Drying Kinetics of Tomato Slices: Thin Layer Modelling of Temperature and Slice Thickness Using Cabinet Tray Drying Technique

Mohit Rank[1], S. S. Kapdi[2]

[1]M. Tech Research Scholar, Department of Food process engineering, College of food processing technology and bio-energy, Anand agricultural University, Anand, Gujarat, India
[2]Professor, Department of Food process engineering, College of food processing technology and bio-energy, Anand agricultural University, Anand, Gujarat, India

---***---

Abstract - *This study investigates the drying kinetics of tomato slices under varying conditions, including temperature and slice thickness, using cabinet tray drying. The drying process reveals distinct behaviors based on these parameters. Thicker slices exhibit higher initial moisture content and, consequently, elevated moisture ratios at the start of drying. As drying progresses, moisture ratios decrease, leading to a reduction in drying rates, particularly during the falling-rate drying phase. The drying time is influenced by initial thickness, with thicker slices requiring more time to reach the desired moisture content. Six thin-layer drying models are employed, including the Henderson-Pabis, Page, and Newton models, to analyses the experimental data. The Henderson-Pabis model consistently demonstrates the best fit, as indicated by high R^2 values and low RMSE and SSE values. These findings offer valuable insights into optimizing tomato drying processes and enhancing food preservation practices.*

Key Words: Tomato, Tray dryer, Thin layer modelling, Drying rate, Drying behaviour

1.INTRODUCTION

Drying stands as one of the earliest methods for preserving food, employed by humanity to extend the longevity of food items. This process facilitates year-round availability of seasonal foods, catering to the cravings of culinary enthusiasts. Moreover, it cuts down on transportation expenses by reducing weight, volume, packing requirements, and storage space [1]. Within drying, both heat and mass transfer occur in tandem. Moisture is extracted from food products and conveyed away by hot drying air. Among renewable energy sources, solar energy finds application in directly drying food items under the sun. However, this traditional method necessitates substantial space, offers limited drying control, incurs high labour costs, and compromises product quality due to exposure to dust, insects, birds, and external particles [2]. To surmount these challenges, enhancements in sun drying have given rise to solar drying, shielding food from contaminants and weather fluctuations while preserving its nutritional attributes [3].

Tomatoes (Lycopersicon esculentum) hold a significant position among vegetables and are the second most produced vegetable crop [4]. Despite their importance, tomatoes have high water content and are easily spoilable. To make them available and usable during non-growing seasons, dehydration is needed, while preserving their nutritional and sensory qualities. Dried tomatoes can be processed into powder and used as an ingredient in various food products. Interestingly, around 23% of tomatoes with good quality face rejection in the market [5]. Anticipating how fast these tomatoes dry under different conditions is crucial for designing drying systems. Running large-scale tests for various products can be expensive and impractical. Here, a simulation model comes in handy it's a valuable tool for foreseeing how drying systems will perform [2]. This means we can use computer models to predict how well tomatoes will dry using cabinet tray drying method, saving time and resources.

In the field of modelling, the foundation lies in crafting a set of mathematical equations that effectively unravel the intricacies of a system. The ultimate goal is to obtain solutions to these equations that empower us to compute process parameters over time, at any given point within the drying apparatus. This calculation hinges solely on the primary conditions driving the process [6]. In light of this, employing a simulation model assumes significant importance. It emerges as a pivotal tool for foretelling the performance of drying systems. This research had a specific aim: to assess and formulate models that capture the kinetics of drying, which encompasses the mass transfer dynamics during the process of hot-air drying for tomatoes. Additionally, the study delved into how various conditions within the air dryer environment impact the kinetic constants embedded in these proposed models.

2. MATERIALS AND METHODS

2.1 Samples Preparation with Treatments:

Fresh tomatoes of the Anand Roma variety were gathered from the research field at the Regional Research Station, AAU, Anand. To mitigate the heat impact from harvesting, the tomatoes were moved from the field and placed in a shaded area at the Department of Food Process Engineering, FPT&BE, AAU, Anand for an hour. Afterward, the tomatoes were cleaned with tap water to eliminate any remaining dirt and sorted to remove unhealthy, infected, or damaged ones. Following this, the sound tomatoes were sliced into three varying thicknesses: 3mm, 5mm, and 7mm. These slices underwent a preliminary treatment by immersing them in a solution comprising 1% $CaCl_2$ (calcium chloride) and 0.2% KMS (potassium metabisulfite) for 10 minutes. The intention of this preliminary treatment was to enhance the quality and preservation of the tomato slices, facilitating subsequent processing.

2.2 Mathematical Modelling of Drying

Effective moisture diffusivity indicates the effectiveness of drying. It is denoted by D_{eff} and expressed in m^2 /s.

Falling rate drying can be explained by Fick's second law of unsteady state diffusion, which can be represented as follows:

$$\frac{\partial M}{\partial t}=D_{eff}\left[\frac{d^2M}{dx^2}\right]$$

Where, D_{eff} = Effective moisture diffusivity, m^2/s

After applying the boundary conditions, the solution to the above differential equation for a slab with thickness L can be expressed as follows:

$$MR=\frac{8}{\pi^2}\sum_{n=0}^{n=\infty}\frac{1}{(2n-1)^2}\exp\left[-\frac{(2n-1)^2\pi^2 Deff\, t}{4L^2}\right]$$

In cases where drying time is long, the value of second and higher terms in the above equation decreases rapidly, hence the expression can be simplified as:

$$MR=\frac{8}{\pi^2}\exp\left[-\frac{\pi^2 Deff\, t}{4L^2}\right]$$

Taking natural logarithm (ln) on both the sides, the above equation can be further written as:

$$\ln MR=\ln\frac{8}{\pi^2}-\left[\frac{\pi^2 Deff}{4L^2}\right]t$$

A slope is then obtained by plotting ln MR against time t. The graph yields a straight line, hence the D_{eff} can be evaluated as follows:

$$Slope=-\frac{\pi^2 Deff}{4L^2}$$

The experimental value of D_{eff} can thus be evaluated from the above equation.

2.3 Thin Layer Modelling of the Drying Process

Thin layer models are empirical tools used in drying processes without considering the product's physical properties. These models require the calculation of the dimensionless moisture ratio and are assessed to find the most suitable model for a particular drying process. The moisture ratio is plotted against drying time, and the goodness of fit is determined using statistical analysis and value indicates a better fit to the drying process.

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

In the case of tomato drying, six different thin layer drying models were evaluated, including the Newton Model, Page Model, Henderson-Pabis Model, Wang and Singh Model, logarithmic Model, and Midilli Model. These models were applied to analyze and interpret the experimental data, leading to the determination of drying constants through model equations. The evaluation included assessing R^2 (coefficient of determination), R.M.S.E (root mean square error), and S.S.E (sum of squared errors) values to identify the most suitable model. The ideal model selection is based on achieving the highest R^2 value while minimizing R.M.S.E and S.S.E values.

Table -1: Thin layer drying equations

Thin layer model	Equation	Reference
The Newton model:	MR= exp (-kt)	[7]
The Page model:	MR= a*exp ($-kt^n$)	[8]
The Henderson-Pabis model:	MR= exp ($-kt^n$)	[9]
Wang and Singh:	MR=1 + at + bt^2	[10]
Logarithmic:	MR = a*exp(k*t) + c	[11]
Midilli:	MR = a*exp ($-k*t^n$) + bt	[12]

2.4 Statistical Analysis of Thin Layer Models

For drying model selection, drying curves were fitted to 6 well known thin layer drying models which are given in Table 1. The best of fit was determined using three parameters: higher values for coefficient of determination (R^2), reduced sum square errors (SSE) and root mean square error (RMSE) using Equations given below, respectively. The statistical analyses were carried out using SPSS 15 software. Statistical Analysis of Thin Layer Models

For drying model selection, drying curves were fitted to 6 well known thin layer drying models which are given in Table 1. The best of fit was determined using three parameters: higher values for coefficient of determination (R^2), reduced sum square errors (SSE) and root mean square error (RMSE) using Equations given below, respectively. The statistical analyses were carried out using SPSS 15 software.

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{n} \left(MR_{exp,ii} - MR_{pre,i}\right)^2}{\sum_{i=1}^{n} \left(MR_{exp,i} - MR_{pre,i}\right)^2} \right)$$

3 RESULTS AND DISCUSSIONS

3.1 Drying behavior of tomato Slices under different drying conditions

$$SSE = \frac{1}{N} \sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i}\right)^2$$

The study investigated the drying behavior of tomato slices under various drying temperatures and with different thicknesses. The drying process involved a complex interplay between moisture ratio, drying rate, moisture content, and drying time. Thicker slices initially had higher moisture content, leading to elevated moisture ratios at the beginning of drying. As the drying progressed, the moisture ratio decreased, causing a decline in the drying rate, particularly during the falling-rate drying period where moisture movement became more challenging. Over time, the moisture content decreased steadily, and the drying time was influenced by the initial thickness, with thicker slices requiring longer durations to achieve the desired moisture content The drying curves, illustrating drying rate vs. drying time, and moisture ratio vs. drying time, were plotted and depicted in charts 1 to 6.

3.2 Moisture content

The initial moisture content of tomato pieces/slices was 2041.33% d.b. (95.33%, w.b.). They were dried up to moisture content 7.70 to 8.18%, d.b. Reduction in moisture content of tomato was observed faster in case of 3 mm thick slices compared to 5 mm thick and 7 mm thick slices. All these curves show decreasing trend exponentially. There is effect of temperature in case of tray dryer and tray height in case of greenhouse dryer on reduction of moisture content. The total drying time was in range of 8 hours for 65°C and 3mm slice thickness to 25 hours for 45°C and 7mm slice thickness in tray dryer.

3.3 Moisture ratio

The reduction of the moisture ratio from 1 to 0 occurs at varying drying times for different drying temperatures in the tray dryer and different tray heights in the greenhouse dryer during the drying of tomato slices. The moisture ratio, which represents the initial moisture content relative to the moisture content at a specific drying time, has a significant influence on the drying rate. At the initial stages with high moisture ratios, the drying rate is faster due to the substantial difference in moisture content between the slices and the drying medium. As the drying process advances and the moisture ratio decreases, the drying rate slows down, approaching a state of equilibrium between the slices and the drying medium. During the falling-rate drying period with low moisture ratios, the drying rate decreases even further as moisture movement becomes more challenging. Notably, the moisture ratio decreases more rapidly in the case of 3 mm thick tomato slices compared to slices of 5 mm and 7 mm thickness.

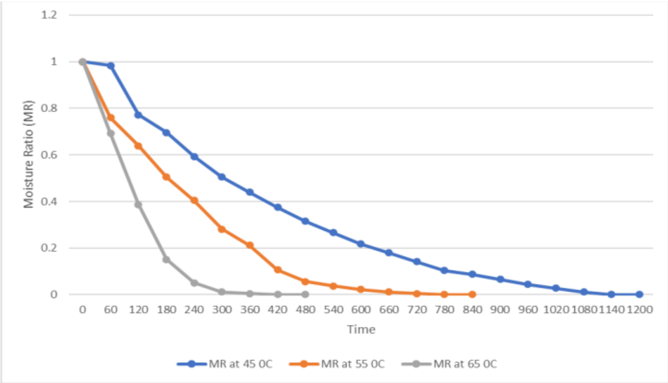

Chart -1: Moisture ratio against drying time at various temperatures for 3 mm slice thickness.

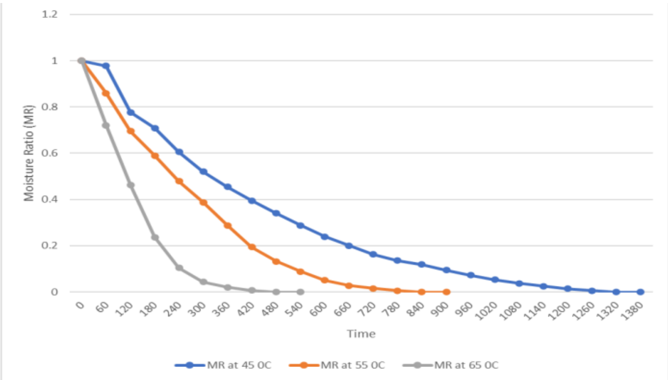

Chart -2: Moisture ratio against drying time at various temperatures for 5 mm slice thickness.

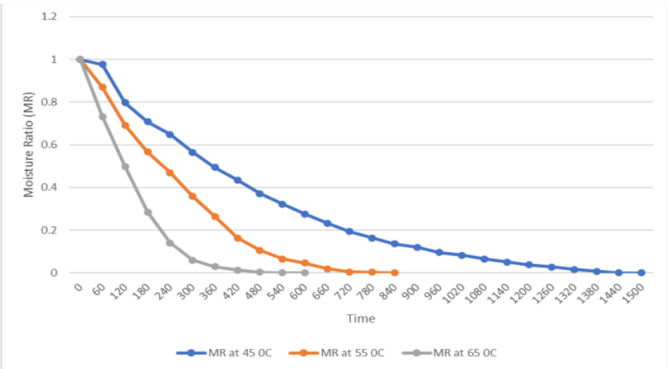

Chart -3: Moisture ratio against drying time at various temperatures for 7 mm slice thickness.

3.4 Drying rate

At the beginning, drying is rapid as there is an excess of moisture in the slices. As the process continues, the drying rate gradually slows down during the constant rate drying phase, governed by heat and mass transfer mechanisms. Subsequently, in the falling rate drying phase, the rate further decreases due to the diffusion of moisture from the interior of the slices to the surface. Eventually, the drying rate approaches zero as the moisture content reaches its equilibrium level with the drying environment. The drying rate of tomato was decreased faster in the case of 3 mm thick slices compared to 5 mm thick and 7 mm thick slices.

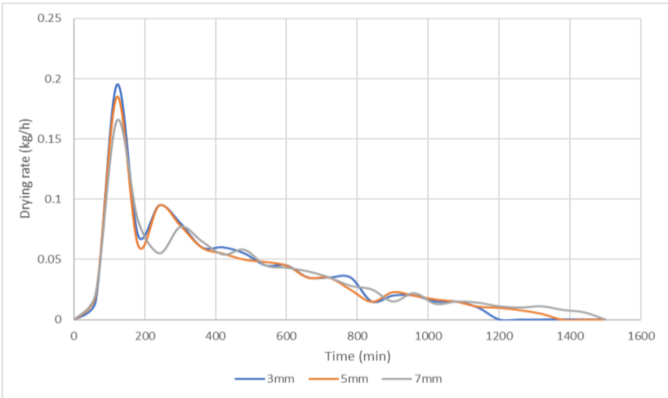

Chart -4: Variation in drying rate with drying time at 45°C in trey dryer

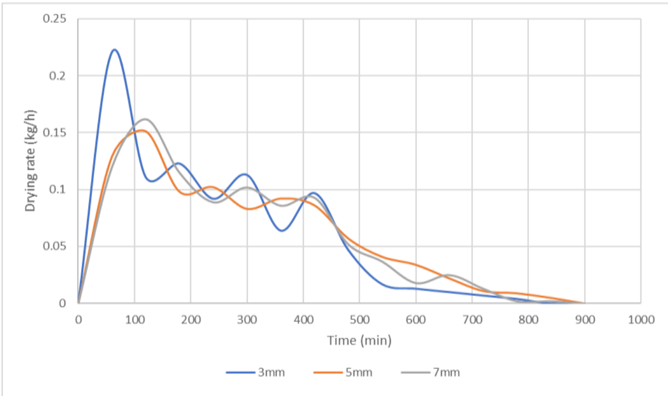

Chart -5: Variation in drying rate with drying time at 55°C in trey dryer

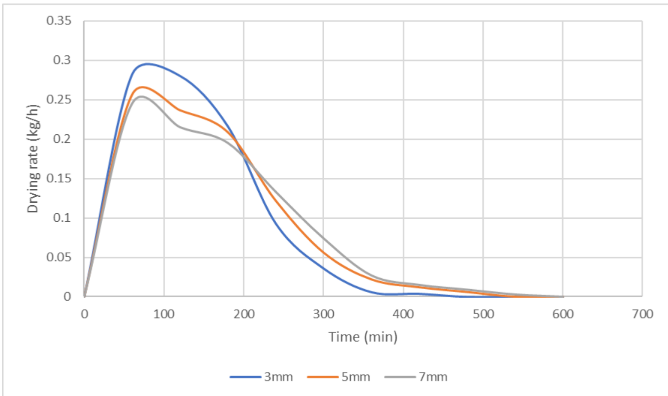

Chart -6: Variation in drying rate with drying time at 65°C in trey dryer

3.5 Thin layer modelling

The parameters corresponding to distinct models at various temperatures are documented in a table 2. Thin layer modelling of different drying techniques at different temperatures has been developed. The data were fitted in six different models suitable of drying similar commodities. Six models namely Newton Model, Page Model, Henderson-Pabis Model, Wang and Sing, logarithmic and Midilli were used to evaluate the data. The observed data were fitted in the given model equations. The drying constants were estimated using these model equations. The models were then analyzed for their R^2, R.M.S.E and S.S.E values to determine the best-fit model for the particular drying operation. The best fit is determined by the highest R^2 value with low R.M.S.E and S.S.E values. The parameters for different models at different temperatures have been given in the Table 2. The graphs were obtained by plotting experimental v/s predicted moisture content of best fit model are shown in chart 7 to 9. The Henderson and Pabis model shows the highest average R^2 value among the six fitted models for different treatments at all drying conditions. The R^2 value of Henderson and Pabis model ranged from 0.99238 to 0.99941 with an average value of 0.99696 in the tray dryer. The R.M.S.E value of Henderson and Pabis model ranged from 0.02849 to 0.00858 with an average value of 0.017 in the tray dryer. The S.S.E value of ranged from 0.00066 to 0.01218 with an average value of 0.00579 in the tray dryer. The highest R^2 values of the Henderson and Pabis model imply that this equation fits the data best. For added reference, the specific constants associated with the Henderson-Pabis model can be found in Table 3, further facilitating its utilization in future analyses and applications.

The Henderson and Pabis model is highly regarded in the context of thin-layer drying kinetics due to its simplicity, assumption of exponential behavior, applicability to thin layers, empirical success, and ease of parameter estimation. In a study by Das Purkayastha *et al.* (2013) [13] on tomato slice drying kinetics, it was found that the Logarithmic model was the most accurate, closely followed by the Henderson Pabis model. In another research conducted by Nabnean *et al.* (2014) [14] on osmotically dehydrated cherry tomatoes, the Page model performed exceptionally well, with the Newton model as well. Additionally, Sadin *et al*. (2014) [15] investigated the effects of temperature and slice thickness on tomato drying and identified the Midilli model as the most suitable for describing the kinetics of drying in an infrared dryer. These studies emphasize the crucial importance of choosing the appropriate model when studying the intricacies of tomato drying and provide valuable insights for similar research.

Table -2: Statistical analysis of different drying models at various tray heights and slice thicknesses for tomato slices drying

Drying parameters		Page model			Newton			Henderson-Pabis		
Temp. (°C)	Slice thickness (mm)	R^2	R.M.S.E.	S.S.E.	R^2	R.M.S.E.	S.S.E.	R^2	R.M.S.E.	S.S.E.
45	3	0.99548	0.02177	0.00995	0.99255	0.04547	0.04343	0.99550	0.02155	0.00976
45	5	0.99655	0.01863	0.00833	0.99483	0.03823	0.03507	0.99658	0.01841	0.00814
45	7	0.99732	0.01623	0.00685	0.99541	0.03640	0.03445	0.99732	0.01623	0.00685
55	3	0.99308	0.02686	0.01082	0.98811	0.04152	0.02586	0.99238	0.02849	0.01218
55	5	0.97849	0.36558	1.13837	0.98829	0.04984	0.03974	0.99639	0.02051	0.00673
55	7	0.99239	0.03889	0.02269	0.98738	0.05308	0.04227	0.99677	0.01951	0.00571
65	3	0.99942	0.00849	0.00065	0.98347	0.05349	0.02575	0.99941	0.00858	0.00066
65	5	0.99930	0.00905	0.00082	0.98728	0.04757	0.02263	0.99929	0.00920	0.00085
65	7	0.99908	0.01028	0.00116	0.98861	0.04480	0.02208	0.99905	0.01051	0.00121
Average		0.99457	0.05731	0.13329	0.98955	0.04560	0.03236	**0.99696**	**0.01700**	**0.00579**
Drying parameters		**Logarithmic**			**Midilli**			**Wang and Wing**		
Temp. (°C)	**Slice thickness (mm)**	R^2	**R.M.S.E.**	**S.S.E.**	R^2	**R.M.S.E.**	**S.S.E.**	R^2	**R.M.S.E.**	**S.S.E.**
45	3	0.99681	0.01771	0.00659	0.99685	0.01762	0.00652	0.99395	0.02447	0.01258
45	5	0.99670	0.01763	0.00746	0.86792	0.22769	0.24417	0.99226	0.02731	0.01790
45	7	0.00000	0.30420	2.40605	0.99809	0.01330	0.00460	0.99323	0.02548	0.01689
55	3	0.99286	0.02633	0.01040	0.84168	0.27573	0.14037	0.99479	0.02706	0.01099
55	5	0.99453	0.02376	0.00903	0.87364	0.26862	0.15448	0.99900	0.01020	0.00167
55	7	0.99378	0.02569	0.00990	0.99785	0.01509	0.00342	0.99864	0.01225	0.00225
65	3	0.98592	0.04089	0.01505	0.70599	0.35450	0.13102	0.98763	0.03892	0.01364
65	5	0.98958	0.03433	0.01178	0.99932	0.00880	0.00077	0.98974	0.03497	0.01223
65	7	0.99056	0.03205	0.01130	0.99910	0.00991	0.00108	0.98837	0.03727	0.01528
Average		0.88231	0.05806	0.27639	0.92005	0.13236	0.07627	0.99307	0.02644	0.01149

Table -3: Constants of drying model for drying of tomato

Drying parameters		constants of model MR = exp(-k*t^n)		Henderson-Pabis		
Temp. (°C)	Slice thickness (mm)	k	n	R^2	R.M.S.E.	S.S.E.
45	3	0.00000	1.27200	0.99550	0.02155	0.00976
45	5	0.00100	1.22800	0.99658	0.01841	0.00814
45	7	0.00100	1.22300	0.99732	0.01623	0.00685
55	3	0.00100	1.22600	0.99238	0.02849	0.01218
55	5	0.00100	1.33700	0.99639	0.02051	0.00673
55	7	0.00000	1.36900	0.99677	0.01951	0.00571
65	3	0.00100	1.51500	0.99941	0.00858	0.00066
65	5	0.00000	1.42100	0.99929	0.00920	0.00085
65	7	0.00100	1.38600	0.99905	0.01051	0.00121

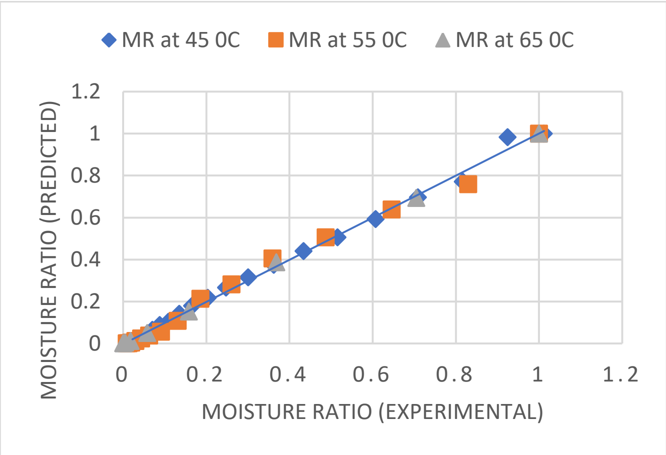

Chart -7: Experimental v/s predicted moisture ratio (Henderson-Pabis model) for 3 mm slice thickness.

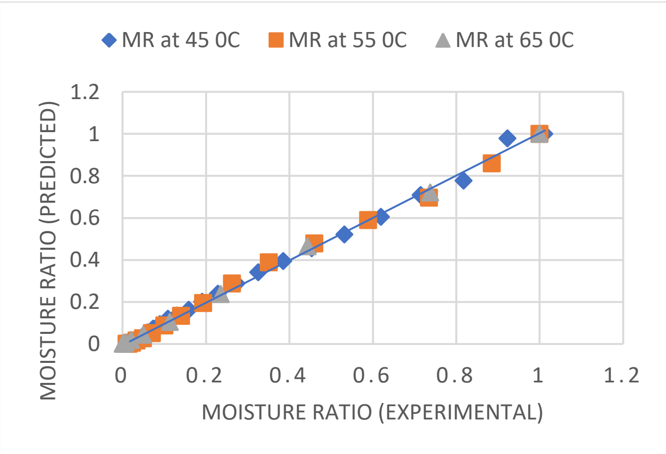

Chart -8: Experimental v/s predicted moisture ratio (Henderson-Pabis model) for 5 mm slice thickness.

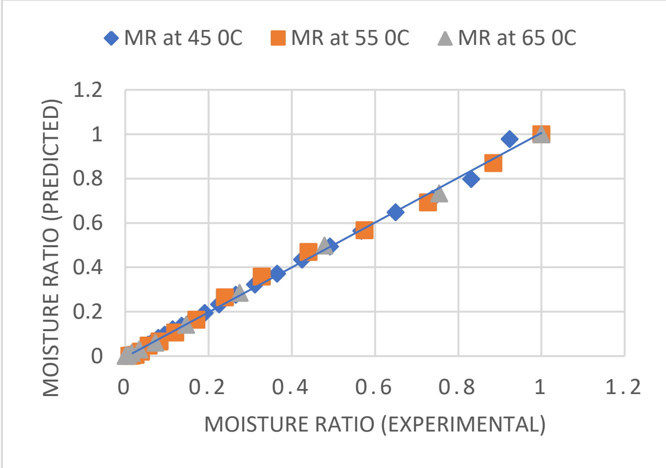

Chart -9: Experimental v/s predicted moisture ratio (Henderson-Pabis model) for 7 mm slice thickness.

4. CONCLUSIONS

This study sheds light on the drying kinetics of tomato slices, highlighting the significant impact of temperature and slice thickness on the drying process. Thicker slices, characterized by higher initial moisture content, exhibit distinct drying patterns compared to their thinner counterparts, with moisture ratios diminishing as drying advances, particularly during the falling-rate drying phase. The application of six thin-layer drying models underscores the robust performance of the Henderson-Pabis model, consistently demonstrating superior fit with the experimental data, as indicated by consistently high R^2 values and low RMSE and SSE values. These findings hold practical significance for the optimization of tomato drying procedures, reduction of post-harvest losses, and enhancement of food preservation methods. By discerning the effects of temperature and slice thickness on drying kinetics, this research paves the way for the design of more efficient and cost-effective tomato drying systems, ultimately ensuring the preservation of nutritional and sensory attributes. Overall, this study contributes to advancing food processing techniques and bolstering food security efforts.

REFERENCES

[1] Demir K, Sacilik K. Solar drying of Ayaş tomato using a natural convection solar tunnel dryer. Journal of Food Agriculture and Environment. 2010; 8(1):7-12.

[2] Basunia MA, Abe T. Thin-layer solar drying characteristics of rough rice under natural convection. Journal of Food Engineering. 2001; 47(4):295-301.

[3] Ukegbu PO, Okereke CJ. Effect of solar and sun drying methods on the nutrient composition and microbial load in selected vegetables, African spinach (Amaranthus hybridus), fluted pumpkin (Telferia occidentalis), and okra (Hibiscus esculentus). Sky Journal of Food Science. 2013; 2(5):35-40.

[4] Abano EE, Ma H, Qu W. Influence of air temperature on the drying kinetics and quality of tomato slices. Journal of Food Process Technology. 2011; 2(123):2.

[5] Singh S, Singla N. Fresh Food Retail Chains in India: Organisation and Impacts. Centre for Management in Agriculture (CMA) (Publication No. 238). Allied Publishers. 2011, 1.

[6] Kaleta A, Górnicki K. Some remarks on evaluation of drying models of red beet particles. Energy Conversion and Management. 2010 Dec 1;51(12):2967-78.

[7] Tiris C, Ozbalta N, Tiris M, Dincer I. Performance of a solar dryer. Energy. 1994 Sep 1;19(9):993-7.

[8] Page GE. Factors Influencing the Maximum Rates of Air Drying Shelled Corn in Thin layers. Purdue University; 1949.

[9] Henderson SM. Grain drying theory, I. Temperature effect on drying coefficient. J. Agr. Eng. Res.. 1961;6(3):169-73.

[10] Wang C Y; Singh R P. A single layer drying equation for rough rice. Transactions of the American Society of Agricultural Engineers. 1978; 3001 (3), 572-581.

[11] Toğrul İT, Pehlivan D. Modelling of thin layer drying kinetics of some fruits under open-air sun drying process. Journal of food Engineering. 2004 Dec 1;65(3):413-25.

[12] Midilli AD, Kucuk HA, Yapar Zİ. A new model for single-layer drying. Drying technology. 2002 Jul 23;20(7):1503-13.

[13] Das Purkayastha M, Nath A, Deka BC, Mahanta CL. Thin layer drying of tomato slices. Journal of food science and technology. 2013 Aug; 50:642-53.

[14] Nabnean S, Thapa S, Janjai S. Thin-layer drying kinetics of osmotic dehydration of cherry tomato. In2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE) 2014 Mar 19 (pp. 1-5). IEEE.

[15] Sadin R, Chegini GR, Sadin H. The effect of temperature and slice thickness on drying kinetics tomato in the infrared dryer. Heat and Mass Transfer. 2014 Apr;50:501-7.