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**Research Paper**

# Drying kinetics modelling of refractance window dried bitter-gourd

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ABSTRACT

**This research aimed to examine the drying kinetics of bitter gourd slices in a Refractance Window Dryer. The study investigated the drying time, dehydration ratio, and color change of the samples while considering water temperature (70, 80, and 90°C), sample size (1, 2, and 3 mm), and blanching times (2, 3, and 4 min). A total of 18 experimental runs were conducted following the Box Behnken design. Various mathematical models, including exponential, Henderson and Pabis, Page's, and Power law models, were applied to the kinetics data of bitter gourd's Refractance window drying, and their suitability was evaluated. The best amongst these models was selected as per the higher value for co-efficient of determination ($R^2$), and lowest standard error of estimation (SEE) values. Page's model demonstrated a good fit to all the experimental drying data, exhibiting higher $R^2$ (0.9955) value compared to the other three models.**

**Key words:** Bitter gourd, box behnken design, mathematical models, refractance window dryer

Bitter gourd (*Momordica charantia* L.), often known as Karela, is consumed throughout the Asian subcontinent for its culinary and therapeutic benefits (Ünal *et al.,* 2013). It is both nutritious and energetic. It is a tropical and subtropical vine with numerous medicinal properties. It's also utilised to complement vitamins, minerals, bioactive chemicals, and antioxidants. It contains DPPH (2, 2, diphenyl picrylhydrazyl), TPC (total phenolic compound), and ferric reducing antioxidant compounds (Budrat and Shotipruk, 2008; Myojin *et al.,* 2008).

However, due to its seasonal nature, it is necessary to preserve bitter gourd to enjoy its therapeutic benefits throughout the year. Traditional preservation methods often involve drying, but this can lead to a reduction in the vegetable's nutritional content and damage its flavor, color, and bioactive compounds. To overcome these challenges, researchers have developed new and improved drying techniques, such as Refractance Window Drying (RWD), which has gained popularity recently.

MCD Technologies Inc. (Tacoma, Washington, USA) invented refractance window drying (RWD) technology, which is a new and emerging technology (Ocoro-Zamora and Ayala-Aponte, 2013; Topuz *et al.,* 2009). It is a one-of-a-kind fourth-generation drying method that offers better outcomes in terms of energy consumption, product quality, environmental impact, dehydration cost, safety, and productivity.

Using mathematical models is crucial for simulating and validating the drying process (Sabarez *et al.,* 2015). Mathematical modeling, encompassing thin-layer modeling, serves a crucial role, not just in describing experimental data, but also in optimizing the drying process (Onwude *et al.,* 2016). The goal of our research is to analyze the kinetics and to provide valuable insights into optimizing the drying conditions, enhancing energy efficiency, and preserving the quality of the dried bitter gourd.

**Understanding Refractance window drying:** Refractance window drying (RWD), a variant of Cast-Tape Drying (Zotarelli *et al.,* 2017), incorporates the use of hot water as a heat transfer medium while maintaining a temperature below boiling point (Hashem HA *et al.,* 2019; Rostami H, *et al.,* 2018).

A basic refractance window dryer involves components like a stainless steel frame, conveyor belt, hot water pump, water tank, and heating unit (Fig.1). Hot water, circulating at around 95-97°C, transfers thermal energy to the moist material spread thinly on the conveyor belt, enabling rapid drying through convection, conduction, and radiation (Akinola AA and Ezeorah SN, 2016). The cooled section of the belt prevents product adhesion, simplifying removal (Azizi *et al.,* 2017). This method is quick and operates at moderate temperatures (Jalgaonkar *et al.,* 2020).

Refractance window drying stands out for its energy efficiency, enhancing both the efficiency and effectiveness of the drying process (Raghavi *et al.,* 2018). Particularly beneficial for heat-sensitive items like juices and purees, this method preserves the product's color, aroma, antioxidants, and nutritional qualities (Ochoa-Martínez *et al.,* 2012).

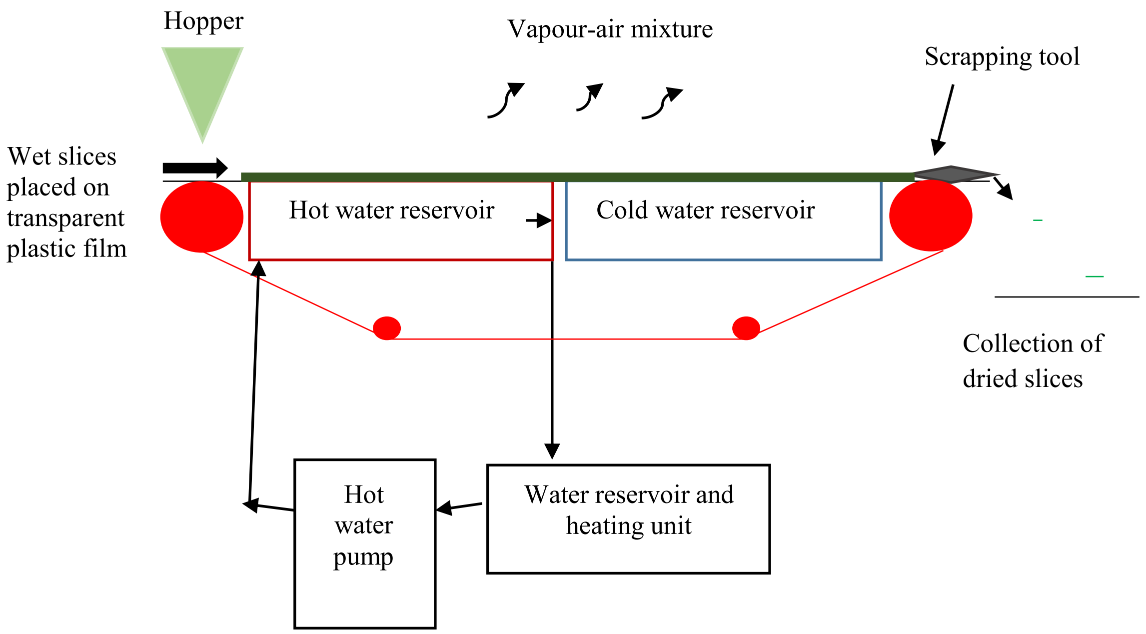


**Fig. 1: Diagram illustrating components of refractance window dryer adapted from Zalpouri *et al.*, 2022 with some modifications**



## MATERIALS AND METHODS

**Sample Preparation and drying unit:** Fresh and high quality bitter-gourds were sourced from the local market of downtown area Srinagar, cleaned and washed thoroughly. Drying experiment was performed using laboratory-scale water-bath that served as a batch-type refractance window dryer in Food Processing Laboratory of College of Agricultural Engineering and Technology, Sher-e-Kashmir University of Agricultural Sciences and Technology, Shalimar, Srinagar (J&K), Fig. 2. Bitter gourds were sliced as per the experimental levels (1, 2 and 3 mm). The blanching temperature was consistently maintained at the boiling point of water, 100°C, for all selected durations following the standard hot water blanching method, Fig.3. The blanched slices were spread over the polyethylene film resting on the water bath (Fig. 4), where the polyethylene film temperature matched the water temperature, ensuring uniformity across different temperature levels.


**Fig.2: Water bath used as refractance window dryer**

Polyethylene is a thermoplastic polymer that has excellent thermal properties, including low thermal conductivity and high melting point. It is a good insulator and can withstand a wide range of temperatures, making it suitable for various applications, including packaging, pipes, and insulation (Lailun*, et al.,* 2009). It has also been reported that a polyethylene film demonstrates excellent refractance window drying properties, contributing significantly to the effectiveness of RWD process while being cost-effective (Ali, *et al.,* 2024).

The water temperature (70, 80, and 90°C), slice thickness (1, 2, and 3 mm), and blanching times (2, 3, and 4 min) was set according to different experimental runs of Box Behnken design. The samples were drawn at regular intervals of 5 min / 10 min until the moisture content was reduced below 10 (% db.), which is considered safe for storage (Pandey, 2000). The material was removed after the drying process and packaged in zip-lock plastic pouches and safely stored in the desiccator, Fig.5.


**Fig.3: Hot water blanching using laboratory hot plate**

**Fig.4: Blanched slices resting over the Polyethylene film**

**Fig. 5: Dried slices stored safely in a dessicator**


**Fig.6: Infrared moisture meter**

**Analytical Procedure for studying drying behavior of bitter gourd**

**Determination of moisture content**: Moisture content of bitter gourd was first determined using an infrared moisture meter from Toshiba India Limited and checked with the hot air oven method. The infrared moisture meter is a semi-automatic moisture meter (Fig.6) that directly reports moisture content on a wet basis. Samples were weighed on an infrared moisture balance. The moisture content was read after about 15 minutes and it was observed that moisture content reading becomes constant in this duration. Weight differential was converted into corresponding moisture loss for calculating moisture content using the following equation:

$$Moisture\ content\ (\%\ db.) = \frac{W_s - W_d}{W_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

where,

$W_s$ = Weight of the sample (g)
$W_d$ = Bone dry Weight of sample (g)

The initial moisture content of bitter gourd ranged from 1234.15 to 1011.1 (% db.), equivalent to 92.5 to 91 (% wb.). It was observed that the time required to bring the moisture content to a safe limit (≤ 10%) ranged from 50 to 130 minutes across the different experimental conditions.

**Determination of moisture ratio:** Moisture ratio (MR) was determined using the following equation (Brooker *et al.,* 1997).

$$MR = \left[\frac{M - M_e}{M_o - M_e}\right] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

where,

M = Moisture content of sample at any time of drying (%db)
$M_e$ = Equilibrium moisture content attained (%db)
$M_o$ = Initial moisture content of sample (%db)

**Determination of drying rate:** The rate of drying was calculated by the decrease in moisture content (% db.) of the bitter-gourd sample per unit time (min), as determined by the following equation (Brooker *et al.,* 1997).

$$\frac{dM_{i+1}}{dt_{i+1}} = \left[\frac{M_i - M_{i+1}}{t_{i+1} - t_i}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

where,

$\frac{dM_{i+1}}{dt_{i+1}}$ = drying rate, loss of moisture per min, at $i^{th}$ drying time (% db.)
$M_i$ = Moisture content at $i^{th}$ time interval
i = Drying interval

**Determination of equilibrium moisture content:** The equilibrium moisture content of the bitter-gourd slice was tried at 1 and 2% less than final moisture content obtained during the experiment as suggested by (Goyal,2002; Faisal,2013).

**Determination of dehydration ratio:** Determination of the dehydration ratio was carried out by the procedure mentioned by Sebii *et al.,* (2020). The known sample weight was dried, and the dried sample weight was recorded. By using the following formula, the dehydration ratio is calculated:

$$Dehydration\ Ratio\ (DR) = \frac{Weight\ of\ product\ prior\ to\ drying}{Weight\ of\ dried\ product} \ldots\ldots\ (4)$$

In the realm of food drying, the dehydration ratio holds significant importance. It serves as a metric indicating the efficiency of water removal from food samples throughout the drying process.

**Process Modelling using Mathematical Models:** Process dynamics were investigated using temperature independent and moisture dependent parameters such drying time, drying rate, and moisture ratio. Various models related to these variables were studied and mathematical relationships were developed. The experimental data was fitted in different drying models to see their feasibility to characterize the drying behavior of bitter gourd in refractance window drying. The experimental moisture ratio (MR) determined using equation (2) was fitted to these four mathematical models (Table 1) Using the statistical program, Non-Linear Regression Analysis NLREG Version 4.1, the coefficients and the constants of the model were predicted.

The selection of the best-fitting equation was based on the statistical indicators $R^2$ and SEE. $R^2$, a measure of data closeness to the regression line, was used to assess how well the data aligned with the fitted model. The choice of the most suitable model for agricultural produce drying kinetics depended on the $R^2$ value (Jackis *et al.,* 2018; Mphahlele *et al.,* 2019). The model that has highest coefficient of determination ($R^2$), is considered as the most relevant model (Hashim *et al.,* 2014; Onwude *et al.,* 2016a). Additionally, SEE, another statistical parameter, was employed to measures the dispersion of actual data points around the regression line, providing insight into the model's reliability in estimating future values. A lower SEE indicates a better fit of the model to the data, suggesting higher accuracy in predicting drying behavior (Jackis *et al.,* 2018).

**Table 1. Mathematical models used to study the drying behaviour of RW dried bitter gourd**

| S. No. | Model name | Model |
|---|---|---|
| 1. | Page Model | MR= exp $(-kt^n)$ |
| 2. | Exponential Model | MR= exp(-kt) |
| 3. | Henderson and Pabis Model | MR= a*exp(-kt) |
| 4. | Power Law Model | MR= $a*t^b$ |

where:

MR = Moisture ratio; t: Drying time (min);
k: Drying constant ($min^{-1}$); a, b, n: empirical constants in drying model.



## RESULTS AND DISCUSSION

Experiments were conducted to characterize the drying behavior of bitter gourd slices. The effect of temperature and blanching time on drying behavior of 1mm, 2mm and 3mm slices of bitter gourd were investigated on different responses. The drying of bitter gourd slices followed falling rate period only. The drying time ranged from 50 to 130 minutes, with the shortest duration recorded at 90°C with 1 mm slice thickness and 3 minutes blanching time. The longest drying time was 130 minutes, occurring at 70°C with 3 mm slice thickness and 3 minutes blanching time. Dehydration ratios ranged from 6.8 to 9.7, with the lowest ratio at 70°C and the highest at 90°C. Color changes ranged from 51.256 to 63.335, being minimal at 70°C for 1 mm slices and maximal at 90°C for 3 mm slices. Various mathematical models were fitted to the kinetics data of refractance window drying of bitter gourd and adequacy of fit was investigated.

### Mathematical models for predicting drying behavior of bitter gourd

**Exponential model:** Drying and statistical parameters obtained from Exponential model are shown in **Table 2**

**Table 2: Drying and statistical parameters of Exponential model (MR= exp(-kt))**

| Experiment No. | Drying Parameters | Statistical Parameters | |
|---|---|---|---|
| | k | $R^2$ | SEE |
| 1 | 0.090596236 | 0.9927 | 0.028013 |
| 2 | 0.067498604 | 0.9959 | 0.0224465 |
| 3 | 0.038560991 | 0.9952 | 0.0234961 |
| 4 | 0.029052159 | 0.9939 | 0.0262502 |
| 5 | 0.035979399 | 0.9917 | 0.0323291 |
| 6 | 0.027365763 | 0.9906 | 0.0333936 |
| 7 | 0.0531129 | 0.9961 | 0.0200098 |
| 8 | 0.05383007 | 0.9961 | 0.0203955 |
| 9 | 0.052472385 | 0.9976 | 0.0157353 |
| 10 | 0.074934484 | 0.9962 | 0.0220999 |
| 11 | 0.035067142 | 0.9949 | 0.0227525 |
| 12 | 0.024825159 | 0.9933 | 0.0268643 |
| 13 | 0.026287154 | 0.9846 | 0.0423654 |
| 14 | 0.055496402 | 0.9881 | 0.0342975 |
| 15 | 0.024223777 | 0.9876 | 0.0366797 |
| 16 | 0.028363183 | 0.9927 | 0.0283065 |
| 17 | 0.027002267 | 0.9832 | 0.0447773 |
| 18 | 0.029266358 | 0.9902 | 0.0338691 |
| **Average values** | **0.042996357** | **0.992256** | **0.028560072** |

**Henderson and Pabis Model:** Drying and statistical parameters obtained from Henderson and Pabis model are shown in **Table 3**

**Table 3: Drying and statistical parameters of Henderson and Pabis Model {MR= a*exp (-kt)}**

| Experiment No. | Drying Parameters | | Statistical Parameters | |
|---|---|---|---|---|
| | k | a | $R^2$ | SEE |
| 1 | 0.087831 | 0.972403 | 0.9937 | 0.027801 |
| 2 | 0.069049 | 1.021807 | 0.9965 | 0.022096 |
| 3 | 0.039396 | 1.019115 | 0.9956 | 0.023332 |
| 4 | 0.028928 | 0.996227 | 0.9939 | 0.027131 |
| 5 | 0.03726 | 1.031796 | 0.9929 | 0.03112 |
| 6 | 0.028018 | 1.020972 | 0.9912 | 0.033565 |
| 7 | 0.051572 | 0.97614 | 0.9968 | 0.019051 |
| 8 | 0.05238 | 0.97775 | 0.9967 | 0.019681 |
| 9 | 0.051114 | 0.978473 | 0.9982 | 0.014463 |
| 10 | 0.075935 | 1.012837 | 0.9964 | 0.023132 |
| 11 | 0.033645 | 0.966238 | 0.9963 | 0.02004 |
| 12 | 0.024804 | 0.999268 | 0.9933 | 0.027959 |
| 13 | 0.026992 | 1.024849 | 0.9855 | 0.042689 |
| 14 | 0.05192 | 0.947905 | 0.9916 | 0.030263 |
| 15 | 0.024591 | 1.012658 | 0.9879 | 0.03786 |
| 16 | 0.028349 | 0.999567 | 0.9927 | 0.029462 |
| 17 | 0.027792 | 1.027349 | 0.9842 | 0.045024 |
| 18 | 0.029933 | 1.019541 | 0.9908 | 0.034328 |
| **Average values** | **0.04275** | **1.000272** | **0.993011** | **0.028278** |

**Page model**: Drying and statistical parameters obtained from Page model are shown in **Table 4.**

**Table 4: Drying and statistical parameters of Page model {MR= exp (-kt$^n$)}**

| Experiment No. | Drying Parameters | | Statistical Parameters | |
|---|---|---|---|---|
| | k | n | $R^2$ | SEE |
| 1 | 0.14154408 | 0.825664 | 0.9992 | 0.009677 |
| 2 | 0.04423081 | 1.15306 | 0.9994 | 0.008791 |
| 3 | 0.02620641 | 1.116067 | 0.9978 | 0.016634 |
| 4 | 0.0239473 | 1.052495 | 0.9946 | 0.025571 |
| 5 | 0.0211249 | 1.156063 | 0.997 | 0.020306 |
| 6 | 0.01712776 | 1.126506 | 0.9942 | 0.026257 |
| 7 | 0.07058573 | 0.905812 | 0.9984 | 0.013423 |
| 8 | 0.07044095 | 0.91043 | 0.9982 | 0.014544 |
| 9 | 0.06609524 | 0.923803 | 0.999 | 0.010455 |
| 10 | 0.05618288 | 1.107143 | 0.9983 | 0.016065 |
| 11 | 0.04505213 | 0.928116 | 0.9965 | 0.019637 |
| 12 | 0.02194119 | 1.032647 | 0.9936 | 0.027266 |
| 13 | 0.0147619 | 1.151874 | 0.9904 | 0.034716 |
| 14 | 0.09224226 | 0.830914 | 0.9966 | 0.01913 |
| 15 | 0.01661479 | 1.099862 | 0.9905 | 0.033604 |
| 16 | 0.02599953 | 1.023655 | 0.9929 | 0.029109 |
| 17 | 0.01450946 | 1.164344 | 0.9898 | 0.036267 |
| 18 | 0.02078146 | 1.094655 | 0.9927 | 0.030573 |
| **Average values** | **0.04385493** | **1.033506** | **0.995506** | **0.021779** |

**Power Law model**: Drying and statistical parameters obtained from Power Law model are shown in Table 5.

**Table 5: Drying and statistical parameters of Power Law model {MR= a*t^b}**

| Experiment No. | Drying Parameters | | Statistical Parameters | |
|---|---|---|---|---|
| | **a** | **b** | **$R^2$** | **SEE** |
| 1 | 2.69481405 | -0.920205022 | 0.9378 | 0.055011 |
| 2 | 3.66274176 | -0.942573986 | 0.9127 | 0.085149 |
| 3 | 3.15833473 | -0.741498301 | 0.8581 | 0.113647 |
| 4 | 2.75334433 | -0.627340552 | 0.8243 | 0.127757 |
| 5 | 3.08307762 | -0.706293654 | 0.8514 | 0.12485 |
| 6 | 2.72193998 | -0.60504948 | 0.8261 | 0.134289 |
| 7 | 2.98549906 | -0.803584739 | 0.9143 | 0.076226 |
| 8 | 2.92407002 | -0.794745555 | 0.9156 | 0.076846 |
| 9 | 2.94905515 | -0.794917589 | 0.9054 | 0.08081 |
| 10 | 3.40551119 | -0.940413556 | 0.9121 | 0.085553 |
| 11 | 2.75679263 | -0.682565617 | 0.8634 | 0.102765 |
| 12 | 2.49793006 | -0.55699361 | 0.8425 | 0.121049 |
| 13 | 2.7485106 | -0.603468401 | 0.8102 | 0.139299 |
| 14 | 2.48364137 | -0.745505806 | 0.8859 | 0.083136 |
| 15 | 2.43091454 | -0.535355525 | 0.8207 | 0.132476 |
| 16 | 2.65498386 | -0.606428557 | 0.8521 | 0.117073 |
| 17 | 2.8019961 | -0.616109546 | 0.8072 | 0.141628 |
| 18 | 2.73708528 | -0.616064038 | 0.8458 | 0.125521 |
| **Average values** | **2.858346796** | **-0.713284085** | **0.865867** | **0.106838** |

**Selection of best fitted model:** Various drying models (Exponential, Henderson and Pabis, Page's Model and Power law model) were fitted to the experimental data using Non Linear Regression technique and the applicability of all four models was done on the basis of coefficient of determination ($R^2$). The best fitted model was selected on the basis of higher $R^2$. Page's model fitted well to all the experimental drying data as it yielded highest $R^2$ (0.9955) and values compared to other three models (Table 6).

**Table 6: Average value of coefficient of determination and standard error of estimation of various mathematical models**

| Models | Constants | $R^2$ | SEE |
|---|---|---|---|
| Page Model | k = 0.04385493<br>n = 1.033506 | 0.995506 | 0.021779 |
| Exponential Model | k = 0.042996357 | 0.992256 | 0.028560072 |
| Henderson and Pabis Model | k = 0.04275<br>a = 1.000272 | 0.993011 | 0.028278 |
| Power Law Model | a = 2.858346796<br>b = -0.713284085 | 0.865867 | 0.106838 |

## CONCLUSION

The drying kinetics of bitter gourd were analysed with selected four mathematical models namely Exponential, Henderson and Pabis, Page's Model, and Power law model. The goodness of fit of model was tested using $R^2$ mainly. Among all the models, Page model described the best drying characteristics of bitter gourd. Page's model fitted well to all the experimental drying data as it yielded higher $R^2$ (0.9955) compared to other three models. Additionally, it showcased a lower Standard Error of Estimation (SEE) at 0.0217. Although this SEE value was not the lowest among the models tested, it still falls within an acceptable range, indicating a reasonable level of accuracy.

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