer takes place simultaneously. Dried product can be affected by many drying internal parameters which include moisture content, thermophysico properties and external parameters which include hot air temperature, relative humidity, air velocity etc [1]. Most of the drying models have been proposed by several authors to study the drying characteristic of the different fruits and vegetables. In convective air drying, temperature and moisture play a significant role for final assessment of the product, but the temperature can be ignored within the material due to small value of Biot number. For example, in spray drying of liquid droplet, practically difficult to measure the temperature distribution within the droplet, but theoretically it cannot be ignored [2]. In mass transport during processing, different mechanisms (Knudsen diffusion, molecular diffusion, liquid diffusion, vapour diffusion, and capillary flow) have been studied to predict the moisture distribution with in material. There are different CFD software packages to predict the physical mechanism that happening during processing and inside the material.

Pineapple (*Ananas comosus*) is one of the non citrus tropical and subtropical fruit, and is a seasonal and perishable fruit (due to higher moisture content), so that it is necessary to dehydrate without changing its nutritional and sensory characteristics to use in off season. Among all the dryers, tray dryer is the most commonly used for drying of fruits and vegetables, but using high air temperature and longer drying time may lead to decrease in nutritive values and sensory characteristics. Dying process for agricultural material is mainly divided into two ways: thin layer and deep bed layer drying. Thin-layer drying is the best method for the mathematical modelling and simulation of food drying process [3].

Thin layer drying models are useful to study the drying behaviour of any food material. Simulating models are reliable and successfully applied to drying or any other processing to study the well pattern of the temperature and moisture profile, to modify the any existing equipment, to design any new equipment to attain the better quality of the product and enhance the processing efficiency [4]. Now a day's energy is a very important cost factor in food processing industry so that it is big challenging task to any food industry to save the energy. Therefore, it is required to reduce the energy consumption and provide optimum processing conditions for obtaining good quality product. The objective of the present research work was to select the suitable model to describe the thin layer drying of pineapple at various drying air temperatures, and to develop the moisture profile various at different drying times at different drying temperatures using COMSOL multiphysics.

2. METHODOLOGY

2.1 Drying Procedure

In the present investigation, pineapple (*Ananas comosus*) was chosen for the drying Prior to drying, the pineapple pointed ends were trimmed, peeled off, sliced into 10 mm thick. The samples (100 g) were uniformly spread onto the cleaned rectangular aluminium perforated trays and trays were kept in the hot air batch dryer as shown in Fig. 1. The drying was performed at different air temperatures of 55, 60, 65, 70 and 75℃ with constant air velocity of 1.5 m/s. Prior to start the experiment, the dryer was preheated for approximately one hour to ensure equilibrium conditions with set temperatures and air velocity for each run. During the drying process, moisture loss was recorded in every 10 min of intervals up to first 1 h, later every 30 min of intervals up to 2 h followed by 1 h intervals by a digital balance of ±0.001 g accuracy (Testing Instrument Pvt. Ltd., India) till a constant weight was achieved. The experiment was stopped when the moisture content approached to 6-7% (w.b.) from an initial value of 85.85±1.19% (w.b.). The drying process was carried out for all runs with three replications and the average values were taken.

3. MATHEMATICAL MODELLING

In the present work, the experimental data of moisture ratio (MR) and drying time (t) were fitted to different empirical drying models as shown in Table 1. Mathematical modelling of thin layer drying is a useful tool to predict and simulate the drying behaviour, and contributing to better understanding of the drying mechanism. The

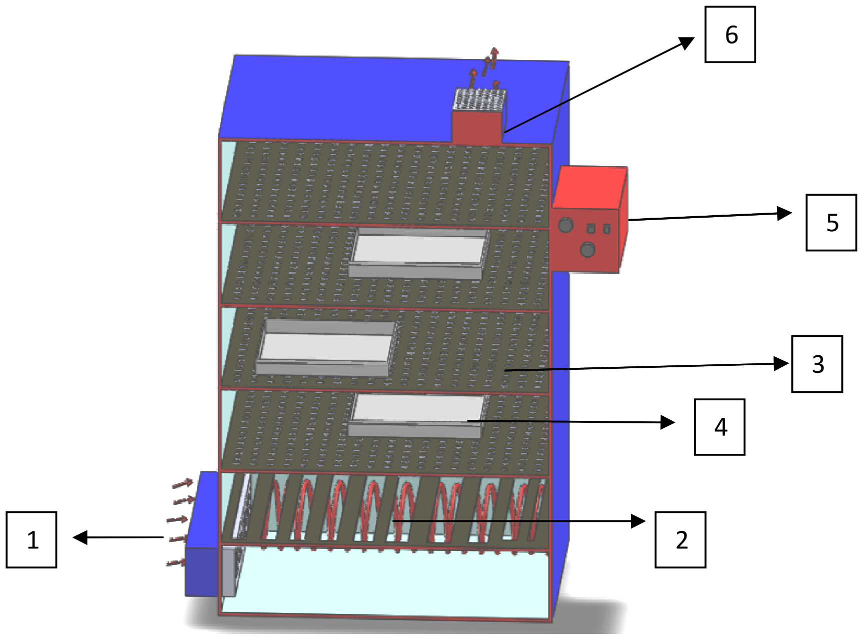


Fig. 1. Tray dryer

1) Inlet air 2) Air heater 3) Tray 4) Sample Tray 5) PID Controller 6) Exit air

non linear regression analysis was carried out by using curve fitting tool in MATLAB software package (R2015a (8.5.0.197613)) to ascertain the drying rate constants and coefficients of the model equations, and to select the best fit model. Comparison criteria were used to evaluate the goodness of fit for the selected empirical models based on lower Root mean square error (RMSE), reduced chi-square χ^2 and higher coefficient of determination R^2. The same criteria have been used by several authors to select the best models for drying of different biological materials [3-7]. The different following statistical equations were used to describe the goodness of fit of the dried pineapple slices:

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

$$RMSE = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pred,i} - MR_{exp,i}\right)\right]} \tag{2}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pred,i}\right)^2}{N - n} \tag{3}$$

Where MR_{expt}, and MR_{pred} are the i^{th} experimental MR and i^{th} predicted MR, N is the number of observations, and n is the number of model constants.

3.1 Modelling of Heat and Mass Transfer

The governing equation for the heat and moisture transport within the pineapple slice is given by following governing equation:

$$\frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = 0 \quad (4)$$

$$\frac{\partial M}{\partial t} + \nabla.(-D\nabla M) = 0 \quad (5)$$

Where k is the thermal conductivity (W/(m.K)), M is the moisture content (kg of water/kg of dry matter), D is the moisture diffusivity (m^2/s), t is the time (s). Heat and mass transfer was coupled in COMSOL even though there was no much effect of heat transfer on mass transfer. The mathematical analysis for moisture transfer, the pineapple slice was considered as rectangular slab. Initial moisture content of the sample is uniformly distributed throughout the product. No shrinkage is considered. Diffusion coefficient is assumed as constant and homogeneous throughout the drying period. Thermal gradient in the sample on the mass transfer was not considered due to the very thin slab. In this paper, 2D axi-symmetric geometry and quarter of the sample was considered. The mass transfer was taken into account only top and side surfaces. It is assumed that there is no mass transfer at the bottom so that bottom surface was insulated.

Based on the selected assumptions, the following initial and boundary conditions are applied for heat and mass transfer:

$$t=0 \qquad T(r,z) = T_0 \qquad M(r,z) = M_0 \quad (6)$$

At the line of symmetry

$$r = 0 \qquad \frac{\partial T}{\partial r} = 0 \qquad \frac{\partial M}{\partial r} = 0 \quad (7)$$

At the top and side surfaces, convective heat transfer coefficient with heat loss due to evaporation and water vapour leaves due to concentration gradient between the product and bulk air were considered with the following boundary conditions:

$$n.k\,\nabla T = h(T_a - T) + D\lambda\rho\frac{\partial M}{\partial n} \quad (8)$$

$$n.D\,\nabla M = k_c(M_e - M) \quad (9)$$

Where h is the convective heat transfer coefficient in W/(m^2.K), D is the moisture diffusivity in m^2/s, λ is the latent heat vapourization in J/kg, ρ is the density in kg/m^3, k_c is the convective mass transfer coefficient in m/s, Mis the moisture content at any time t in dry basis and M_b is the equilibrium moisture concentration in dry basis. In this paper, moisture concentration is expressed in kg/m^3.

The convective heat transfer coefficient h on W/m^2.K was calculated with the following empirical formula [8]:

$$Nu = 0.664(Re)^{0.5}(Pr)^{0.33} \quad (10)$$

Where Nu is the Nusselt number, Re is the Reynolds number and Pr is the Prandtl number. At the top of product is contact with hot air inside the dryer and mass flux is calculated with following equation [8]:

$$m_w = \frac{k_c M_w}{R}\left(\frac{P}{T} - \frac{P_\infty}{T_\infty}\right) \quad (11)$$

Where P_∞, T_∞ are the vapour pressure of the water and ambient temperature of the air, R is the gas constant and convective mass transfer coefficient (k_c) is obtained by using the Chilton-Colburn analogy [8].

$$k_c = \frac{h}{\rho_\infty Cp_\infty Le^{2/3}} \quad (12)$$

Where h is the convective heat transfer coefficient in W/m^2.K, ρ_∞ and Cp_∞ are the density in kg/m^3 and specific heat in J/kg.K, respectively and Le is Lewis number. Model parameters for the simulation is presented in Table 3.

Table 1. Empirical models applied to drying kinetics

Sl. No	Model	Expression	References
1	Henderson and Pebis	a exp(-kt)	[11]
2	Midilli et al.	a exp(-kt^n) + bt	[12]
3	Wang and Singh	1+at+bt^2	[13]
4	Silva et al.	exp(-at-b sqrt(t))	[14]
5	Verma et al.	a exp(-kt) + (1-a) exp(-gt)	[15]

3.1.1 Model setting

Finite element method was used to solve the non linear partial differential equation in COMSOL 4.4 software. Two dimensional axi-symmetry geometry was specified with the dimensions of 10 mm×5 mm. Triangular mesh was created. Mesh quality is very important in order to improve the accuracy of the model results so that mesh was refined at the top and side surfaces where maximum mass transfer occurs. The mesh grid contains for all the simulations the triangular elements, edge elements, vertex elements, average elements quality, mesh area, maximum growth rate were: 2485, 247, 7, 0.9453, 50 mm^2 and 2.309, respectively. The initial values were taken from the experiments. The maximum element size at the top and side surfaces was 0.1 mm for all the simulations. The relative tolerance was chosen at 10^{-3}. The process was simulated for the total drying time of 720 min, 600 min, 480 min, 420 min and 360 min at their respective moisture diffusivities. Volume average of the product was considered for the computation of moisture ratio. The simulation was developed using a HP computer with 4 GB RAM, 2.54 GHz processor.

4. RESULTS AND DISCUSSION

The initial moisture content of pineapple slice was found to be (85.85±1.19 w.b.). The drying process was carried out from initial moisture content to final moisture contents of less than 7 kg water/kg dry matter in convective hot air dryer by using different air temperatures of 55, 60, 65, 70 and 75℃ with constant air velocity 1.5 m/s. All these drying temperatures had a significant effect on drying kinetics of pineapple slices. It is clearly evident from the Fig. 2, moisture content was reduced exponentially as the drying time progresses at all the drying air temperature. Similarly, as drying air temperature increases drying time decreases. Continuous decrease in moisture ratio indicates that diffusion has governed the internal mass transfer.

It was observed that the drying rate increases with increase in drying air temperature due to higher temperature gradient between samples and drying air and similarly drying rate decreased with decrease in moisture content as shown in Fig. 3. Furthermore, the drying process was occurred in falling rate period, as there is no constant drying rate period in drying of pineapple slices at all drying conditions, indicating that diffusion had governed the internal mass transfer. These obtained results are in good agreement with several authors for fruits and vegetables [9,10].

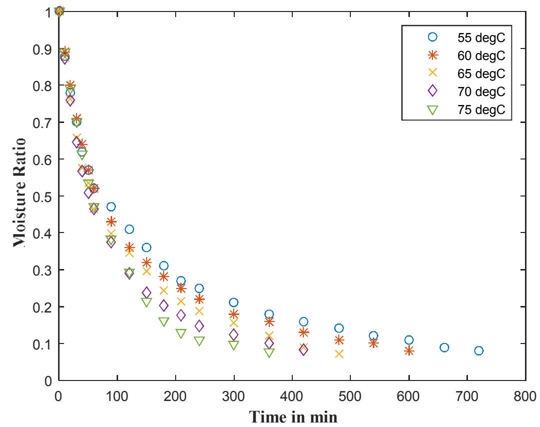


Fig. 2. Plot of moisture ratio versus drying time at various drying air temperatures

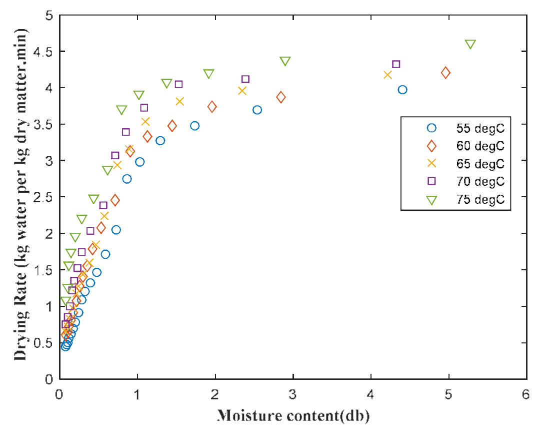


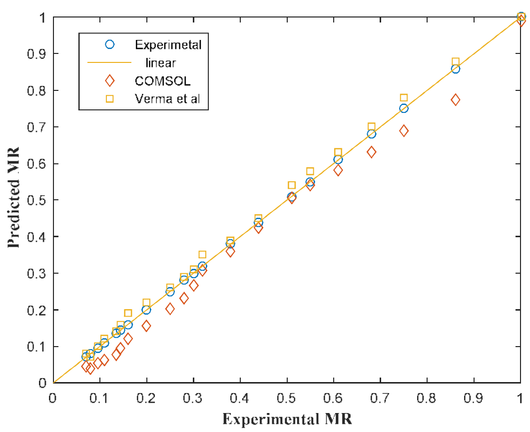
Fig. 3. Plot of drying rate and moisture content (d.b) at different ait temperatures for thin layer drying of pineapple

4.1 Mathematical Modelling

The dimensionless moisture ratio against drying time for the experimental data at different air temperatures was fitted to the 5 thin layer drying models (Table 1). It was observed from the Table 2, the best statistical values given for the Verma et al. based on comparison criteria. The highest correlation coefficient, lowest RMSE and chi-square values were ranged from 0.9995 to 0.9981 and 0.0070 to 0.0128 and $6.17×10^{-05}$ to $1.58×10^{-04}$ for Verma et al. respectively and these values are superior to other models. As shown in Fig. 4 for the temperatures of 55 and 65℃, the values of predicted MR from COMSOL and Vermal et al. were found to be good agreement with the experimental MR. It is said that, experimental MR values were closely bound to the predicted MR values and these values lay around the straight line. Moreover, it is also observed from Figs. 5 (a-e), predicted MR from COMSOL simulation and Verma et al. was good consistency with experimental data when plotted against drying time at all temperatures. Hence these models can be successfully applied for prediction of MR and operating conditions.

Table 2. Statistical parameters and model constants at different drying temperatures

	Model	R-squared	RMSE	Reduced Chi square	Parameters
55℃	Hendeson and Pebis model	0.9424	0.0683	4.67E-03	a = 0.8478; k = 0.005291
	Midilli et al.	0.9961	0.0188	3.52E-04	a = 1.019 b = 5.793e-05 k = 0.04437 n= 0.639
	Wang and Singh	0.7373	0.1459	2.13E-02	a = -0.004202 b = 4.40E-06
	Silva et al	0.9911	0.0269	7.21E-04	a = 0.001432 b = 0.06393
	Verma et al.	0.9981	0.0127	1.61E-04	a = 0.495 g = 0.002723 k = 0.02547
60℃	Hendeson and Pebis model	0.9553	0.0626	3.92E-03	a = 0.8892 k = 0.006519
	Midilli et al.	0.9962	0.0194	3.76E-04	a = 1.021 b = 0.00010 k = 0.03295 n = 0.721
	Wang and Singh	0.8080	0.1297	1.68E-02	a = -0.0049 b = -6.19E-06
	Silva et al	0.9875	0.0331	1.10E-03	a = 0.002641 b = 0.0553
	Verma et al.	0.9995	0.0070	4.85E-05	a = 0.4358 g = 0.02042 k = 0.002834
65℃	Hendeson and Pebis model	0.9558	0.0616	3.80E-03	a = 0.8829 k = 0.007677
	Midilli et al.	0.9947	0.0230	5.29E-04	a = 1.018 b = 6.644e-05 k = 0.0412 n =0.6884
	Wang and Singh	0.8082	0.1302	1.72E-02	a = -0.00601 b = 9.17E-06
	Silva et al	0.9900	0.0293	8.60E-04	a = 0.003158 b = 0.06074
	Verma et al.	0.9983	0.0126	1.58E-04	a = 0.5216 g = 0.02935 k = 0.004124
70℃	Hendeson and Pebis model	0.9671	0.0547	2.99E-03	a = 0.9136 k = 0.009339
	Midilli et al.	0.9975	0.0163	2.67E-04	a = 1.015 b = 0.000159 k = 0.0313 n =0.7812
	Wang and Singh	0.8412	0.1194	1.43E-02	a = -0.00692 b = 1.206E-05
	Silva et al	0.9895	0.0309	9.55E-04	a = 0.004746 b = 0.05377
	Verma et al.	0.9994	0.0079	6.17E-05	a = 0.6091 g = 0.003829 k = 0.0227
75℃	Hendeson and Pebis model	0.9896	0.032888	1.08E-03	a = 0.9659 k = 0.01037
	Midilli et al.	0.9985	0.013555	1.84E-04	a = 1.008 b = 0.000176 k =0.0163 n = 0.9286
	Wang and Singh	0.9371	0.0808	6.54E-03	a = -0.0076 b = 1.498E-05
	Silva et al	0.9937	0.025645	6.58E-04	a = 0.008186 b = 0.02366
	Verma et al.	0.9985	0.01284	1.65E-04	a = 0.8532 g = 0.001979 k = 0.01428



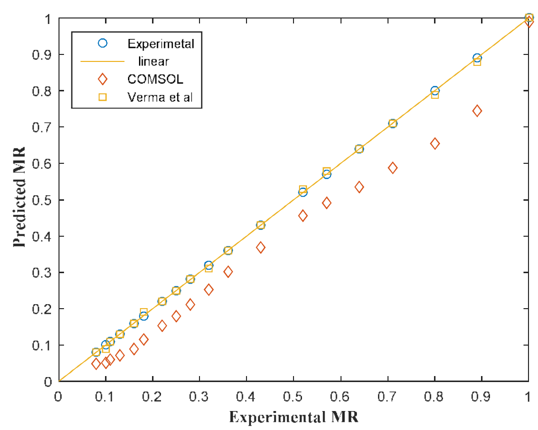
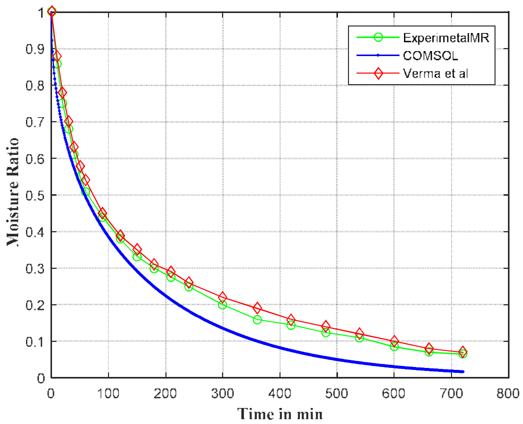
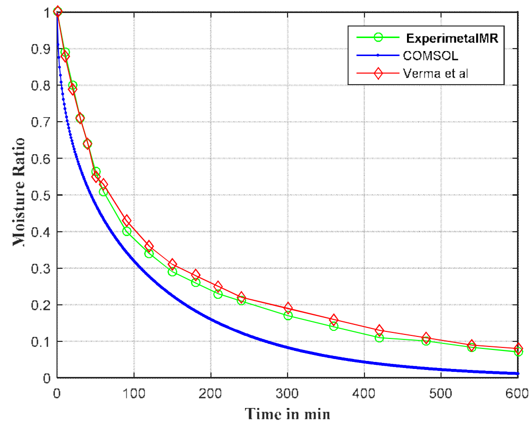


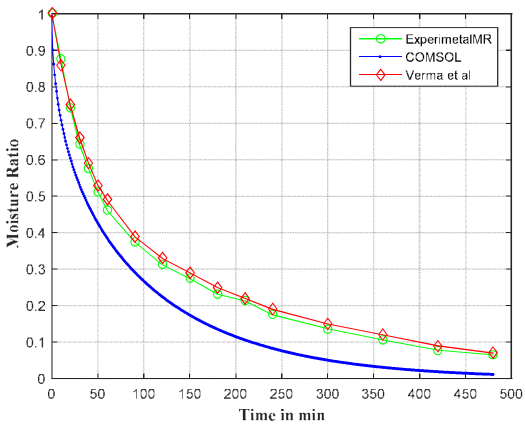
Fig. 4. Plot of experimental data against predicted data obtained from COMSOL and Vermal et al. at the temperature of 55 and 65℃



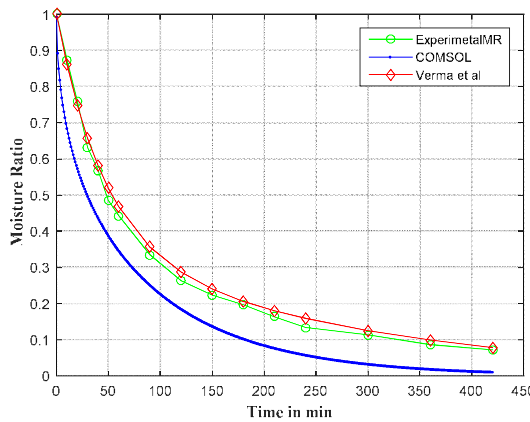
a) 55℃



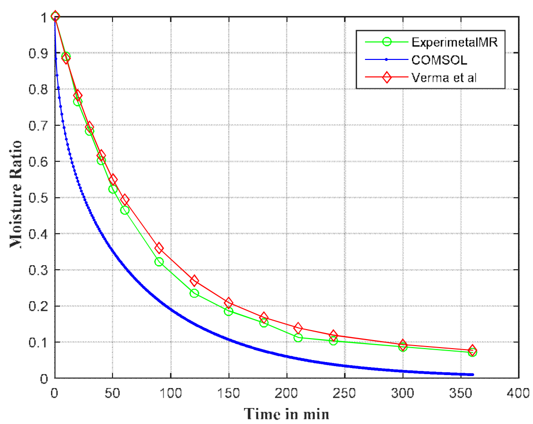
b) 60℃



C) 65℃

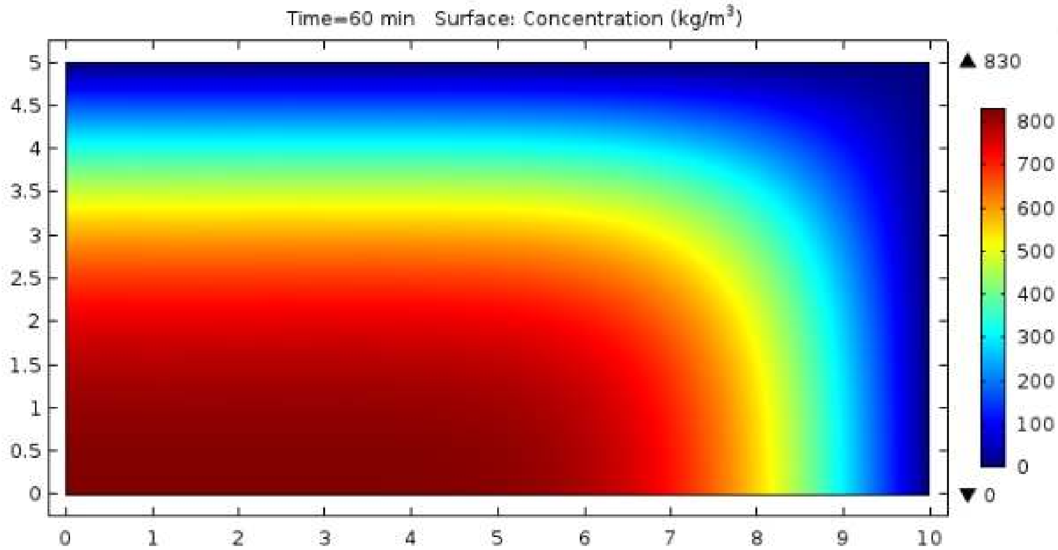


d) 70℃

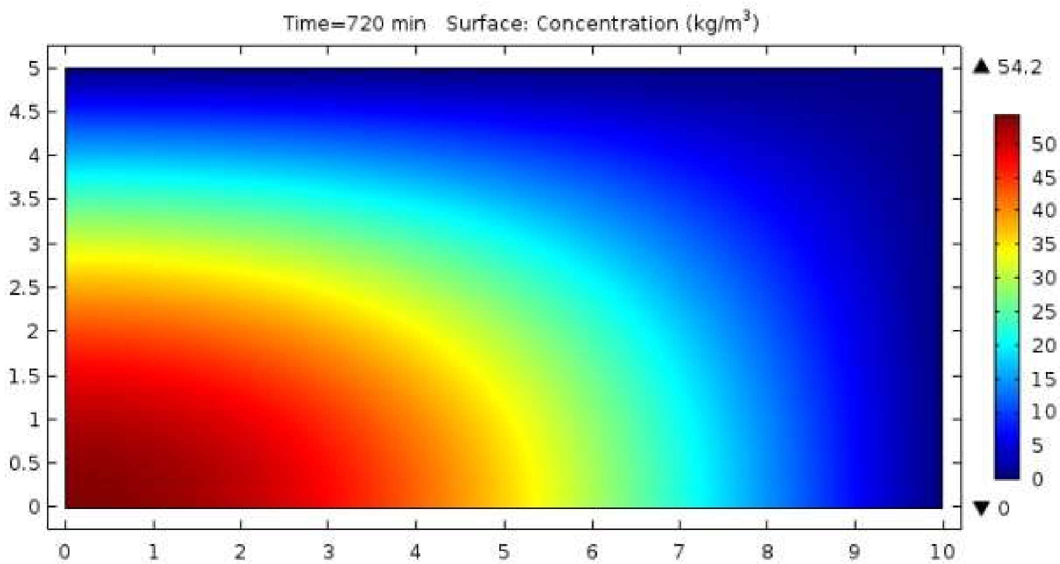


e) 75℃

Fig. 5. Plot of experimental MR with COMSOL model and Verma et al.



a)

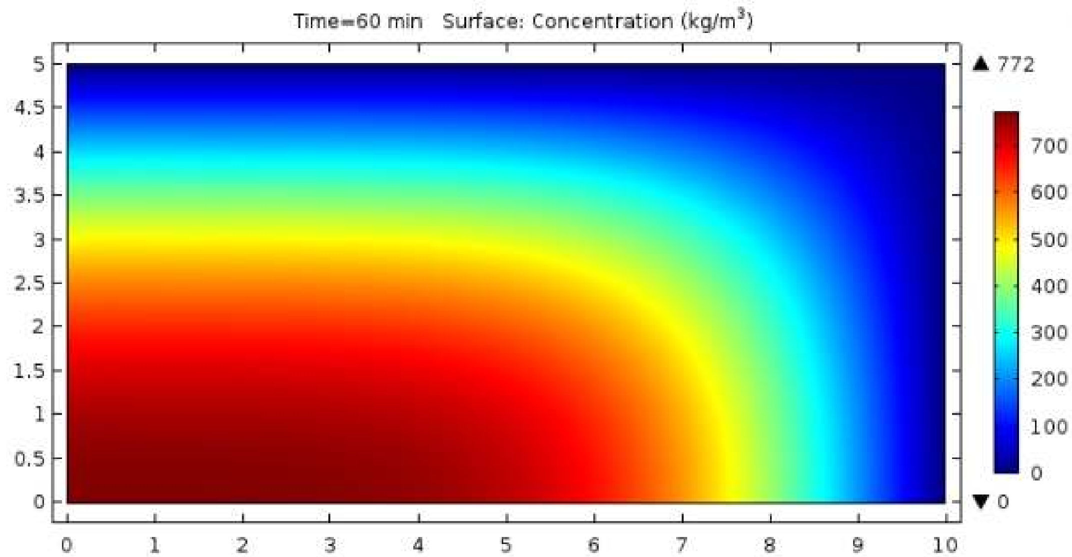


b)

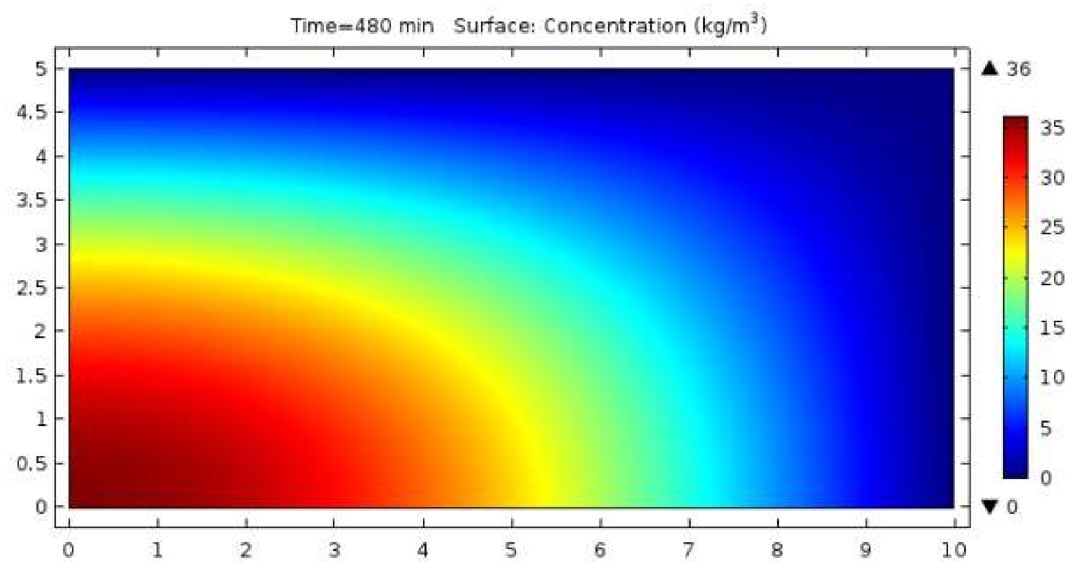
Fig. 6. Moisture profile at a temperature of 55℃; a) 60 min b) 720 min

Table 3. Model parameters assigned to COMSOL model development

Parameter	Value	Reference
Convective Heat transfer coefficient ($W/m^2.K$)	Eq. (10)	Calculated from this study
Convective Mass Transfer Coefficient (m/s)	Eq. (11)	Calculated from this study
Moisture Diffusivity (m^2/s)	Eq. (5)	Calculated from this study
Density (kg/m^3)	980	[16]
Thermal Conductivity (W/m.K)	0.148+0.00493M	[16]
Specific heat (kJ/(kg.K))	1.675+0.025M	[16]
Initial Temperature, T_0 (℃)	25	Measured from this study
Initial Moisture concentration, M_0 (kg/m^3)	833	Measured from this study



a)

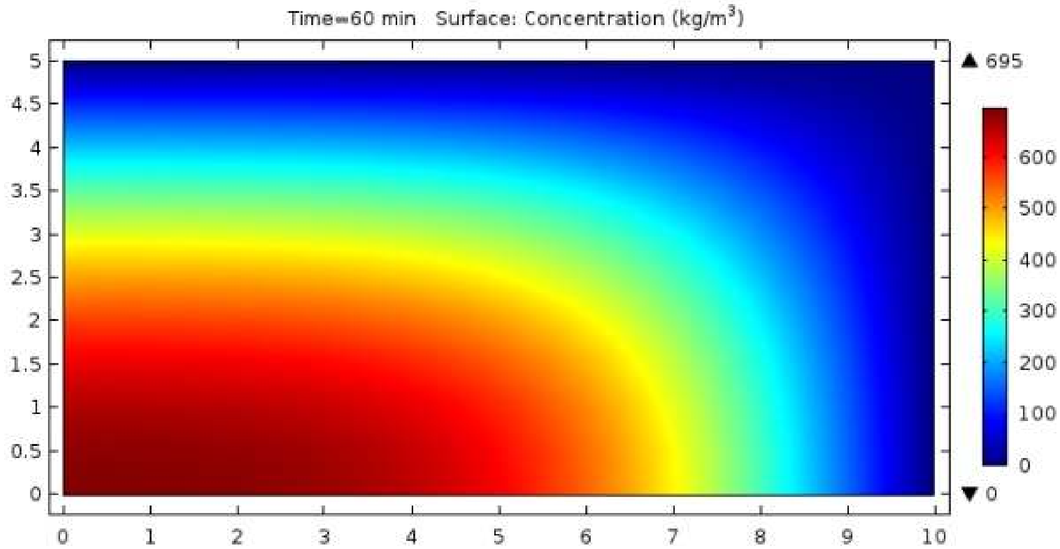


b)

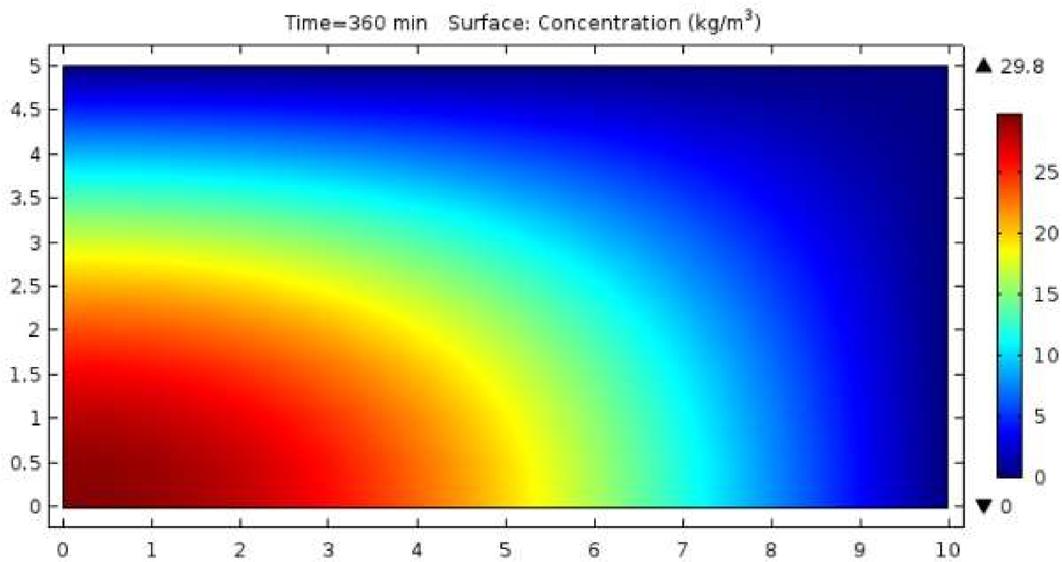
Fig. 7. Moisture profile at a temperature of 65℃; a) 60 min b) 480 min

4.2 Moisture Profile at Different Drying Times

The nodal solutions of the moisture variation of the pineapple sample at different drying times and different air temperatures are presented in the Figs. 6-8. It is clearly understood that the moisture concentration at the integral parts of the sample is more compared to the surface boundary in all the cases. The water vapour diffuses from the surface into the air and surface starts to dry out and an integral part of the water in the sample probably diffuses to the surface, and then by more water evaporates until there was no liquid water inside the material. At the initial period of drying, as drying air temperatures increases from 55 to 75℃, the rate of moisture removal also increases as shown in surface diagram in 6 (a), 7 (a) and 8 (a). As drying time progresses moisture concentration decreases.



a)



b)

Fig. 8. Moisture profile at a temperature of 75 ℃; a) 60 min b) 360 min

As we can observe the moisture concentration from the Figs. 6 (b), 7 (b), 8 (b), the reduction in drying time was found to be 33.33% and 25% with increase in every 10℃ of drying air temperature from 55 to 75℃ to attain same level of moisture concentration at the end of drying time. The predicted moisture content of pineapple slice against drying time at centre point at different air temperatures is presented in Fig. 9. It was observed that experimentally moisture concentration of the pineapple sample decreases from the 835.45 kg/m^3 to the 65.75 kg/m^3 at the end of the drying period whereas simulated moisture concentration decreased from range of 835 kg/m^3 to the 30-50 kg/m^3. It can be observed that results of the simulated moisture concentration were observed to be good agreement with the experimental data as show in Fig. 5 (a-e). So it is clearly understood that the developed simulated model can be able to predict the moisture profile during drying and can be successfully applied for prediction of MR in drying.

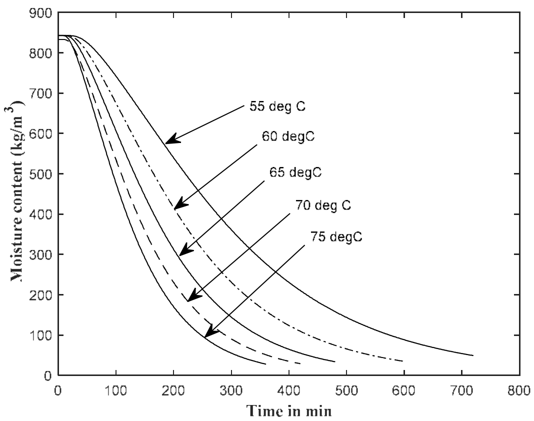


Fig. 9. Predicted moisture content of pineapple slice at centre point

In this work, a comparison between the volume average of experimental and predicted moisture ratio values were evaluated for all drying conditions. The goodness of the predicted model was evaluated with the following equation:

$$e_{abs}(\%) = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{T_{Exp} - T_{Pred}}{T_{Exp}}\right)_i \qquad (13)$$

Where n is the number of moisture content values taken into account during the drying, e_{abs} is the mean absolute relative error. In this work, whole moisture content of the sample was determined not the crust of the sample. So the relative absolute error between the experiment and simulation from COMSOL for the whole sample was 0.62, 0.94, 1.12, 1.32 and 1.76% at air temperatures from 55 to 75℃.

5. CONCLUSION

Among all the models, Verma et al. was best fit model for the experimental data. The COMSOL Multiphysics was used to generate the moisture profile during drying of pineapple. According to the statistical results, the drying air temperature 60℃ was best condition. The obtained MR values from COMSOL simulation and Verma et al. are good agreement with the experimental MR. Hence these models are able to predict the good pattern of moisture concentration profile during drying.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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