Determination of Effective Moisture Diffusivity Considering Shrinkage for Vibration-Assisted Infrared Drying of Pumpkin

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Abstract. Drying characteristics and physical properties of pumpkin slices during vibration-assisted infrared (VIR), infrared (IR), and hot air (HA) drying were investigated. VIR drying exhibited the highest drying rate (0.1 g water/g dry matter·min) and shortest drying time (100 min), with drying efficiency influenced by IR intensity. Pumpkin slices dried under VIR drying at a middle IR intensity of 750 W/m² demonstrated superior product properties. Shrinkage was linearly correlated with moisture ratio. Effective moisture diffusivity (D_{eff}) ranged from 1.44×10^{-8} to 5.78×10^{-8} m^2/s for HA and VIR drying, respectively. Incorporating shrinkage effects, $D_{eff\text{-}S}$ decreased linearly with decreasing moisture ratio. $D_{eff\text{-}S}$ exhibited a strong negative correlation with shrinkage and a strong positive correlation with moisture content, moisture ratio, projected area, and volume.

Keywords: Moisture diffusivity; Shrinkage; Infrared drying

1 Introduction

Pumpkin, a versatile agricultural product, is widely cultivated and consumed globally. However, its high moisture content renders it susceptible to spoilage during post-harvest handling. Traditional drying methods are often time-consuming and result in product quality deterioration. To address these challenges, innovative drying techniques are required.

Infrared (IR) drying has emerged as a promising alternative due to its rapid heating and energy efficiency. However, the drying process can lead to uneven moisture distribution and shrinkage, affecting the final product quality. Vibration has been shown to enhance heat and mass transfer in various drying processes. Vibration-assisted infrared (VIR) drying has been effectively employed to process *Cissus quadrangularis* Linn., resulting in a dried product with significantly improved functional properties [1].

Accurate prediction of drying kinetics is essential for optimizing the drying process. Effective moisture diffusivity (D_{eff}) is a critical parameter in drying models, influencing the rate of moisture removal. Nonetheless, material shrinkage during drying can significantly alter the diffusion path, affecting the accuracy of D_{eff} estimation [2].

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This study focuses on determining the effective moisture diffusivity of pumpkin during VIR drying while considering the impact of shrinkage. By incorporating shrinkage into the diffusivity calculations, we aim to enhance our understanding of the drying process. In addition, the effectiveness of VIR drying in improving the drying characteristics and properties of pumpkin was investigated. The findings of this research will contribute to the development of more efficient and effective drying technologies for pumpkin and other agricultural products.

2 Materials and methods

2.1 Pumpkin and its preparation

Thai pumpkins (*Cucurbita moschata*) with an average weight of approximately 5 kg were selected for this experiment. The pumpkins were prepared in a rectangular shape with a dimension of 2 cm x 2 cm x 0.5 cm. The initial moisture content of the pumpkin flesh was determined using the moisture analysis method outlined in Section 2.3. This analysis revealed a moisture content of 9 g water/gram dry matter.

2.2 Drying experiments

The pumpkin flesh weighing approximately 200 g each was prepared for single-layer drying experiments. Three drying methods were investigated: vibration-assisted infrared (VIR), infrared (IR), and hot air (HA) drying. For the VIR and IR drying, the experiments employed varying infrared intensities of 500 W/m^2, 750 W/m^2, and 1000 W/m^2, chosen based on preliminary pumpkin drying trials. The VIR drying used a 750-rpm vibration, the minimum needed to flip pumpkin pieces for even drying. The HA drying method employed a drying temperature of 60 °C and an air velocity of 0.5 m/s. During drying, drying characteristic data, including moisture content, moisture ratio, and drying rate, was collected to determine the optimal drying time for a final moisture content of 0.5 g water/g dry matter in the dried pumpkin product. Experiments were conducted in triplicate. Physical properties of the pumpkin were also monitored throughout the drying process. These properties included area, volume, density, shrinkage, and color. This research investigates the diffusivity of water within the pumpkin material during drying by calculating the effective diffusion coefficient (D_{eff}) of moisture transfer. While traditionally calculated as a constant value, this study takes a more nuanced approach. We determine the effective moisture diffusivity as a function of shrinkage ($D_{eff\text{-}S}$), providing a more accurate representation of the changing diffusivity throughout the drying process.

2.3 Drying characteristic determination

Moisture content (MC) was determined using the standard oven-drying method. Samples were dried at 105°C for 24 hrs until a constant weight was achieved. MC was subsequently calculated using Eq. (1). Moisture ratio (MR) and drying rate (DR) were calculated using Eq. (2) and Eq. (3), respectively. Then, drying curves and drying rate curves were constructed to graphically represent the pumpkin's drying behavior.

$$MC = \frac{w_w - w_d}{w_d} \tag{1}$$

where MC is the moisture content (g water/g dry matter), w_w is the wet weight (g), and w_d is the dry weight (g).

$$MR = \frac{MC_t - MC_e}{MC_i - MC_e} \tag{2}$$

where *MR* is moisture ratio; and MC_t, MC_i, and MC_e are *MC* at specific time, and initial and equilibrium conditions (g water/g dry matter). For this study, MC_e was to zero.

$$DR = \frac{MC_{t1} - MC_{t2}}{\Delta t} \tag{3}$$

where *DR* is drying rate (g water/g dry matter·min); MC_{t1} and MC_{t2} are moisture at the previous time and any time (g water/g dry matter); and Δt is time difference (min)

2.4 Physical property evaluation

The physical properties of pumpkin samples, including projected area, volume, bulk density, shrinkage, and color, were assessed. The projected area was obtained by capturing images using a 3D microscope and processing them with EOS software. The dimensions were then measured using AxioVision SE64 software. The volume was determined using liquid displacement in n-heptane. The bulk density was subsequently calculated from the sample mass and bulk volume. The shrinkage was calculated as the percentage reduction in the sample's volume after drying, relative to its initial volume.

Pumpkin color was measured using a spectrophotometer (MiniScan EZ 4500, HunterLab, USA) and expressed in CIELab color space as L* (lightness), a* (red/green), and b* (yellow/blue) values. Then, total color difference (ΔE) was calculated as follows:

$$\Delta E = \sqrt{[(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2]} \tag{4}$$

where L_0*, a_0* and b_0* represent the color values of fresh samples, and L*, a* and b* represent the color values of samples dried at a specific time.

The physical properties of pumpkin were evaluated with five replications. Data were analyzed using analysis of variance (ANOVA) with a completely randomized design. Duncan's multiple range test ($p \leq 0.05$) was employed to compare treatment means. All statistical analyses were performed using SPSS V.29.

2.5 Effective moisture diffusivity calculation: Material shrinkage consideration and its correlation with drying characteristics and material properties

The falling rate period is typically the dominant phase in the drying of biological products. As moisture movement during this period is primarily governed by effective moisture diffusion, this mechanism is generally considered to control water transport. Fick's second law provides a foundational framework for describing diffusion, and its solutions have been applied to various regularly shaped bodies.

For an infinite plate like the pumpkin samples of this study, the moisture diffusion was modelled with the assumption that the plate is thin enough for one-dimensional diffusion to be considered. The effective moisture diffusivity (D_{eff}) can be determined from experimental drying data by fitting the MR over time (t) to a simplified analytical solution of Fick's second law. For an infinite plate, the moisture ratio is given by:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \tag{5}$$

where L is the half-thickness of the plate

The series can be approximated by considering the first term of the series for long drying time:

$$MR = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{6}$$

Taking the natural logarithm of both sides simplifies to:

$$ln\, MR \; = \; ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{4L^2} \tag{7}$$

Then, D_{eff} can be determined from the slope of the linear relationship between ln(MR) and t.

D_{eff} is a critical parameter in drying modelling, and its accurate estimation is essential for process optimization. However, the preceding calculations assumed constant diffusivity and temperature, negligible volume shrinkage, and insignificant external resistance. Considering the reality of material shrinkage over time, which alters both area and volume, this study aimed to determine the effective moisture diffusivity of pumpkin drying by incorporating shrinkage effects ($D_{eff\text{-}S}$) [3]. Accordingly, the moisture diffusion equation should be:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff-S} t}{\left(\frac{V}{A}\right)^2}\right) \tag{8}$$

where V and A are the volume and projected area of the material, respectively.

The correlation between $D_{eff\text{-}S}$ and various drying characteristics and pumpkin properties was quantified and visualized using a correlation matrix generated in MATLAB R2022a.

3 Results and discussion

3.1 Drying characteristics of pumpkin

Drying curves and representative drying rate (DR) curves are presented in Figs. 1 and 2, respectively. To achieve a final moisture content (MC) of 0.5 g water/g dry matter in dried pumpkin, infrared (IR) drying required 180, 130, and 105 min at IR intensities of 500, 750, and 1000 W/m², respectively. Vibration-assisted infrared (VIR) drying under the same IR intensities yielded drying times of 175, 120, and 100 min, respectively. In contrast, hot air (HA) drying at 60 °C took 420 min. These results demonstrate that IR radiation significantly reduced drying time compared to HA drying, more than halving the process duration. As anticipated, increasing IR intensity led to shorter drying times. VIR drying further reduced drying time by 5-10 min compared to IR drying.

DR curves revealed distinct drying stages. HA drying exhibited a long constant rate drying period with a low DR. This finding is consistent with findings by Diamante et al. [4] for hot air drying of kiwifruit under similar temperature (60-100 °C) and low air velocity (0.2 m/s) conditions. The occurrence of a constant rate period in this study is likely attributed to the low air velocity employed. In contrast, IR and VIR drying displayed exclusively falling rate periods, accompanied by significantly higher DRs compared to HA drying. Notably, VIR drying consistently yielded slightly elevated DRs relative to IR drying. Similar results were previously reported by Thanimkarn et al. [1].

3.2 Physical properties of pumpkin

Material shrinkage during drying is a common phenomenon attributed to heat and mass transfer, which induce stresses within the cellular structure, often leading to collapse. As depicted in Fig. 3, pumpkin shrinkage exhibited a linear correlation with MR, a trend consistently observed across all drying methods. This suggests that volume reduction primarily corresponds to water loss. Similar findings have been reported for banana [5] and potato slices [6].

Table 1 presents the projected area, volume, bulk density, shrinkage, and color difference (ΔE) of the dried pumpkin products. Marked differences were observed between the fresh and dried samples for all properties evaluated. HA-drying resulted in the lowest projected area and volume, coupled with the highest bulk density and shrinkage, indicating inferior product quality. Conversely, VIR750-drying yielded the most desirable product, characterized by the highest projected area and volume, and the lowest bulk density and shrinkage. Notably, VIR drying also minimized color changes in the pumpkin.

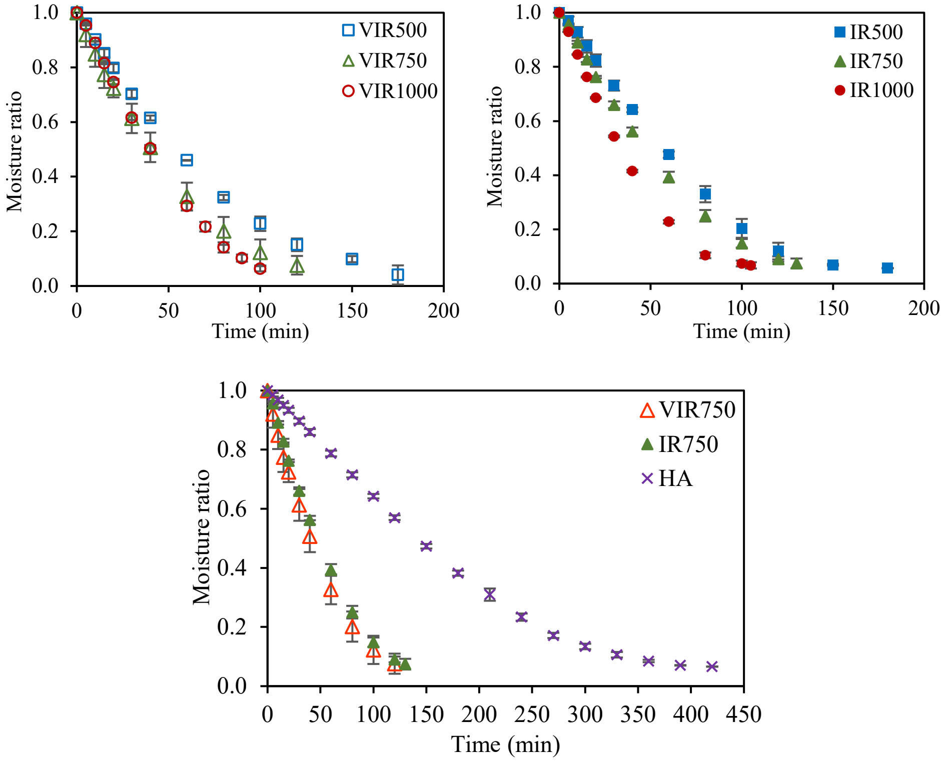


Fig. 1. Drying curves for VIR, IR, and HA drying of pumpkin under different drying conditions.

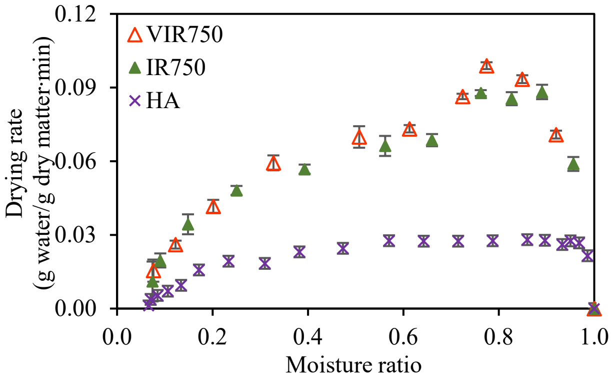


Fig. 2. Representative drying rate curves for VIR, IR, and HA drying of pumpkin.

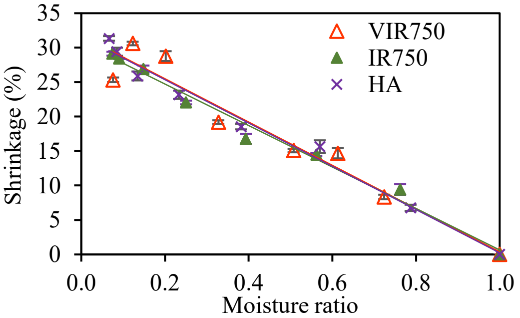


Fig. 3. Relationship between shrinkage and moisture ratio during VIR, IR, and HA drying of pumpkin.

Table 1. Properties of fresh and dried pumpkin produced by VIR, IR, and HA drying.

Treatment	Project area (cm²)	Volume (cm³)	Bulk density (g/cm³)	Shrinkage (%)	ΔE	Representative product*
Fresh	4.13±0.06	2.09±0.16	0.38±0.01	-	-	
VIR500	2.30±0.24bc	0.24±0.07c	0.48±0.08b	29.92±0.76c	1.07	
VIR750	2.58±0.21a	0.53±0.03a	0.31±0.02d	24.95±0.34d	0.95	
VIR1000	2.48±0.20ab	0.37±0.09b	0.41±0.01c	27.51±1.13c	9.29	
IR500	2.23±0.05c	0.22±0.01cd	0.49±0.01b	30.28±0.18ab	15.51	
IR750	2.43±0.03ab	0.27±0.01c	0.33±0.01d	29.13±0.28b	26.37	
IR1000	2.48±0.24ab	0.17±0.02de	0.60±0.04a	31.27±0.49ab	41.94	
HA	1.42±0.15d	0.16±0.02e	0.64±0.04a	31.34±0.34a	26.11	

*Micrographs were taken of HA, IR750, and VIR750 dried pumpkin samples under the same magnification of ×6.3.
Identical letters following mean ± SD values within the same column indicate no significant difference among the dried samples (p>0.05).

3.3 Effective moisture diffusivity of pumpkin

Effective moisture diffusivity (D_{eff}) values determined using the slope method for pumpkin dried under different drying methods and conditions are presented in Table 2 with R^2 greater than 0.9. Notably, D_{eff} values for IR and VIR drying were more than double those obtained from HA drying, indicating the superior efficiency of IR radiation in drying pumpkin. Furthermore, increasing IR intensity led to a corresponding increase in D_{eff}.

A comparison of these results with previous studies reveals some discrepancies. Tunde-Akintunde and Ogunlakin [7] reported D_{eff} values for 0.5 cm thick pumpkin slices dried by hot air at 40-80 °C and 1.5 m/s air velocity ranging from 1.19×10^{-9} to 4.27×10^{-9} m²/s. Onwude et al. [8] reported higher D_{eff} values (2.14×10^{-8} to 4.43×10^{-8} m²/s) for thinner pumpkin slices (0.4 cm). Ghaboos et al. [9] also reported lower D_{eff} values (0.71×10^{-9} to 2.86×10^{-9} m²/s) for 0.5 cm thick pumpkin slices dried using combined IR-vacuum drying. The observed differences in D_{eff} values may be attributed to variations in drying conditions, sample thickness, and drying methods employed in these studies. The higher D_{eff} values obtained in this study indicate enhanced moisture diffusion during the drying process, suggesting the effectiveness of the proposed IR and VIR methods for drying pumpkin.

As the diffusion path is influenced by material shrinkage during drying, incorporating this phenomenon into modeling can significantly enhance the prediction of moisture diffusivity. Katekawa and Silva [2] provide a comprehensive overview of various approaches employed to address shrinkage in drying models. While these methods often rely on empirical formulations, they have theoretical underpinnings and can effectively replace the momentum balance for fluid phases. Our findings, presented in Fig. 4, demonstrate a clear relationship between effective moisture diffusivity considering shrinkage ($D_{eff\text{-}S}$) and MR. A decreasing MR corresponds to a reduction in $D_{eff\text{-}S}$, with IR and VIR drying exhibiting more than double the $D_{eff\text{-}S}$ values compared to HA drying. In contrast to our findings, Touil et al. [10] observed an initial increase in $D_{eff\text{-}S}$ for prickly pear fruit and cladode during the first falling rate period of IR drying, followed by a stabilized value during the second period. This discrepancy indicates that factors beyond the simple diffusion path, such as changes in cell wall structure or alterations in moisture binding forces, may significantly influence moisture diffusivity in these specific materials [10].

Fig. 5 illustrates the correlation between $D_{eff\text{-}S}$ and various drying characteristics and properties of pumpkin. A strong positive correlation was observed between $D_{eff\text{-}S}$ and MC, MR, projected area, and volume, while a pronounced negative correlation existed with shrinkage. Interestingly, DR exhibited no significant correlation with MC, MR, or any other parameter. Similarly, bulk density and ΔE displayed minimal correlations with the other variables.

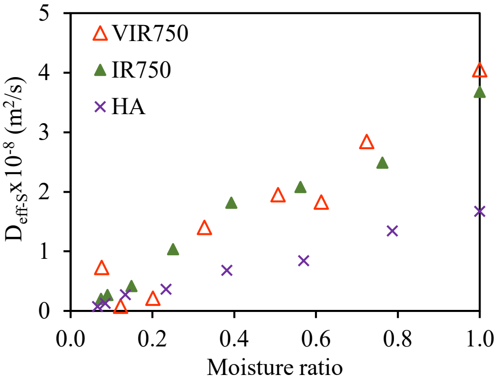
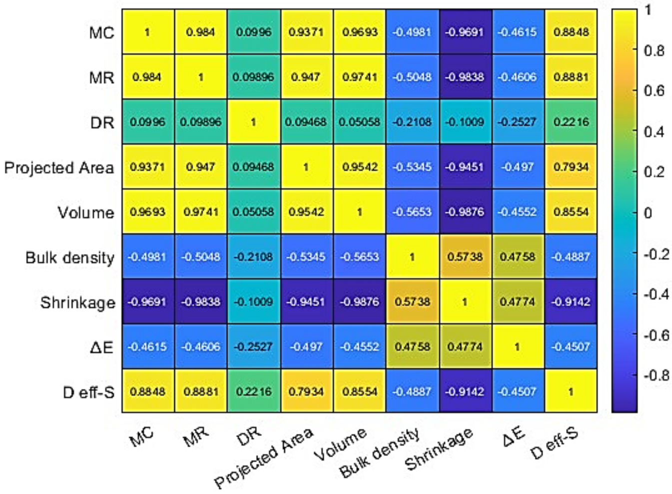


Fig. 4. Relationship between effective moisture diffusivity considering shrinkage ($D_{eff\text{-}S}$) and moisture ratio for VIR, IR, and HA dried pumpkin.



	MC	MR	DR	Projected Area	Volume	Bulk density	Shrinkage	ΔE	D eff-S
MC	1	0.984	0.0996	0.9371	0.9693	-0.4981	-0.9691	-0.4615	0.8848
MR	0.984	1	0.09896	0.947	0.9741	-0.5048	-0.9838	-0.4606	0.8881
DR	0.0996	0.09896	1	0.09468	0.05058	-0.2108	-0.1009	-0.2527	0.2216
Projected Area	0.9371	0.947	0.09468	1	0.9542	-0.5345	-0.9451	-0.497	0.7934
Volume	0.9693	0.9741	0.05058	0.9542	1	-0.5653	-0.9876	-0.4552	0.8554
Bulk density	-0.4981	-0.5048	-0.2108	-0.5345	-0.5653	1	0.5738	0.4758	-0.4887
Shrinkage	-0.9691	-0.9838	-0.1009	-0.9451	-0.9876	0.5738	1	0.4774	-0.9142
ΔE	-0.4615	-0.4606	-0.2527	-0.497	-0.4552	0.4758	0.4774	1	-0.4507
D eff-S	0.8848	0.8881	0.2216	0.7934	0.8554	-0.4887	-0.9142	-0.4507	1

Fig. 5. Correlation matrix of drying characteristics, material properties, and effective moisture diffusivity considering shrinkage ($D_{eff\text{-}S}$) for VIR, IR, and HA dried pumpkin.

Table 2. Effective moisture diffusivity (D_{eff}) and coefficient of determination (R^2) for linear drying models (ln(MR) vs. drying time) of VIR, IR, and HA dried pumpkin.

Treatment	D_{eff} (m^2/s)	R^2	Treatment	D_{eff} (m^2/s)	R^2
VIR500	3.5969×10^{-8}	0.9285	**IR500**	3.6222×10^{-8}	0.9308
VIR750	4.4835×10^{-8}	0.9499	**IR750**	4.1795×10^{-8}	0.9301
VIR1000	5.3194×10^{-8}	0.9010	**IR1000**	5.7753×10^{-8}	0.9481
HA	1.4438×10^{-8}	0.9347			

4 Conclusions

VIR and IR drying outperformed HA drying, reducing drying time by 76%. While HA drying exhibited constant and falling rate periods, VIR and IR drying occurred primarily in the falling rate phase. Notably, VIR and IR drying rates were approximately threefold higher than that of HA drying. Shrinkage displayed a linear relationship with moisture ratio, consistent across all drying methods. VIR drying at 750 W/m² yielded superior product properties. Effective moisture diffusivity (D_{eff}) for VIR and IR drying ranged from 3.6×10^{-8} to 5.8×10^{-8} m^2/s, increasing with IR intensity. In contrast, HA drying exhibited a significantly lower D_{eff} of 1.4×10^{-8} m^2/s. Incorporating shrinkage effects, $D_{eff\text{-}S}$ decreased with decreasing moisture ratio. $D_{eff\text{-}S}$ demonstrated a strong negative correlation with shrinkage and positive correlations with moisture content, moisture ratio, projected area, and volume.

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