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Vacuum drying kinetics of kiwifruit and sensory evaluation

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Abstract
This study focused on the vacuum drying of thinly sliced kiwifruit at three different temperatures (50, 60, and 70 ºC) and the effect of vacuum along with the temperature combinations on the drying kinetics of kiwifruit were investigated. Ten mathematical thin layer drying models were employed on the drying data obtained experimentally and the best fit model was determined based on the statistical parameters like the coefficient of determination (R^2), the sum of squared error (SSE) and root mean square error (RMSE) using MATLAB R2019a curve fitting non-linear least square regression tools. Midilli *et al*. model were found to be the best among other models to describe the drying behaviour of kiwifruits. The effective moisture diffusivity and activation energy were found out by correlating with the Arrhenius equation. The activation energy was found to be around 37.77 kJ/mol. Sensory evaluation test was also performed using a 9-point hedonic scale and the sample dried at 60 ºC was preferred by most judges based on the overall ratings.

Keywords: Vacuum, drying kinetics, diffusivity, activation energy

1. Introduction
Kiwifruit (*Actinidia deliciosa*), one of the tastiest berry with a sweet, acidic, and unique flavour have gained a lot of popularity in the world market. China is the highest producer of kiwifruit with 50 per cent (%) of world production in 2017 (UN Food and Agriculture Organization, 2018) [20]. In India, the top kiwifruit producing states are Arunachal Pradesh, Nagaland, Mizoram, Sikkim, Himachal Pradesh, and Jammu and Kashmir (National Horticulture Board (NHB), 2015-16) [22]. There are different cultivars of kiwifruit but the most common one is the Hayward, which is oval in shape with just the size of an egg. It has light brown skin with thin fuzzy hairs over it and light-green fleshy pulp with little tiny black seeds inside. They are an excellent source of many nutrients such as vitamin A, B, and C, phosphorus, potassium, calcium, magnesium, fibres, etc. However, they have a very short shelf-life with just a week or two after harvesting if proper storage is not provided. It can be noted that the storage life of kiwifruit deteriorate even at refrigerated condition due to loss of vitamins and softening while storage (Agar *et al.*, 1999) [1].
In the context of India, when it comes to fruits, 93 million tonnes (MT) were produced during the year 2016-17 according to the report of the committee of doubling farmers income, Ministry of Agriculture and Farmers’ Welfare [21]. It has also projected an increase in demand for fruits in 2030 by 103 per cent (%). But the losses incurred in fruits after harvesting is still at a higher pace of around 34 per cent (%) due to several problems such as lack of cold storage and the absence of robust and sustainable logistics mechanisms which causes wastage of more than half of the produce before arriving in the market. So it is high time to take remarkable steps towards meeting the rising demand of the fruits in the coming years.
One of the viable and promising ways to reduce post-harvest losses of fruits is drying. Drying is a unit operation during which the product is rapidly dried until it reaches the "safe-moisture" or equilibrium moisture level. Drying reduces the water activity of the food products thereby increasing the shelf-life period. It prevents the attack of bacteria, yeast, mould, insects, suppresses enzymatic activity, and any other moisture inducing deteriorative reactions. In fact, it enables the storability of the final product under the normal environmental condition for a longer time if suitable conditions are provided. Many drying methods are available at present depending on the range of application such as sun drying, convection drying, drum drying, freeze drying, fluidized bed drying, vacuum drying, microwave-vacuum drying, tray drying, spray drying, infrared radiation drying, combined thermal hybrid drying, etc.

One of the widely used industrial methods of drying of food is the convective hot air drying because they are simple and easy to design, construct and maintain. They retain most of the nutritional properties of food if dried using appropriate drying conditions. However, if the food qualities such as colour, aroma, structure, and nutritive values are concerned, vacuum drying is preferred (Methakhup *et al.,* 2005; Alibas, 2007) [12, 4] since they preserve the food qualities with their ability to dry at low drying temperature, higher drying rate, and low oxygen drying conditions, etc.

Several researchers have studied the thin layer drying kinetics of different product using different dryers at different conditions. Many evaluated the drying parameters, sensory parameters, and optimization using different optimization techniques and proposed the best model in predicting the drying behaviour of the product.

Shahi *et al.* (2014) [16] studied the optimization of thin layer drying kinetics of kiwifruit slices using a genetic algorithm. The effects of temperature (50, 60, and 70 ºC) on drying characteristics of kiwifruit in a hot air tray dryer show that raising drying temperature reduced drying duration and increased the speed and degree of effective diffusion. Out of the four different mathematical models employed to fit the experimental data, Verma *et al*. were the most efficient in predicting the moisture ratio of dried kiwi fruit slices. Moreover, the genetic algorithm method was used to optimize the best experimental model and found that the algorithm method could very accurately predict the moisture ratio of dried kiwifruit when compared. Darvishi *et al.* (2016) [6] studied the energetic and exergetic performance analysis and modelling of drying kinetics of kiwi slices. Constant drying rate period was not observed and drying occurred in the falling rate period. They found that energy and exergy efficiency increased with increasing microwave power and decreasing slice thickness while values of energy efficiency were higher than exergy efficiency. Effective diffusivity also increased with decreasing moisture content and increasing microwave power and slice thickness. Midilli *et al.* model showed the best fit but Page's model was selected since it had almost a similar performance but the model is simpler with two parameters instead of four. Aidani *et al.* (2016) [2] studied the experimental and modelling investigation of mass transfer during combined infrared-vacuum drying of Hayward kiwifruits at infrared radiation power (200–300 W) and system pressure (5–15 kPa). They found a reduction in drying time when the system pressure was decreased. The results of the regression analysis indicated that the quadratic model was the best to describe the drying behaviour. Mahjoorian *et al.* (2017) [11] studied the modelling of drying kiwi slices and its sensory evaluation by using a laboratory-scale hot-air dryer. The drying process was carried out at three different temperatures of 50, 60, and 70°C. They found that increasing drying temperature caused a reduction in time and raise of velocity and effective diffusion coefficient. Out of the models employed, the Two-term model gave better performance to monitor the moisture ratio. Product sensory characteristics were evaluated by panellists and found no significant differences among colour acceptance, odour, taste, and texture crispiness (chewiness). Ozgen and Celik (2019) [13] evaluated the design parameters on the drying of kiwifruit. Kiwi slices having a thickness of 4 and 8 mm were dried in the dryer under the conditions of 45 °C temperature of the drying air, 10% relative humidity and 0.5–1.5 m/s drying air velocity. The drying rate and the moisture content of the sample are affected by the thickness of the kiwifruit and the speed of the drying air. Increased drying air velocity and reduced fruit thickness cause drying time to be reduced. It has been determined that working the convective dryer at different speeds is advantageous in terms of preserving brightness and colour quality.

This study focuses on the effect of vacuum and different temperature on the drying of thin kiwifruit slices. The sensory analysis also conducted to investigate the buying intention of the dried product based on the human perception ability for the possible development of the dried kiwi slices product for sale in the market.

Materials and methods

Sample preparation

Fresh kiwifruits were procured from the market and kept in a refrigerator at a temperature of 5ºC in order to reduce the respiration and other physiological changes. Before cutting, the samples were washed clean, sorted of uniform size, peeled off using a sharp knife and sliced into 4±0.2 mm thickness. About 200 g of sliced kiwi samples were used for each drying experiments. The initial moisture content was determined by using an infrared moisture analyzer (Aczet brand, 110-220 V, Precision-1mg) and found to be around 85±1%w. b.

Experimental setup

A laboratory 2 kW double shelves vacuum oven (TANCO, OVV-2 Model, New Delhi) shown in figure 1 was used for conducting the drying experiments. Before keeping the samples for drying, the vacuum oven was allowed to run for 30 minutes to obtain a stable temperature condition. Drying experiments were carried out for three temperatures of 50, 60, and 70 ºC at a fixed vacuum condition of 630-650 mm Hg. The weight loss of the samples was measured after every 30 minutes using a high accuracy digital weighing balance (TECHway high accuracy lab scale, 600 g capacity, and ±0.01 g accuracy) till the final moisture content reached to around 2-4 % w.b. Experiments were replicated to get the optimum readings and the average values were used for analysis.

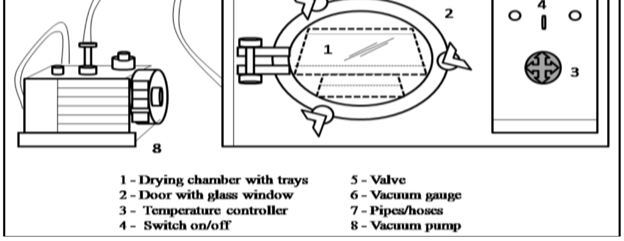

Fig 1: Schematic diagram of vacuum oven along with a vacuum pump.

Mathematical modelling of moisture reduction from drying

Experimental data obtained were analyzed in terms of moisture reduction ratio using MATLAB R2019a software where the data of moisture ratio (MR) and drying time were plotted to understand the drying behaviour of the sliced kiwifruit. Moisture ratio was determined by the equation below.

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad [1]$$

Where M_t is the moisture content of the sample at a particular time; M_e is the equilibrium moisture content of the sample; M_o is the initial moisture content of the sample. The value of equilibrium moisture content (M_e) for vacuum drying is considered very small as compared to initial moisture content (M_o) and at a particular time period (M_t). So the M_e can be neglected.

The moisture ratio versus drying time curve obtained for the three different temperatures were fitted using ten thin layer drying models shown in table 1, available from the literature using non-linear least square regression analysis.

Table 1: Thin layer drying models

Model	Equation	References
Page	MR = exp(-kt^n)	Izli *et al.* (2017) [10]
Modified Page	MR = exp(-kt)^n	Demir *et al.* (2007) [7]
Logarithmic	MR = a exp(-kt)+c	Doymaz & Sahin (2016) [9]
Two term	MR = a exp(-k_ot)+b exp(-k_1t)	Aidani *et al. (*2016) [2]
Two term exponential	MR = a exp(-kt)+(1-a) exp(-kat)	Akpinar & Toraman (2016) [3]
Wang and Singh	MR = 1+at+bt^2	Sarimeseli (2011) [14]
Diffusion approach	MR = a exp(-kt)+(1-a) exp(-kbt)	Artnaseaw *et al.* (2010) [5]
Modified Henderson and Pabis	MR = a exp(-kt)+b exp(-gt)+c exp(-ht)	Togrul and Pehlivan (2003) [18]
Verma *et al.*	MR = a exp(-kt)+(1-a) exp(-gt)	Shahi *et al.* (2014) [16]
Midilli *et al.*	MR = a exp(-kt^n)+bt	Doymaz (2009) [8]

Statistical analysis for selecting the goodness of fit

The coefficient of determination (R^2) was one of the main determinants which measure how successful the fit is in explaining the variation of the data. It is also called the square of the multiple correlation coefficients and the coefficient of multiple determinations. Along with R^2, the sum of the squared differences between each observation and its group's mean (SSE), and the roots mean square error (RMSE) was used to determine the best equation which fit the drying behaviour of the dried sample. The values of R^2 as obtained from the regression analysis should be higher (close to 1) while the SSE and RMSE should be lower (close to 0) for selecting the best fit. These parameters can be expressed as.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(y_{pre,i} - y_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\bar{y}_{pre,i} - y_{exp,i}\right)^2} \quad [2]$$

$$SSE = \sum_{i=1}^{N}\left(y_{exp,i} - \bar{y}_{exp,i}\right)^2 \quad [3]$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(y_{exp,i} - y_{pred,i}\right)^2\right]^{1/2} \quad [4]$$

Where, $y_{exp,i}$ is the experimental moisture ratio; $y_{pred,\,i}$ is the predicted moisture ratio; $\bar{y}_{exp,i}$ is the mean of the experimental moisture ratio; $\bar{y}_{pre,i}$ is the mean of predicted moisture ratio; N is the number of readings.

Determination of moisture diffusivity and activation energy

Fick's diffusion equation was used for the calculation of moisture diffusivity. The analytic solution of Fick's law considering an infinite slab is expressed as (Van Arsdel and Copley, 1963) [19].

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(-2n+1)^2\pi^2\frac{D_{eff.}t}{4L^2}\right) \quad [5]$$

Where, M_t is the moisture content of the sample at a particular time; M_e is the equilibrium moisture content of the sample; M_o is the initial moisture content of the sample; D_{eff} is the effective diffusion coefficient (m^2/s); L is the half thickness of the sample (m); t is the drying time (min).

Equation [4] can be reduced to the following equation by substituting n=1and taking logarithm on both side.

$$\ln(MR) = \ln\frac{8}{\pi^2} - \frac{\pi^2}{4L^2}D_{eff}.t \quad [6]$$

From equation [5], the effective moisture diffusivity, D_{eff} can be calculated from the slope of the best fit straight line after plotting a graph between ln(MR) and drying time, t. The slope can be expressed by.

$$Slope = -\frac{\pi^2}{4L^2}D_{eff} \quad [7]$$

For the calculation of activation energy (E_a), effective moisture diffusivity was related to the temperature by Arrhenius equation which upon taking logarithm on both sides gives the following equation.

$$\ln(D_{eff}) = \ln(D_o) - \frac{E_a}{R_o}\left(\frac{1}{T}\right) \quad [8]$$

Where Do is the constant equivalent to diffusivity (m^2/s); E_a is the activation energy (kJkg/mol); Ro is the universal gas constant (kJ/kg mol); T is the absolute temperature (K). From equation [7], activation energy and the constant D_o were determined by plotting ln(D_{eff}) versus 1/T.

Sensory analysis

To determine the degree of acceptability of the dried kiwi samples at three different temperatures, one of the widely used scales for measuring food acceptability 9-point hedonic scale test was performed by 20 numbers of judges. The quality parameters such as colour, aroma, taste, buying intention were evaluated by the pre-trained judges in a clean and quiet room. The 9-point scale signifies the following meanings: 9-Like Extremely; 8-Like Very Much; 7-Like Moderately; 6-Like Slightly; 5-Neither Like nor Dislike; 4-

Dislike Slightly; 3-Dislike Moderately; 2-Dislike Very Much; 1-Dislike Extremely.

Results and discussion

Effect of temperature on moisture ratio and drying rate

With the increase in drying temperature from 50-70 ºC, the drying time becomes smaller. The total time required to bring the sliced kiwifruit from the initial moisture content of 85% w.b. to a final moisture content of 2-4% w.b was lowest for 70 ºC around 390 minutes against 720 minutes and 540 minutes for 50 and 60 ºC drying temperature respectively. Figure 2 shows the moisture ratio reduction trend during vacuum drying of kiwifruits at different temperatures. At higher temperature (70 ºC), the heat and mass transfer rate was maximum and thus moisture content reduced very fastly.

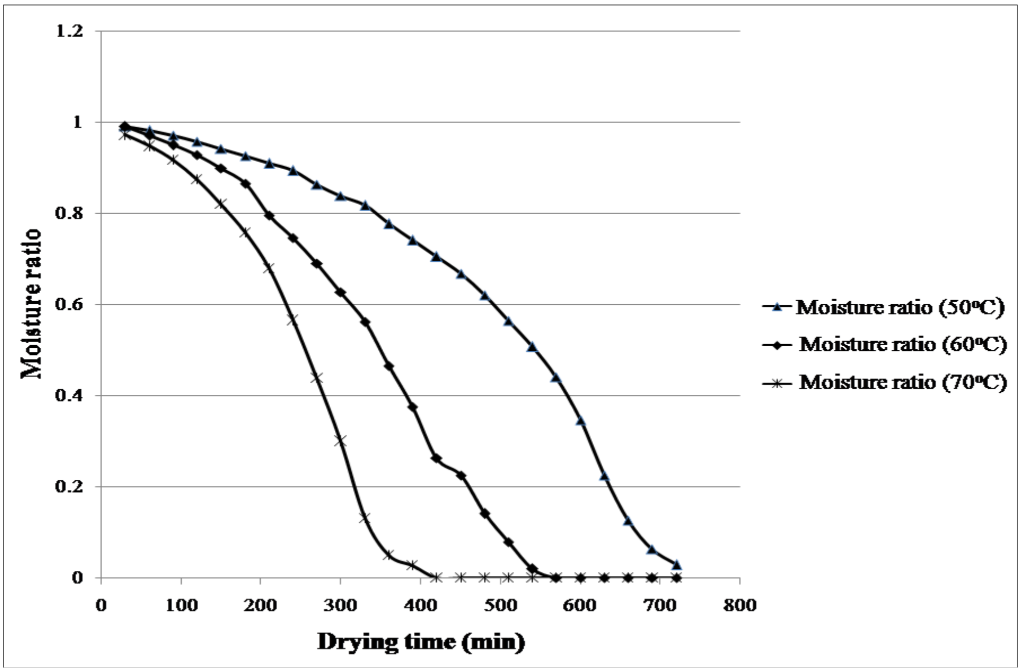

Fig 2: Variation of moisture ratio with drying time at different temperatures.

From figure 3, we can observe that the constant drying rate period was absent and only the falling rate period could be found during the entire drying period. The reason for the absence of constant rate period may be attributed to the quick removal of moisture from the surface at the beginning of the drying process. Drying rate was found to be maxima at the 70 ºC drying temperature as compared to 50 and 60 ºC. Drying rate was maximum during the initial stage when there was saturated moisture on the surface but later decreases due to the unavailability of free moisture and the moisture had to removed through diffusion process from the inside of the sample to the surface on further drying.

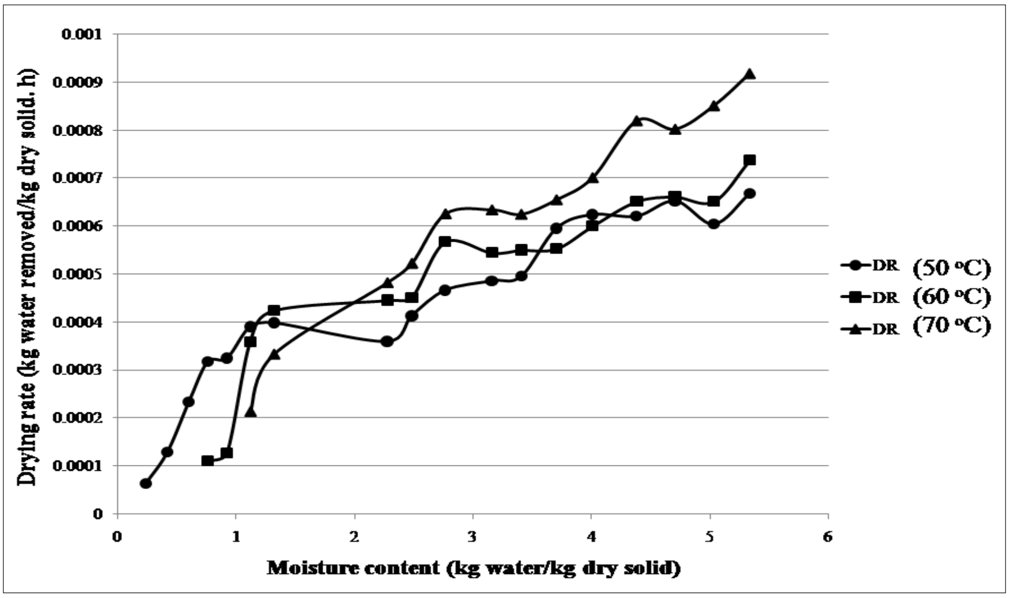

Fig 3: Variation of drying rate with moisture content at different temperatures.

Mathematical modelling of moisture reduction

In order to estimate the moisture reduction behaviour, ten selected thin layer drying models were employed. Values of drying constant and other coefficients were obtained by performing a non-linear regression analysis in the curve fitting tools of MATLAB R2019a software and are shown in table 2. It can be observed that the coefficient of determination (R^2) obtained from the models ranges from 0.6992 to 0.9950. At all the three drying temperatures, the R^2 values for Midilli *et al.* model were found to be maxima. SSE value ranges from 0.0093 to 0.7529 while the RMSE value ranges from 0.0258 to 0.1917. In addition to the highest R^2 value obtained in Midilli *et al.* model, the lowest values of SSE and RMSE were also found in the Midilli *et al.* model which is 0.0093 and 0.0258 respectively. Thus the Midilli *et al.* model gave the best fit and can better describe the drying behaviour of sliced kiwifruit. Figure 4 shows the comparison of experimental and predicted moisture ratio at the three drying temperatures for the best fit model and found to be very close to each other which indicates the drying characteristic can be explained better. Similar results were reported by Tavakolipour and Mokhtarian (2012) [17] and Mahjoorian *et al.* (2016) [11].

Table 2: Statistical parameters for different drying for determining the goodness of fit

Model	T(°C)	Coefficients	R^2	SSE	RMSE
Page	50	$k = 4.617\times10^{-8}$ n = 2.653	0.9586	0.0909	0.0643
	60	$k = 5.357\times10^{-8}$ n = 2.719	0.9923	0.0144	0.0300
	70	$k = 6.508\times10^{-8}$ n = 2.942	0.9851	0.0219	0.0446
Modified page	50	k = 0.0022 n = 0.5922	0.6992	0.6603	0.1732
	60	k = 0.0037 n = 0.5866	0.7674	0.7529	0.1657
	70	k = 0.0053 n = 0.5854	0.7330	0.3939	0.1892
Logarithmic	50	a = 2.2070 c = -1 k = 0.0007	0.8565	0.3150	0.1225
	60	a = 2.2230 c = -1 k = 0.0012	0.9340	0.1246	0.0911
	70	a = 2.1660 c = -1 k = 0.0016	0.8955	0.1717	0.1249
Two term	50	a = 1.2490 b = 1.2290 k_0 = 0.78057 k_1 = -0.0018	0.7848	0.4724	0.1537
	60	a = 1.8410 b = 1.276 k_0 = 0.7816 k_1 = 0.0030	0.8576	0.2688	0.1386
	70	a = 1.7840 b = 1.3020 k_0 = 0.8171 k_1 = 0.0043	0.8257	0.2572	0.1690
Two term exponential	50	a = -0.2658 k = 0.0067	0.7830	0.4764	0.1471
	60	a = -0.0004 k = 5	0.7671	0.4397	0.1658
	70	a = 0.0006 k = 4.999	0.7326	0.3945	0.1894
Wang and Singh	50	a = 0.0001 $b = -2.065\times10^{-6}$	0.9915	0.0187	0.0291
	60	a = -0.0004 $b = -2.777\times10^{-6}$	0.9929	0.0133	0.0289
	70	a = -0.0004 $b = -5.88\times10^{-6}$	0.9861	0.0205	0.0432
Diffusion approach	50	a = -0.2292 b = 0.0035 k = 0.5015	0.7848	0.4724	0.1500
	60	a = -0.2758 b = 0.0060 k = 0.5024	0.8576	0.2688	0.1339
	70	a = -1 b = 0.3673 k = 0.5159	0.8953	0.1545	0.1243
Verma *et al.*	50	a = -1 g = 0.0026 k = 0.0072	0.8708	0.2835	0.1162
	60	a = -1	0.9278	0.1362	0.0953

		g = 0.0042 k = 0.0114			
	70	a = -1 g = 0.0058 k = 0.0159	0.8953	0.1545	0.1243
Modified Henderson and Pabis	50	a = 4.9750 b = 1.2290 c = 0.2000 g = 0.0018 h = 0.9157 k = 0.6270	0.7848	0.4724	0.1620
	60	a = 4.9970 b = 1.2760 c = 0.2000 g = 0.0030 h = 0.9157 k = 0.7971	0.8576	0.2688	0.1497
	70	a = 4.9940 b = 1.3030 c = 0.2000 g = 0.0043 h = 0.9157 k = 1.0990	0.8257	0.2571	0.1917
Midilli and Kucuk	50	a = 5 b = -0.0023 k = 1.7190 n = -0.1466	0.9638	0.0794	0.0630
	60	a = 4.9850 b = -0.0029 k = 2.2930 n = -0.1126	0.9950	0.0093	0.0258
	70	a = 4.9940 b = -0.0046 k = 2.5940 n = -0.1547	0.9876	0.0183	0.0451

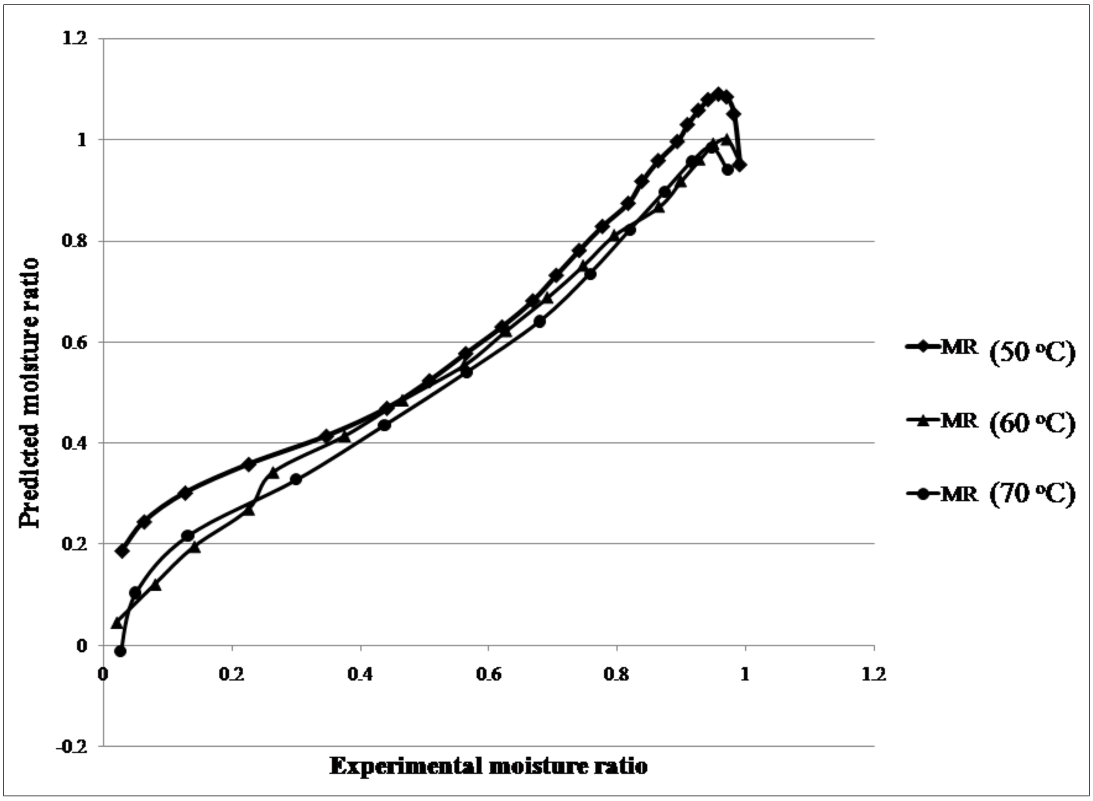

Fig 4: Experimental and predicted moisture ratio comparison at different temperature for the best fit model (Midilli *et al.*)

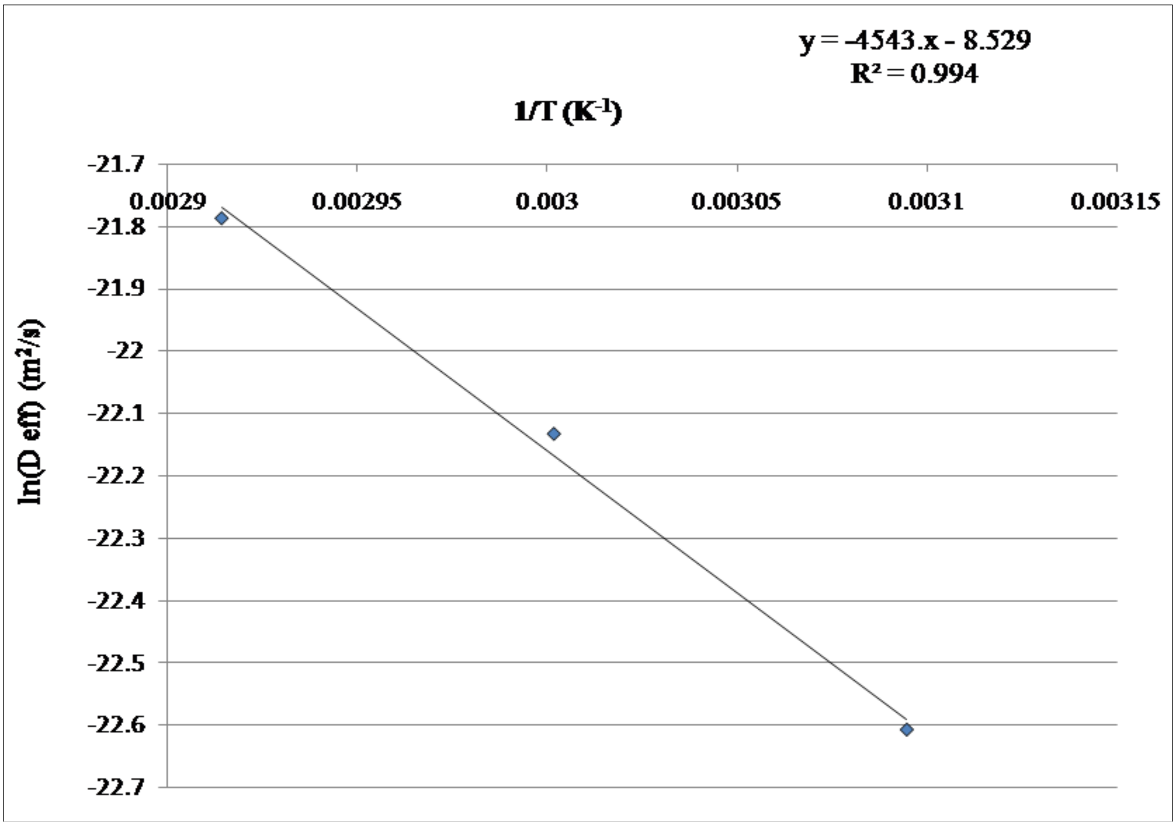

Fig 5: Arrhenius plot of moisture diffusivity at different temperature

Determination of moisture diffusivity and activation energy

Effective moisture diffusivity was calculated from equation [6] and [7] by plotting graphs between ln(MR) with the drying time for all the three drying temperatures. Effective diffusivity increases with the increase in drying temperature from 1.521×10^{-10} m^2/s at 50°C to 2.282×10^{-10} m^2/s at 60°C and found to be the maximum at 70 °C i.e. 3.448×10^{-10} m^2/s. Similar values were reported for dried kiwifruit 1.743×10^{-10}, 1.929×10^{-10} and 2.241×10^{-10} m^2/s at 50, 55 and 60°C respectively (Doymaz, 2009) [8]. When moisture diffusivity obtained at different temperatures were plotted with the inverse of absolute temperature using equation [8], a satisfactory fit of $R^2 = 0.994$ was obtained which is shown in figure 5 and the activation energy and diffusivity constant were calculated from the slope of the fit line. The activation energy was found to be 37.770 kJ/mol and diffusivity constant as 1.976×10^{-4} m^2/s. Similar reports on activation energy for kiwifruit slices were found to be 22.48 kJ/mol (Doymaz, 2009) [8] and 27 kJ/mol for kiwifruit drying (Simal *et al.* 2005) [15].

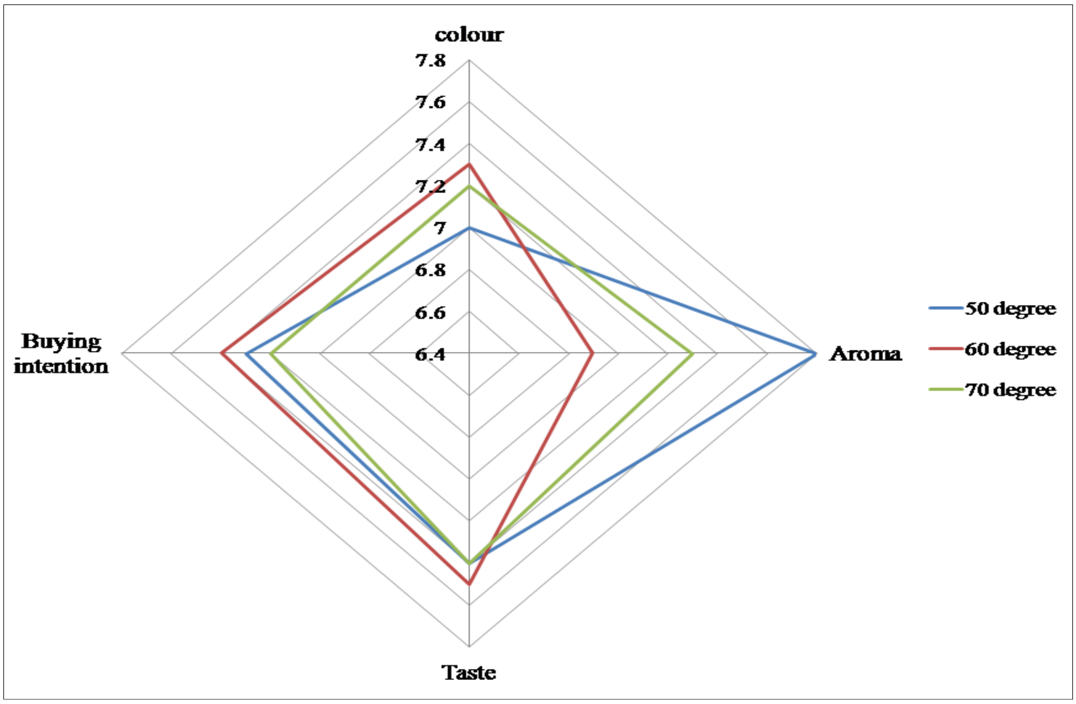

Fig 6: Sensory test hedonic scale readings for dried kiwi slices at different temperatures.

Sensory evaluation

Figure 6. indicates the sensory evaluation analysis using 9-point hedonic scale acceptability test on four parameters such as colour, aroma, taste, and buying intention based on the overall performance of the dried kiwi slices. The samples dried at 50 and 70 °C showed a little darkness in colour as compared to the dried sample of 60°C due to their longer time of drying and higher temperature treatment respectively. In case of aroma, the samples dried at 50 °C scored the highest rating which may be due to the higher retention of aromatic volatile components when exposed to low temperature as compared to other higher temperatures. The tastes in all the three samples were found to be almost similar based on the judges. Finally, considering all the above parameters for their acceptability in buying, the sample dried at 60 °C was preferred by most judges and thus we can conclude that temperature and time effect is a very important factor for evaluating the quality parameters in drying purpose.

Conclusion

Experiments on vacuum drying of kiwifruits at three temperatures 50, 60, and 70 °C were investigated. Drying time was reduced with the vacuum effect and minimum drying time of 390 min was achieved at 70 °C in bringing the initial moisture content of around 85 % (w.b.) down to 2.27 % (w.b). Out of the ten thin layer drying models used, the Midilli *et al.* model was found satisfactory in describing the drying pattern of the sliced kiwifruits because of the higher value of the coefficient of determination (R^2) and lower values of SSE and RMSE. Moisture diffusivity and activation energy calculated by plotting graph after correlating with Arrhenius equation was within the range of $1.521\times10^{-10} m^2/s$ to $3.448\times10^{-10} m^2/s$ and 37.770 kJ/mol respectively which were in close agreement with the references on kiwifruit drying. Lastly, sensory evaluation results show that the samples dried at 60 °C to be the best considering the quality parameters such as colour, aroma, taste, and the overall buying intention.

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