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Research article

Drying mechanism of Indian dark red onion slices at high velocity

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Abstract: Drying of onion is a moisture removal process to increase shelf life. Convection drying experiments are conducted at a drying temperature of 50 ℃, 60 ℃, 70 ℃, and at four high airflow velocity (2, 3.6, 5.7, and 7.7 m/s) for Indian dark red onion. The objective is to analyze the drying mechanism of Indian dark red onion slices at high velocity. The work diverges from the literature in analyzing the drying mechanism of Indian dark red onion slices at air velocity above 2 m/s.

Moisture content removal curves for upper velocities (i.e., for 5.7 and 7.7 m/s), shows seamless logarithmic in nature. Dehydration process from Indian dark red onion accelerates as velocity increases. Air velocity 2, 3.6, and 5.7 m/s exhibit a better moisture removal rate at 60 ℃ than 50 and 70 ℃. It is observed that the weight basis moisture content per unit mass flow rate of air decreases as velocity increases.

The effective moisture diffusivity averagely increases with an increase in air temperature and air velocity. The values for the arithmetic mean of effective moisture diffusivity lies between 1.096646×10^{-11} to 1.295467×10^{-11} and activation energy observed in the range of 10.8709 to 12.7719 kJ mol^{-1}.

Keywords: drying; mechanism; Indian dark red onion; high velocity; slices

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1. Introduction

Drying is the moisture elimination process from agriculture produce or food. In drying, the concurrent heat and mass transfer process occurs, and moisture gets evaporated. Drying is used to increase shelf life and maintain nutritional value. Convection drying is one of the conventional and simplest method adopted universally.

Onion is agriculture produce, very commonly used in culinary preparations since ancient times. Onion adds a delightful taste and flavor to food products. It also evidenced as a decent medicinal compound. Onion contains hypocholesterolemic, thrombolitic, and antioxidant. These therapeutic compound make onion useful for cataract, cardiovascular illness, and cancer, as quantified by Nuutila et al. [1] and Vidyavati et al. [2]. Indian dark red onion is indeed old species in the onion group. These onions have a similar flavor, like regular yellow onions with less tenderness and meaty. Anthocyanin produces deep purple outer skin and reddish flesh. Also, high levels of the antioxidants anthocyanin and quercetin make these onions are more effective in cancer pugnacious than white species [3]. Red onions exhibit higher antioxidative traces than yellow and white onions. Red onions are potential health food and suitable for humanoid nutrition [4].

The dried onion is used in various food products and culinary preparations. The usages of dried onions, which have augmented in mass, necessitate that an efficient and effective method of dehydrating the onion products be developed.

Lopez et al. experimented with 60, 70, 75, 80 °C drying temperature and with air velocity 0.2, 0.5, 1 m/s for drying of onion slices. Lopez et al. mentioned that the impact of air temperature on the falling-rate is greater than that of velocity [5]. Sarsavadia et al. tested brined onion slices at drying temperature 50, 60, 70, 80 °C and at 0.25, 0.5, 0.75, 1 m/s air velocity. It was found that the drying rate rises with a rise in temperature and velocity [6]. Jain and Pathare conducted convection drying trial with 30, 40, 45 °C drying temperature, and 1, 1.25, 1.5 m/s air velocity [7]. Kinetic modeling of onion quality changes during convection drying accomplished with 50, 60, 70, 75 °C air temperature and 0.6, 1.0, 1.2, 1.5 m/s air velocity. The experiment exhibit that air velocity had no significant effect on reaction rate constants. [8]. Kumar et al. tested suitability of thin layer models with experimentation parameters of 60, 70, 80 °C and 0.8, 1.4, 2 m/s. Kumar et al. stated the rate is not noticeably affected for a decrease in velocity from 2 to 1.4 m/s. Further reduction in air velocity to 0.8 m/s reduced the rate of drying. [9]. Kinetics and nutritional evaluation of onion slices were investigated with 30, 50, 60 °C, and 0.35 m/s in laboratory oven [10]. The drying behavior of onion was analyzed with the horizontal and vertical convective dryer at 50, 60, 70 °C air drying temperature and 0.5, 1.0, 2.0 m/s. It was detected that the rate of moisture removal augmented with the rise of drying air temperature and air velocity [11]. Grewal et al. explored the effect of partial mechanical dewatering, drying air temperature 50, 60, 70 °C, and air velocity 1.2 m/s on energy consumption and onion powder quality [12]. Khan et al. examined a novel drying technique with a combination of 70 °C temperature and air velocity of 2 m/s [13]. Ren et al. explored the effect of ultrasound and blanching on drying with 60 °C air temperature and 0.3 m/s air velocity [14]. Investigation of convective drying of yellow onion was performed in the oven with 1 m/s air velocity and 50, 60, 70, 80 °C air drying temperature [15].

A literature analysis summary for convection drying of onion slice from the parametric view is given in Table 1.

The literature throws light on the research gap for the unattainability of drying mechanism for onion slices in the drying air velocity above 2 m/s in convection drying. Research for the drying process, in the high velocity (above 2 m/s) and temperature regime, needs attention. The objective of the present study is to analyze the drying mechanism of Indian dark red onion slices at drying air velocity 2, 3.6, 5.7, and 7.7 m/s and also to investigate drying mechanism based on the effective moisture diffusivity.

Table 1. Literature analysis summary for convection drying of the onion slice.

Drying air temperature (°C)	Drying air velocity (m/s)	Reference
60, 70, 75, 80	0.2, 0.5, 1	[5]
50, 60, 70, 80	0.25, 0.5, 0.75, 1	[6]
30, 40, 45	1, 1.25, 1.5	[7]
50, 60, 70, 75	0.6, 1.0, 1.2, 1.5	[8]
60, 70, 80	0.8, 1.4, 2	[9]
30, 50, 60	0.35	[10]
50, 60, 70	0.5, 1.0, 2.0	[11]
50, 60, 70	1.2	[12]
70	2	[13]
60	0.3	[14]
50, 60, 70, 80	1	[15]

2. Materials and methods

Convective drying is one of the substantial and prominent ways to dry agriculture produce. In the present study, thin onion slices are exposed to convective drying in high air velocity. The raw material preparation and drying is as discussed.

2.1. Raw material preparation

Fresh Indian dark red onions of medium size (around 50 to 60 mm diameter) were purchased from the local market in Pune, India. Randomly selected onions were cleaned and cut into slices of thickness about 5 to 6 mm perpendicular to the main axis. About 100 grams onion slices were kept in a single layer in the clean and tray, inside a drying chamber.

2.2. Experimental setup

A laboratory air dryer was used for conducting drying of onion slices (Figure 1). Air blower of 1200 CFM capacity with variable frequency drive (VFD) is used to deliver high velocity and volume of air. Thermistor controlled electric resistance heater is used for heating air, delivered by a blower. Heated air allowed to enter into the drying chamber. Drying chamber consists of the inlet, an outlet for air and produce loading glass door. The wire mesh tray was suspended vertically in the drying chamber. The tray was attached to an electronic analytical balance (HMT-EMFC, accuracy: 0.01 gram), which is used to measure moisture loss periodically. The arrangement was made in such manner, that the onion slices remain isolated from ambient. Dry bulb temperatures were measured with PT-100 temperature sensors and recorded periodically with a data acquisition system. The air velocity was measured using a hot-wire anemometer (Lutron-AM 4204, accuracy: ±5%). The velocity of air was measured at the inlet and outlet of the drying chamber.

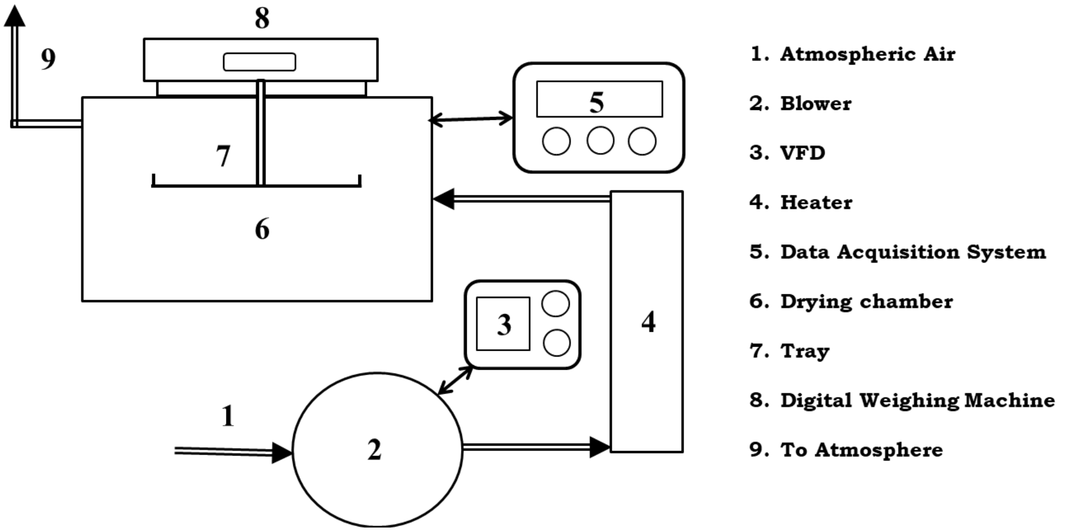

Figure 1. Schematic diagram of the experimental setup for convective drying of onion slices.

The drying tests were performed at a drying temperature of 50, 60, and 70 ℃ and at an air velocity of 2, 3.6, 5.7, and 7.7 m/s. The total duration of the drying test was 390 minutes, including 30 minutes for preheating. The weight of onion slices was measured after an interval of 30 minutes. Each experiment set was repeated thrice with fresh Indian dark red onion slices.

2.3. Wet basis moisture content, drying rate, effective moisture diffusivity, activation energy

The moisture content of the onion slices is measured in wet basis with the following equation (Eq 1).

$$M = \left[\frac{W_1 - W_2}{W_1}\right].100 \tag{1}$$

The drying rate specifies the rate of moisture removal concerning the previous state at a specific time. The average drying rate of the for drying agricultural produce is given by [16] (Eq 2).

$$D_r = \left[\frac{W_1 - W_2}{t_2 - t_1}\right] \tag{2}$$

Effective moisture diffusivity plays a very important role in clarifying the drying characteristic of any agriculture produce. Thin layer onion drying can be considered as an infinite slab. In the experimental setup, drying is taking place from both directions of onion slice. Effective moisture diffusivity can be calculated with Eq 3 proposed by Crank [17,18].

$$D_{eff} = \frac{F_o}{\left({}^{t}/_{L^2}\right)} \tag{3}$$

Fourier number required for calculation of effective moisture diffusivity can be calculated in the derived form as below (Eq 4) [18].

$$F_o = -0.101321183642 \ln MR - 0.021279295652 \tag{4}$$

The modified form of moisture ratio of the onion slices during drying was calculated using Eq 5 [19].

$$MR = \frac{W_2}{W_1} \tag{5}$$

Activation energy is an indicator of the necessity of kinetic energy required for chemical reaction to occur. The activation energy was calculated using the slope of $\ln D_{eff,avg}$ versus the reciprocal of the absolute drying air temperature ($1/T_{abs}$) [17,18]. The activation energy in the derived form can be calculated using Eq 6.

$$D_{eff} = D_o \exp\left[\frac{-10^3 . E_a}{R\ (T+273.15)}\right] \tag{6}$$

3. Results and discussion

The results obtained by analyzing effect temperature, the effect of high velocity, the effect of drying rate, and the effect of moisture removed per mass flow rate. Effective moisture diffusivity and activation energy were calculated and compared.

3.1. Effect of drying air temperature and high velocity on the moisture removal process

The drying air temperature and drying air velocity have a significant effect on the drying of Indian dark red onion slices. The moisture content variation is measured in % of grams of moisture or water removed per gram of dry matter (g/g) in a wet basis (w.b). The moisture content variation at temperatures of 50, 60, and 70 ℃ with drying time are shown in Figures 2–4, respectively.

Drying air velocity 7.7 m/s shows best-wet basis moisture removal at 360 min. drying duration for 50 ℃ (Figure 2). After 270 min drying duration, air velocity 5.7 m/s also shows almost similar moisture removal. It has been observed that for 50 ℃ air temperature in 180 minutes of drying time, 62.90% moisture is removed for 7.7 m/s air velocity, and 61.73% moisture removed for 3.6 m/s air velocity. Lowest moisture removal observed at 2 m/s drying air velocity. Out of total moisture removed, 75% moisture removed at 215 min. with 7.7 m/s, 219 min. with 3.6 m/s, 233 min. with 5.7 m/s and 258 min. with 2 m/s. All the curves show the exponential nature, which indicates that the moisture content removal process shrinks more slowly, as moisture content get reduces.

Drying air velocity 7.7 m/s shows best-wet basis moisture removal at 360 min. drying duration for 60 ℃ (Figure 3). Lowest moisture removal observed at 2 m/s drying air velocity. In 180 min. out of total moisture removed, 68.07% moisture removed with 7.7 m/s, 66.82% with 5.7 m/s, 66.35% with 3.6 m/s. 3.6 and 5.7 m/s drying velocity exhibit almost equivalent moisture removal. Out of total moisture removed, 75%, 50%, 25% moisture removed at 202 min., 135 min., 67 min. respectively with 5.7 m/s. Similarly, for 75%, 50%, 25% moisture removal observed at 203 min., 136 min., 68 min. respectively with 3.6 m/s. For higher velocities (i.e., for 5.7 and 7.7 m/s), it shows seamless logarithmic in nature, compared to 2 and 3.6 m/s.

Drying air velocity 7.7 m/s illustrates the best and 2 m/s illustrate the lowest wet basis moisture removal at 360 min. drying duration for 70 ℃ (Figure 4). Similar to 60 ℃, moisture content removal curves for 5.7 and 7.7 m/s, exhibit logarithmic nature in a better manner.

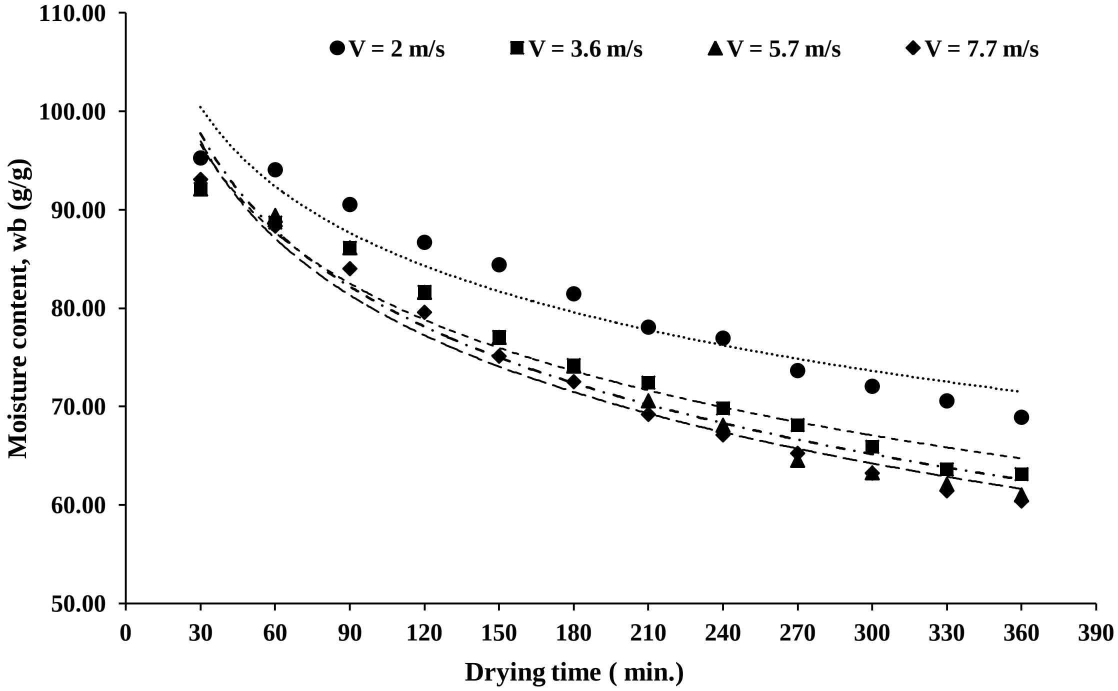

Figure 2. Variation in wet basis moisture content with drying time at 50 °C.

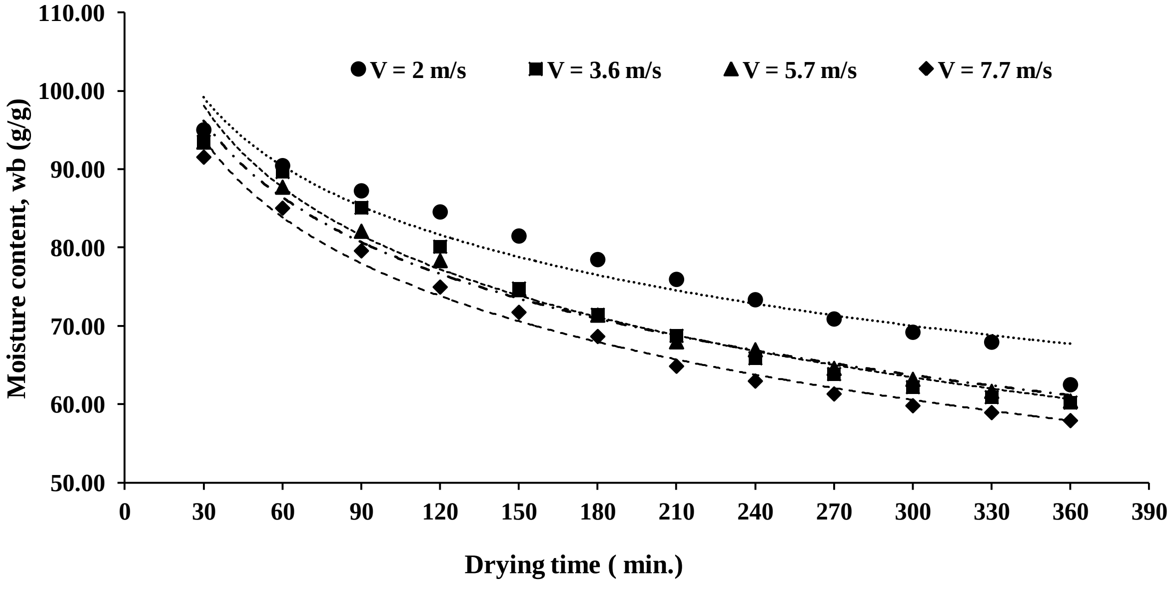

Figure 3. Variation in wet basis moisture content with drying time at 60 °C.

Out of total moisture removed, 75% moisture removed in half duration for 7.7 m/s. By reducing velocity to 5.7 m/s, 20 min. more required to remove 75% moisture, similarly 13 min. more to remove 75% moisture with 3.6 m/s and 13 min. to remove moisture with 2 m/s.

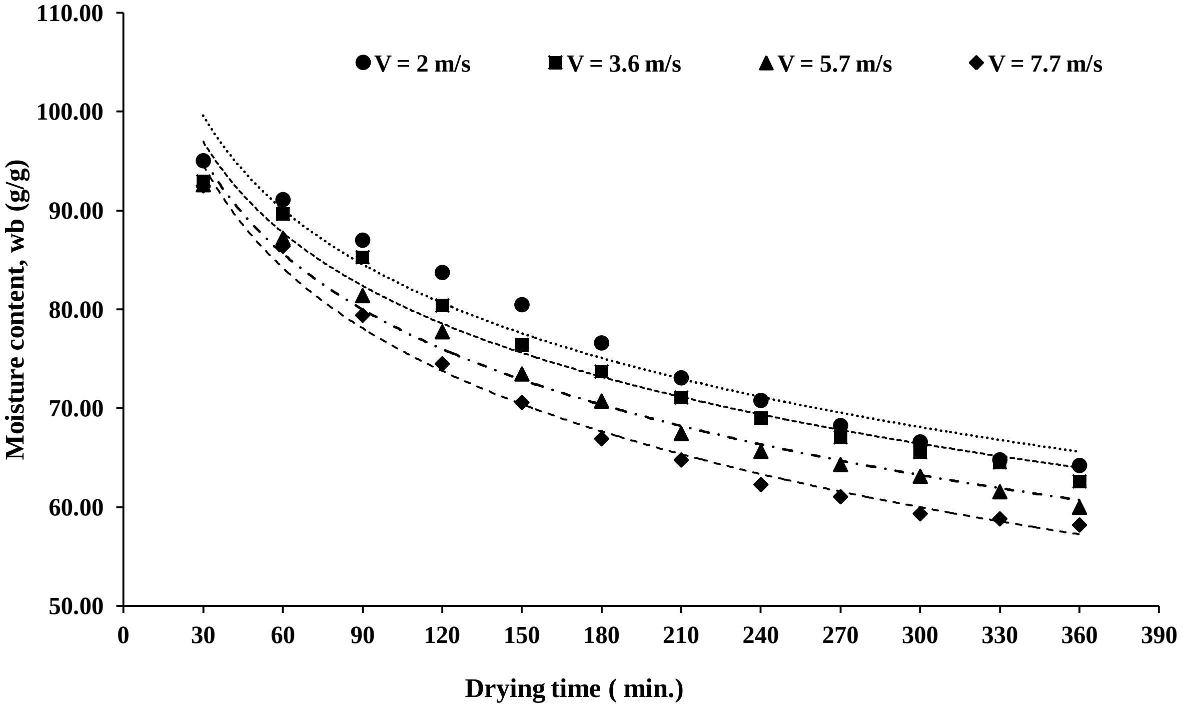

Figure 4. Variation in wet basis moisture content with drying time at 70 °C.

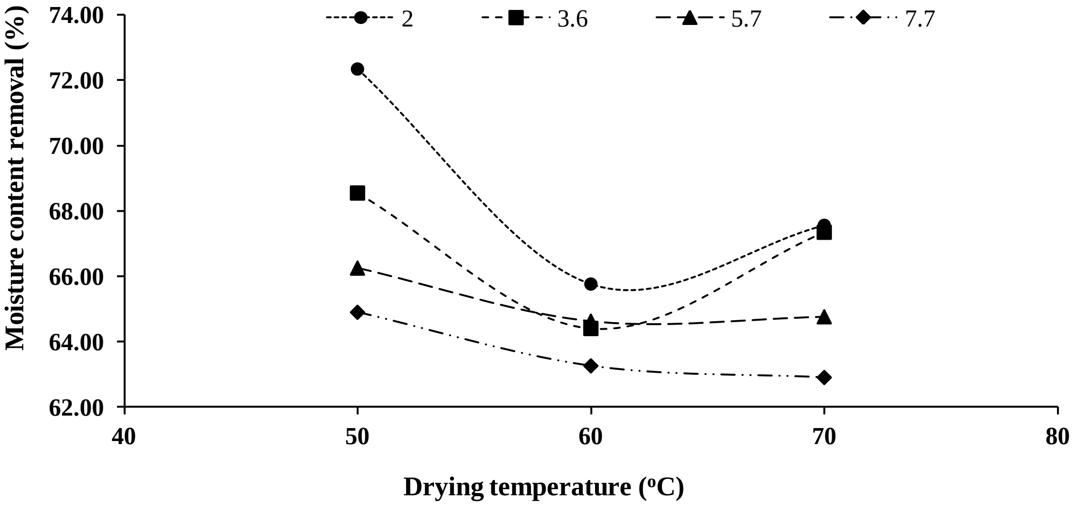

Figure 5. Variation in moisture content removal with drying temperature.

In total, the moisture content—drying time plot is impartially smoother. Processing experimental raw data, similar observation is also stated by Kemp et al. for drying kinetics [20].

Moisture removal process from Indian dark red onion accelerates as temperature increases. Similar observation also stated by Kiranoudis et al. [21], Olalusi [22], and Demiray et al. [23] for the nearly same range of inlet air temperature.

During all drying curves, a falling rate period is observed, whereas the constant drying period is expeditious and challenging to measure. Olalusi [22], Demiray et al. [23], and Kalbasi [24] specified and confirmed that onion is hygroscopic in nature, it rapidly enters and exhibits a falling rate period. A similar observation is detected in the current study, which proves that in onion drying, only a falling rate period is observed.

Randomly selected Indian red onions are used for conducting experiments. Each onion may have a slight variation in initial moisture content. It increases the difficulty level for selecting suitable parametric values for the best results. For selecting appropriate parametric values, analysis is made considering 100% moisture has consisted initially in each onion sample. Based on the final weight observations, the result of this analysis with all velocity is shown in Figure 5 for 360 min. drying duration.

The lower value of the percentage of moisture present in the onion slice indicates a better degree of drying. The best moisture removal rate is observed for 7.7 m/s air velocity irrespective of air drying temperature. The lower moisture removal rate is found at 50 ℃, irrespective of air velocities. For air velocity 2 and 3.6 m/s, the moisture removal rate at 60 ℃ is better than 50 and 70 ℃. Also, for air velocity 5.7 m/s, the moisture removal rate at 60 ℃ is slightly better than 70 ℃. Air velocity 2, 3.6, and 5.7 m/s exhibit a better moisture removal rate at 60 ℃ than 50 and 70 ℃.

In the present study, it is observed that air velocity plays a vital role in the drying process. Dehydration process from Indian dark red onion also accelerates as velocity increases.

These observations are in contrast with the results stated by Kiranoudis et al. [21] for air velocity 3, 4 ,5 m/s. Kiranoudis et al. proposed an empirical mathematical model with nonlinear regression for drying onion and green pepper. Based on model constants, Kiranoudis et al. commented that air velocity does not improve the model further. McMinn and Magee [25] and Sarsavadia et al. [6] reviewed and observed that for high moisture content produce as air velocity increases, the moisture removal process also accelerates. The present results are in line with these comments.

Also, others researchers' comments on air velocity are not evocative in comparison with the present study, as operating velocity range is less than 2 m/s [26–28].

In total, it can be clinched that, moisture content removal curves for upper velocities (i.e., for 5.7 and 7.7 m/s), it shows seamless logarithmic in nature, compared to 2 and 3.6 m/s. Logarithmic curves clearly indicate that moisture content removal initially raises rapidly, then progressively slows down.

3.2. Effect of drying air temperature and high velocity on moisture removal per unit mass flow rate

Airflow is a critical functional constraint in analyzing the moisture removal process. The moisture removal process of Indian dark red onion slices can be better to understand if the comparison is made with a mass of air utilized per unit time. The wet basis moisture content per unit mass flow rate variation at an air velocity of 2, 3.6, 5.7, and 7.7 m/s with drying time are shown in Figures 6–9, respectively.

The ratio of moisture content and mass flow rate for 50, 60, and 70 ℃, displays a downward trend with drying time. For 50 ℃, this ratio is more scattered compared to 60 and 70 ℃ (Figure 6). The moisture removal process at 50 ℃ and 2 m/s is observed slow and may not be smooth. The ratio for 60 ℃ is showing better results for 2 m/s velocity.

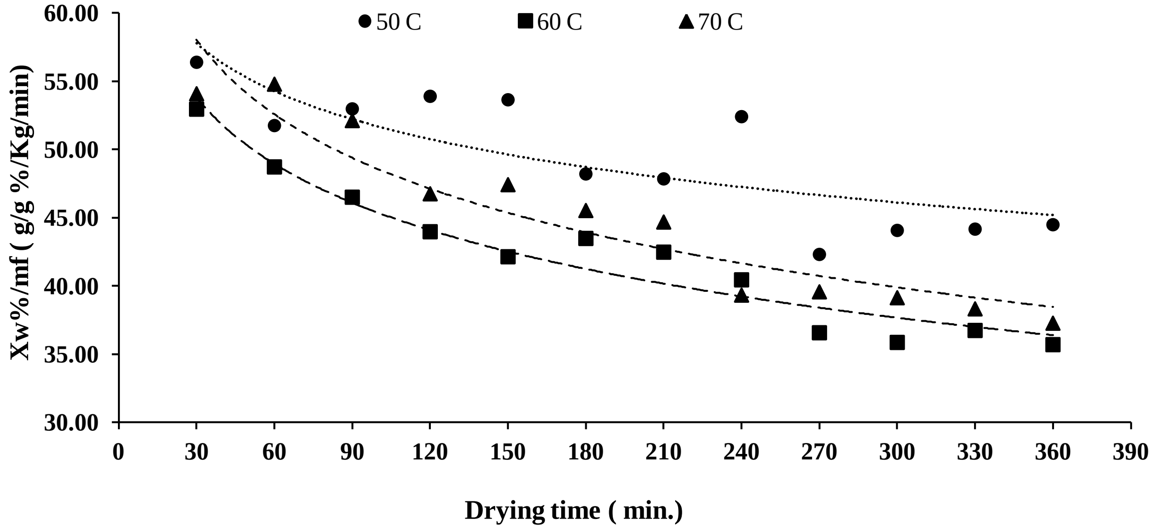

Figure 6. Variation in the ratio of moisture content and mass flow rate with drying time at 2 m/s.

For 3.6 m/s, 50 °C and 70 °C temperature shows almost analogous results for removing moisture content per mass flow rate (Figure 7). Even after 210 min. 50 °C shows a better result than 70 °C, and this may be results of the surface layer of tightly packed shrunk cells, occurring at 70 °C, this situation may delay moisture release activity. At 3.6 m/s, better results are observed for 60 °C.

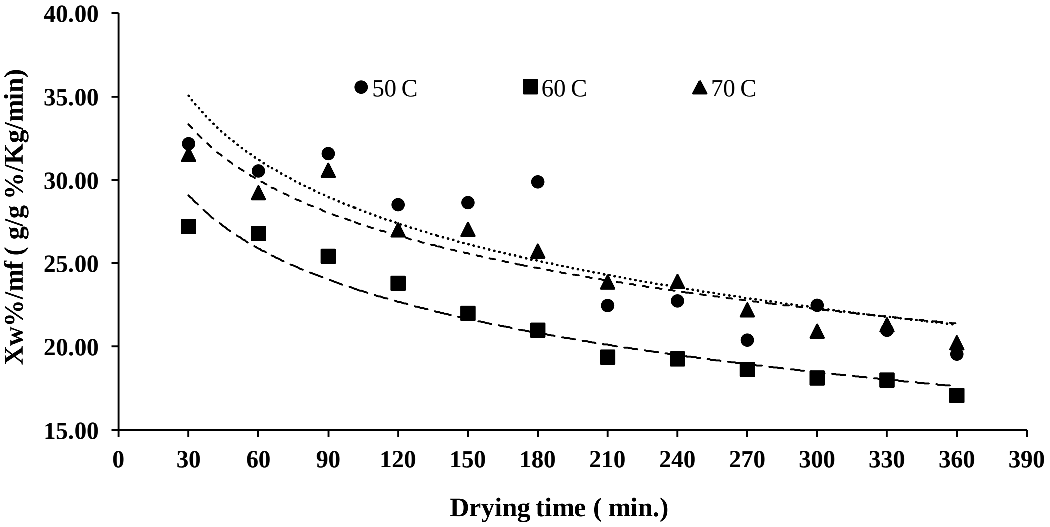

Figure 7. Variation in the ratio of moisture content and mass flow rate with drying time at 3.6 m/s.

For 5.7 m/s, the ratio of moisture content and mass flow rate exhibit converging behavior throughout the drying time (Figure 8). 60 °C air temperature shows a slightly better result before 270 min. After 300 min. all the temperature curves show almost the same results at 5.7 m/s.

For 7.7 m/s, the different behavior has been observed for 50, 60, and 70 °C temperature curves (Figure 9). The temperature curves show diverging behavior opposite to 5.7 m/s. In the initial drying time, until 150 min, the drying profile 60 and 70 °C display the same trends. After 150 min., the drying profile 70 °C at 7.7 m/s, shows better results, in moisture content removed to mass flow rate ratio.

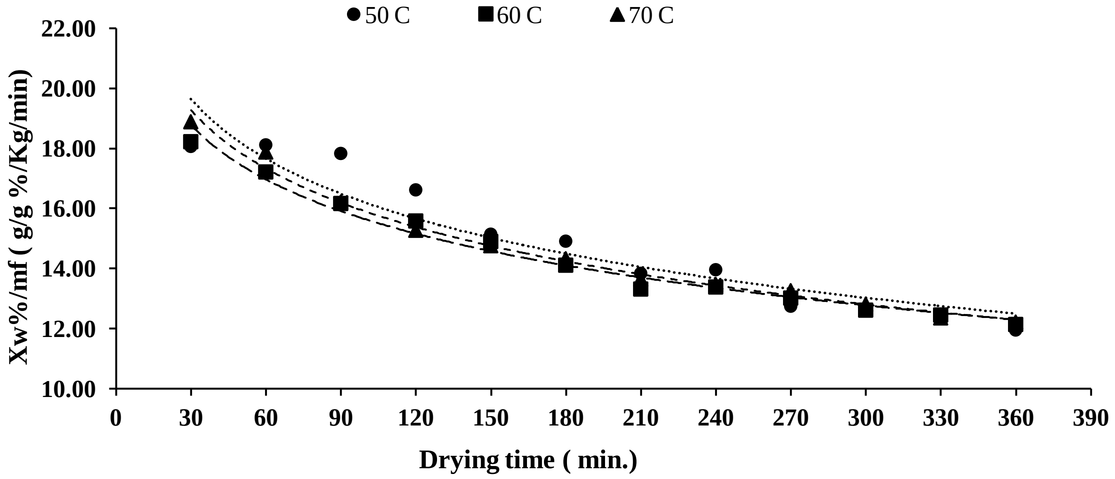

Figure 8. Variation in the ratio of moisture content and mass flow rate with drying time at 5.7 m/s.

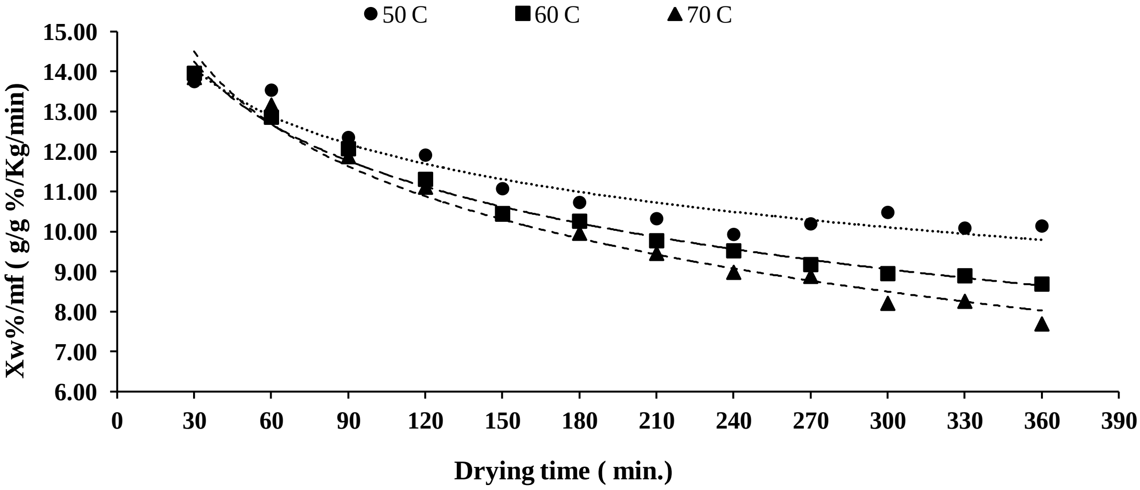

Figure 9. Variation in the ratio of moisture content and mass flow rate with drying time at 7.7 m/s.

The ratio of moisture removal to the mass flow rate range is around 57 to 35 for 2 m/s, 33 to 17 for 3.6, 19 to 11 for 5.7 m/s, and 14 to 7 for 7.7 m/s. In general, it is observed that, as velocity increases, the mass flow rate of air increases, and it leads to reduce the ratio of the wet basis moisture content per unit mass flow rate. It also indicates that at high velocity, the time available for collecting moisture is lesser; hence the ratio is lower. Whereas a high ratio indicates that more moisture is removed per mass flow rate.

3.3. Effect of drying air temperature and high velocity on drying rate

The drying rate specifies the rate of moisture removal concerning the previous state at a specific time. The drying rate of Indian dark red onion slices for 50, 60, and 70 °C with drying time are shown in Figures 10–12 respectively. All the curves for different velocity indicate falling rate behavior.

The drying rate at 50 °C with velocity variation clearly indicate, that in the initial period, the drying rate is rising and after 120 min., it starts falling (Figure 10). Dropped drying rate is observed at 60, 150, 240, and 300 min. at for 2 m/s velocity. Very profound dropping in drying rate observed for 240 min., whereas slight dropping observed for 300 min. This dropping observed may be due to a delay in the migration of moisture from the lower layer to the upper layer. Minor dropping in drying rate observed for 90, 210, and 270 min. for 3.6 m/s. Similar minor dropping observed for 180, 240 min. for 5.7 m/s and at 180 min. for 7.7 m/s. It clearly indicates that, as velocity increases above 2 m/s, the drying rate becomes more stable for the falling period for 50 °C.

At 60 °C, falling of drying rate is observed after 60 min. for 2, 5.7 and 7.7 m/s velocity (Figure 11). For 3.6 m/s drying air velocity, it is observed that till 150 min. drying rate is increasing, and after 150 min., it is falling. An insignificant drop in drying rate is observed at some places for the different velocity at 60 °C, except 240 min. for 5.7 m/s velocity. At 60 °C, the smooth process of migration of moisture from the bottom layer to the surface is taking place.

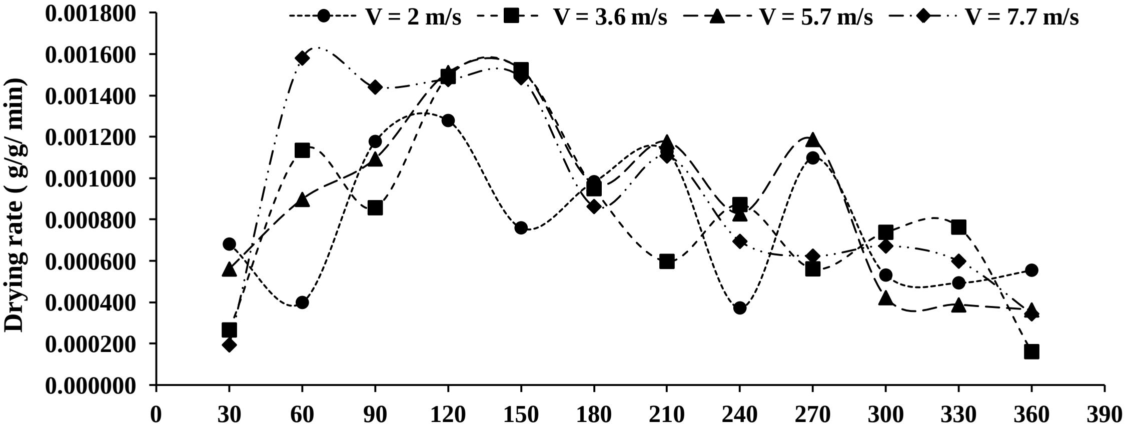

Figure 10. Variation of drying rate with drying time at 50 °C.

The drying rate for 70 °C indicates a falling period after 90 min. for 5.7 and 7.7 m/s (Figure 12). For 3.6 m/s drying air velocity, the falling period observed after 120 min. In the case of 2 m/s, the drying rate is not smooth, as dropping in drying rate is observed at 150, 240, and 300 min. and after

180 min. falling of drying rate is observed. It specifies that at 2 m/s velocity, the moisture migration process is not continuous compared to higher velocity at 70 °C.

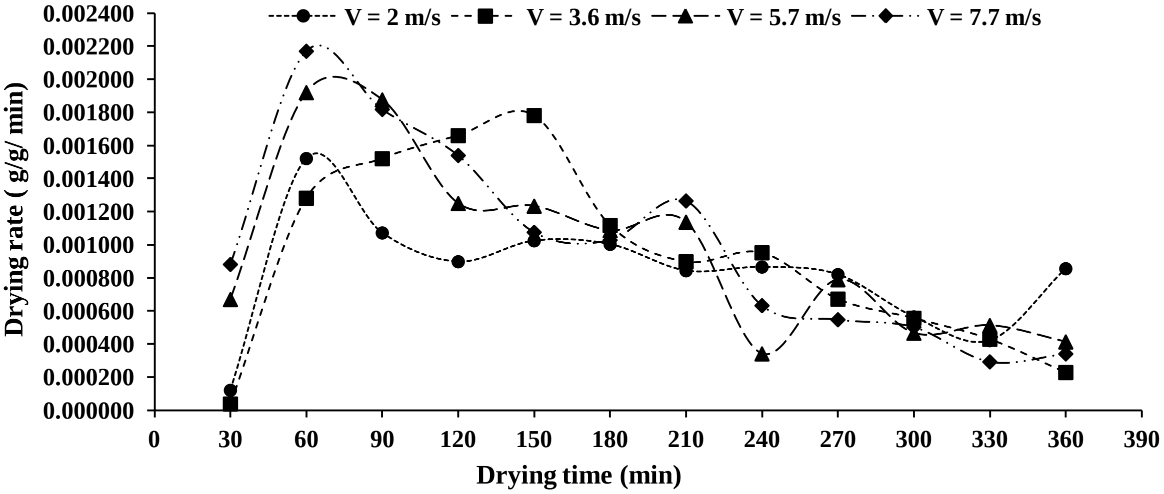

Figure 11. Variation of drying rate with drying time at 60 °C.

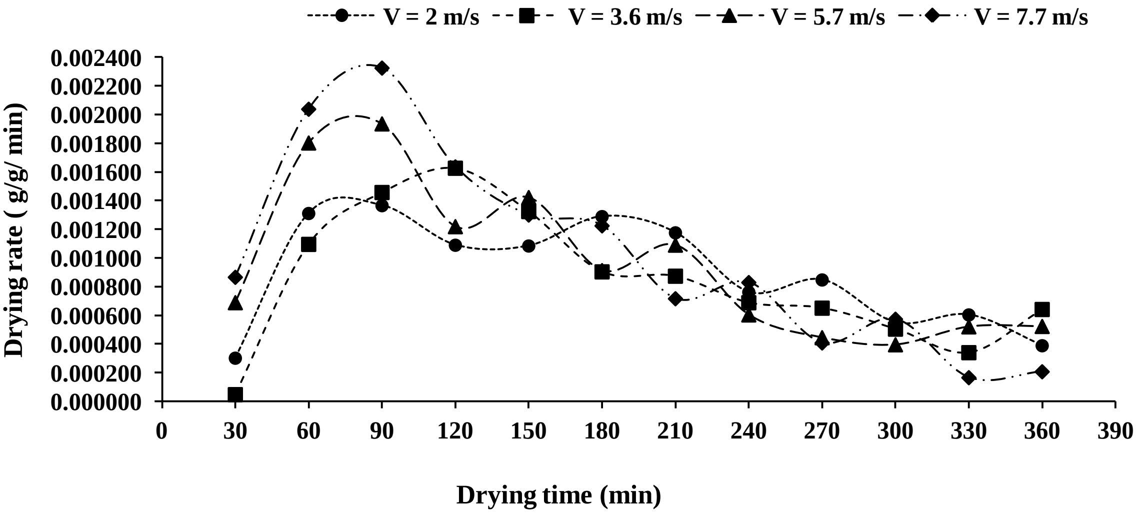

Figure 12. Variation of drying rate with drying time at 70 °C.

Better drying rate for 360 min. drying time observed for 3.6 m/s for 50 and 60 °C. For 70 °C, better drying rate observed for 7.7 m/s and least for 3.6 m/s over 360 min. In general, it can be observed that for 2, 5.7, and 7.7 m/s, a falling drying rate is observed after 90 min. for onion slices at 50, 60, and 70 °C. For 3.6 m/s, a falling drying rate is observed after 150 min. All the drying rate curves indicate that the moisture removal process from Indian dark red onion slices is stable and smooth for 3.6 and 7.7 m/s for 50, 60, and 70 °C. For 2 and 5.7 m/s, due to delay in migration of moisture from the lower layer to the upper surface, the process becomes shingly.

Overall, it is observed that the moisture content curve is smoother than the drying rate curve. In the present study, the drying rate plot typically has a substantial amount of random noise. As moisture content reduction takes place with elongated drying time, noise becomes more turbulent towards the end. Similar observation, also described by Kem et al. [20].

Inclusively it is observed that for 50 ℃, the drying rate is smoothly increasing with the rise in velocity till 5.7 m/s, whereas for 7.7 m/s velocity, the drying rate is decreased. As the mass flow rate of air is very high at 7.7 m/s, the continuous moisture removal process is not able to keep pace with air velocity. For 60 ℃, it is observed that the lowest drying rate is observed for 2 m/s, and at 3.6 m/s, the highest drying rate is found. After 3.6 m/s, with a rise in velocity, the drying rate falls dramatically, and again for 7.7, it is slightly improved. For 70 ℃ at 2, the velocity is sufficient to keep the drying rate smooth; hence it is observed high drying rate. At 70 ℃, due to case hardening of onion slices, with a rise in air velocity, moisture migration process becomes complicated, hence the drying rate is decreased suddenly for 3.6 and 5.7 m/s. At 7.7 m/s, the velocity overcomes the resistance of moisture migration, and high drying rate is observed. Inclusively it can be stated that in dark red onion, internal mass transfer resistance controls the moisture transfer process at high velocity compared to external resistance. This result is in line with McMinn and Magee [25].

3.4. Effect of drying air temperature and high velocity on effective moisture diffusivity and activation energy

The effective moisture diffusivity (D_{eff}) explicates the drying characteristics. Irrespective of the mechanism of diffusion, an effective diffusivity value (D_{eff}) describes the rate of moisture movement. Variation of effective moisture diffusivity for 50, 60, and 70 ℃ with air velocity is shown in Figure 13. The maximum effective diffusivity is observed for 70 ℃ at 7.7 m/s velocity, and the minimum is found for 50 ℃ at 2 m/s velocity. For 70 ℃, moisture diffusivity is maximum for all velocities except for 3.6 m/s. At 3.6 m/s velocity, maximum moisture diffusivity is observed for 60 ℃. The effective moisture diffusivity averagely increases with an increase in air temperature. Similar findings are observed by Bhong and kale [19], Pokharkar [29], Rahman S [30] and Revaskar et al. [31].

As air temperature rises, the capacity of air to absorb moisture increases proportionally. With higher velocity, the mass flow rate of air increases. The overall effect is experimental effective moisture diffusivity increases with a rise in velocity. Pathare and Sharma also noted similar findings for convective drying at lower temperatures and much lower velocity [18].

It is found that, for all drying temperature and velocity variation, the values for the arithmetic mean of effective moisture diffusivity lies between 1.096646×10^{-11} to 1.295467×10^{-11}. These values are within the general range of 10^{-8} to 10^{-12} m^2/s for drying of food materials [25].

Factors affecting diffusion energy are significant to clarify drying kinetics. Temperature is one of the robust parameters affecting diffusion energy. The activation energy (E_a) is the kinetic energy driven by temperature, required for the diffusion process of produce.

It is observed that for 3.6 m/s velocity, minimum activation energy is required (Table 2). Whereas for 7.7 m/s velocity, maximum activation energy is needed. Optimum use of energy for all temperature and air velocity variation observed at 3.6 m/s velocity. Though at 7.7 m/s better drying rate is found, but for this velocity, high activation energy is required.

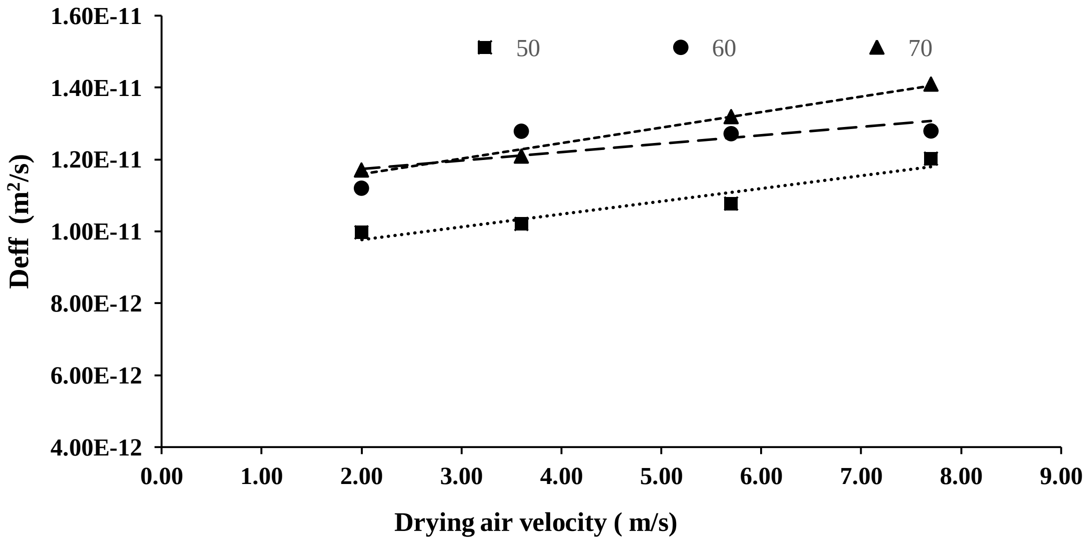

Figure 13. Variation of effective moisture diffusivity with drying velocity.

Table 2. Activation energy for different drying air velocity of onion slices.

Air Velocity (m/s)	Activation energy (kJ mol^{-1})
2	10.87098663
3.6	10.12023926
5.7	10.24719579
7.7	12.77198898

The activation energy for all drying temperature and velocity variation has been observed in the range of 10.8709 to 12.7719 kJ mol^{-1}.

4. Conclusions

From experimental data analysis of Indian dark red onion slices drying, the following findings are derived.

Moisture content removal curves for upper velocities (i.e., for 5.7 and 7.7 m/s), it shows seamless logarithmic in nature, compared to 2 and 3.6 m/s. It clearly indicates that moisture content removal initially raise rapidly, then progressively slows down. During all drying curves, a falling rate period is observed, whereas the constant drying period is expeditious and challenging to measure. Moisture removal process from Indian dark red onion accelerates as temperature increases. Dehydration process from Indian dark red onion also accelerates as velocity increases. Air velocity 2, 3.6, and 5.7 m/s exhibit a better moisture removal rate at 60 °C than 50 and 70 °C.

The ratio of moisture removal to the mass flow rate range is around 57 to 35 for 2 m/s, 33 to 17 for 3.6, 19 to 11 for 5.7 m/s, and 14 to 7 for 7.7 m/s. It is observed that, as velocity increases, the mass flow rate of air increases, and it leads to reduce the ratio of the wet basis moisture content per unit mass flow rate. It also indicates that at high velocity, the time available for collecting moisture is lesser; hence the ratio is lower.

All the drying rate curves indicate that the moisture removal process from Indian dark red onion slices is stable and smooth for 3.6 and 7.7 m/s for 50, 60, and 70 ℃. Owing to delay in migration of moisture, from the lower layer to the upper surface, the process becomes shingly for 2 and 5.7 m/s. In Indian dark red onion, internal mass transfer resistance controls the moisture transfer process at high velocity compared to external resistance.

The effective moisture diffusivity averagely increases with an increase in air temperature and air velocity. The maximum effective diffusivity is observed for 70 ℃ at 7.7 m/s velocity, and the minimum is observed for 50 ℃ at 2 m/s velocity. It is found that the values for the arithmetic mean of effective moisture diffusivity lie between 1.096646×10^{-11} to 1.295467×10^{-11}.

Optimum use of energy for all temperature and air velocity variation is observed at 3.6 m/s velocity. Though at 7.7 m/s better drying rate is found, but it requires high activation energy. The activation energy for all drying temperature and velocity variation observed in the range of 10.8709 to 12.7719 kJ mol^{-1}.

Considering moisture content removal, diffusivity analysis, and required activation energy, the best drying results for 360 min of convection drying attained with 3.6 and 5.7 m/s air velocity at 60 and 70 ℃ air temperature respectively.

The present study can be extended in the analysis of moisture removal at a diverse higher velocity and extended drying duration with different drying methods.

Nomenclature

Capital letters		
M	Moisture content	g water/g dry matter
V	Drying air velocity	m/s
T	Drying air temperature	℃
R	Universal gas constant	KJ/Kmol. k
W	Weight of sample	g
L	Diameter of onion slice	m
Small letters		
t	Drying duration	s
Subscripts		
1	Initial	
2	After time t	
Abbreviation		
CFM	Cubic feet per minute	ft^3/min
wb	Wet basis	
MR	Moisture ratio	
Deff	Moisture diffusivity	m^2/s
Ea	Activation energy for diffusion	KJ/mol
Fo	Fourier no	
Do	Arrhenius factor	m^2/s
Dr	Drying rate	g/g/s

Conflict of interest

The authors declare no conflict of interest in this paper.

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