Refratance Window^{TM} Dryer Dehydration Characterization of Cucumber (*Cucumis Sativus*) Slices at Different Temperatures

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Abstract
Cucumber (Cucumis sativus) slices were dehydrated using a Refractance Window^{TM} dryer in which the flume water temperatures were varied at 65°C, 75°C, and 85°C. The kinetic data obtained experimentally was fitted to 8 dehydration models categorized as empirical and semi-empirical models. The dehydration curves, the effective diffusivities and activation energy of the cucumber slices were estimated. Also, samples of the dried cucumber slices were rehydrated at room temperature (27°C). The experimental rehydration data were used to construct the rehydration ratio plot. The values of the ascorbic acid content of the cucumber's slices were also determined after experimentation for the process conditions studied. Observations indicated that the cucumber slices dried to a moisture content of 0.11 g-water/g-solid (dry basis) in about 40 to 115 minutes for the process conditions studied. The regression analysis results suggest that the Haghi and Ghanadzadeh thin layer model, best described the drying behavior for the 3.0 mm thick cucumber slices at 65°C, 75°C and 85°C and coefficient of determination (R^2) values of 0.9923, 0.9993 and 1.0000 respectively. The rehydration ratio of the cucumber samples increased to 5.25 in about 300 minutes after which the moisture content was about 11.50g-water/g-cucumber (92% wet basis). The rehydration data were also observed to fit a two-term exponential model with a coefficient of determination (R^2) value of 0.9941. Finally, there was a decrease of 7.93 to 38.94% in the ascorbic acid content of the cucumber slices for the process conditions studied.

Keywords: Drying curve; Drying Rate curve; Refractance Window^{TM} drying; Rehydration ratio; Krischer curve; Thin layer dying models

1.0 INTRODUCTION

CUCUMBER (C. sativus) is a member of the botanical family Cucurbitaceae, along with gherkin (C. anguria), melon (C. melo), colocynth (C. colocynthis), watermelon (C. lanatus), etcetera. Cucumbers have a high water content, about 95% (Metaljan, 2015). The skin of the cucumber fruit has high levels of minerals such as Calcium, Magnesium, Phosphorus, and Potassium. The flesh is rich in vitamins B, C, and K. The nutritional value of cucumbers per 100 g is Vitamin C, 2.8 mg, Vitamin K, 16.4 µg, 0.457mg, Calcium, 16 mg, Magnesium, 13 mg, Phosphorus, 24 mg, Potassium, 147 mg (USADA, 2017). Cucumber has a nutrient density score (NDS) of 8.1; being in the highest top twenty for fruits and vegetables (Suchankova *et al.,* 2015).

Although cucumbers are best when consumed fresh and raw and have a taste that makes them a great addition to salads, they are seasonal fruits. Cucumbers, therefore, need to be preserved. Drying is one of the many food preservation methods (Rahman, 2007). Presented in this study, is the investigation into the Refractance Window^{TM} drying method for drying cucumbers. The Refractance Window^{TM} (RW) drying technique is a novel drying technology patented by Magoon (1986) and developed by MCD Technology Inc., Tacoma, WA, USA.

Nindo *et al.* (2003), carried out experiments with pumpkin purée to evaluate the energy efficiency and the effect of the microbial reduction of Refractance Window^{TM} dryer. This technique was able to reduce the moisture content from 80% to 5% (wb) in less than 5 min.

The results showed that Refractance Window^{TM} dryer is energy efficient and has a good capacity for microbial reduction.

In 2007, Nindo and Tang used the Refractance Window^{TM} technique to dry purees and juices prepared from fruits, vegetables, and herb; they observed that within 3-5 minutes, the purees and juices dried to about 4% moisture content when the water temperature in the flumes was about 95 – 97^{o}C.

An investigation by Nindo (2008), on the freeze-drying and the Refractance Window^{TM} drying of asparagus, squash, berries, aloe-vera, and marine algae indicated that freeze-drying, a well-established an expensive technology, and the Refractance Window^{TM} drying technique, a simple and relatively inexpensive method, produced similar results.

Akinola and Ezeorah (2016), used the Refractance Window^{TM} drying technique to dehydrate root tuber slices. Their studies indicated that at a water temperature of 60^{o}C beneath the transparent plastic film, 3.0 mm thick slices of the root tuber slices could be dehydrated to less than 10% moisture content (wet basis) in less than 180 minutes. Akinola *et al.* (2016) also demonstrated that using the Refractance Window^{TM} drying technique, 3.0 mm thick carrot slices could be dried to a moisture content of less than 10% (wet basis) within 200 minutes. However, studies by Akinola and Ezeorah (2016) and Akinola *et al.,* (2016) did not examine the effect of temperature on the drying kinetics of any of the products used as samples in the investigation. This work presents the study of the effect of temperature on the dehydration characteristics of cucumbers using a Refractance Window^{TM} dryer.

2.0 MATERIALS AND METHODS

2.1 Sample preparation

Fresh mature cucumbers obtained from a local market in Lagos, Nigeria, were washed and cut into 3.0 mm thick slices using a Mandolin slicer. The initial moisture content of cucumber slices was determined to be 20.03 g-water/g-solid cucumber, 95% wet basis, using an OHAUS moisture analyzer (OHAUS Corporation, 2011).

2.2 Drying Apparatus

Presented in Figure 1 is a schematic diagram of the equipment used in this study. The apparatus consists of a water bath covered with a 0.15 mm thick transparent polyethylene terephthalate (PET) Mylar plastic film. The film was always in contact with the water, and metal brackets were used to hold the film in place. The water in the bath was heated using a thermostatically controlled electric immersion heater. The dryer had a hood above it from which the moist air that might inhibit the drying process was extracted.

2.3 Drying Procedure

The experiments were carried out with the water in the Refractance Window^{TM} dryer at three temperatures, 65^{o}C, 75^{o}C, and 85^{o}C. The 3.0 mm thick cucumber slices were placed on the transparent PET plastic on the dryer, and at 10-minute intervals, some slices were removed and their moisture content determined. For each temperature and each period, the experiments were performed in triplicates.

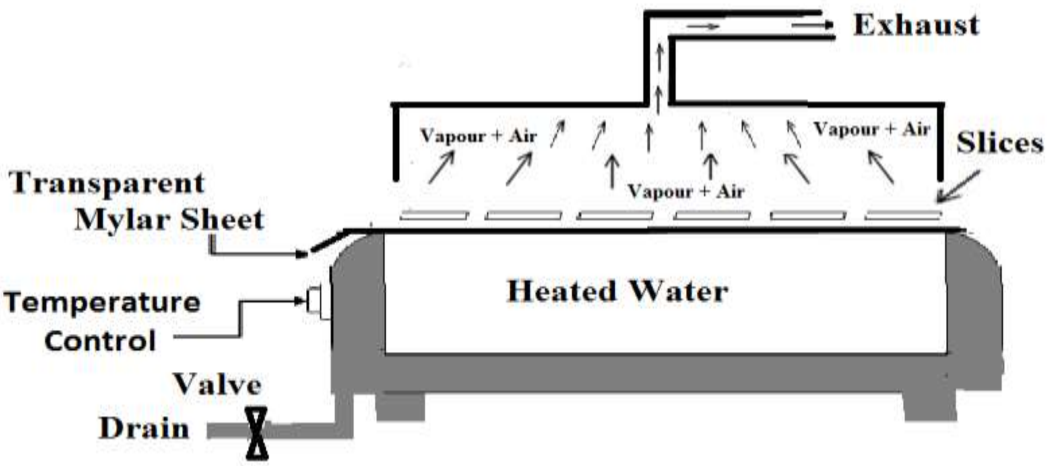

Figure 1: A Schematic Diagram of a Refractance Window^{TM} Dryer

2.4 Thin-Layer Drying Models

The experimental data were fitted to 8 common thin-layer drying models used in the dehydration of fruits and vegetables. Presented in Table 1 are the thin-layer models used for this study

Table 1. Thin-layer drying models used for this study

S/N	Model
1	MR =exp (−k.t^n) Page Model (Page, 1949)
2	MR =a.exp (-k.t) Henderson and Pabis Model (Henderson and Pabis, 1961)
3	MR = exp(-k(t/L^2)^n) Modified Page equation –II (Diamente and Munro, 1993)
4	MR = exp (-k.t) Newton Model (Ayensu, 1997)
5	MR =a.exp (-k.t) + c Logarithmic Model (Togrul and Pehlivan, 2003)
6	MR = a.exp (-b.t^c) + d.t^2 + e.t + f Haghi and Ghanadzadeh Model (Haghi and Ghanadzadeh, 2005)
7	MR = a.exp (-k.t) + (1-a).exp (-k.b.t) Diffusion Approach Model (Demir *et al.*, 2007)
8	MR = a*exp(-k*(t)^n)+(b*t) Midilli and Kucuk Model (Midilli and Kucuk, 2003).

Where

MR is the moisture ratio,

t is the drying time and,

a, b, c, d, e, f, k, k_0, k_1, k_2 and n are all constant determined by regression analysis.

The moisture ratio was determined using Eqn 1.

$$MR = MC_t - MC_e / MC_i - MC_e \quad (1)$$

where

MC_t is the moisture content of the sample after drying for time t; MC_e is the equilibrium moisture content of the sample and MC_i is the initial moisture content of the fresh sample, all in the unit of grams of water removed/grams of solids.

In this analysis, MC_e, the equilibrium moisture content of the sample is assumed to be very small. Therefore, the moisture ratio was simplified as recommended by Akgun and Doymaz (2005), Doymaz (2004) and Sharifian *et al.* (2012). Eqn. 1 can then be expressed as Eqn. 2.

$$MR = MC_t / MC_i \quad (2)$$

2.5 Statistical Analysis

The experimental drying data were fitted to the equations in Table 1. To determine the thin-layer drying model that best describes the drying kinetics of the cucumber slices. Criteria such as the coefficient of determination (R^2), the sum of square-error (SSE), and the root mean-square-error (RMSE) were used to determine which model best describes the drying kinetics of cucumber slices. For quality fit, R^2 should be closest to unity while SSE and RMSE should be closest to zero. The method of estimating R^2, SSE and RMSE are discussed extensively in literature and have been used in literature for work on drying kinetics of fruits, roots, and vegetables (Ertekin and Yaldiz, 2004; Kabiru *et al.,* 2013). The Polymath 6.1 software was used to perform the statistical analysis.

After obtaining the best thin-layer drying model, that fit the drying data, the drying curve (moisture content vs. time plot), the drying rate curve (drying rate vs. time plot), and the Krischer curve (drying rate vs. moisture content plot) were drawn.

2.6 Determining the Rehydration Ratio

The rehydration ratio (RR) was determined by soaking about approximately 4.0±0.2 g of dehydrated cucumber slices with a moisture content of 0.03 g-water/g-solid in about 200 ml of distilled water. The cucumber slices were covered with a perforated steel cup to ensure that the slices did not float and were fully covered in water. The mass of the dehydrated slices and the rehydrated slices were measured, and the rehydration ratio determined using Eqn. 3.

$$RR = M_r / M_d \quad (3)$$

where,

M_r is the mass of the rehydrated solid in grams and
M_d is the mass of the dry sample in grams.

The rehydration ratio values for the 3.0 mm thick cucumber slices was determined at 10-minute time intervals up to 300 minutes. The experiments were performed in triplicates, and the average values obtained.

The rehydration ratios were correlated with rehydration time according to a two-term exponential (Eqn. 4) and a second order polynomial (Eqn. 5) equations.

$$RR = p_1 * \exp(p_2 * t) + p_3 * \exp(p_4 * t) \quad (4)$$

$$RR = p_5 * t^2 + p_6 * t + p_7 \quad (5)$$

Where

p_1, p_2, p_3, p_4, p_5, p_6 and p_7, are constants obtained from regression analysis
t is the rehydration time in minutes.

2.7 Determining Ascorbic Acid Content

The ascorbic acid content of the cucumber slices was determined before and after the dehydration process. This was done in a local laboratory with methods described literature (Hernández *et al.,* 2006; AOAC, 1990; Tee *et al.,* 1988; King, 1941).

3.0 RESULTS AND DISCUSSION

3.1 Drying times

For the three sets of experiments performed, the initial moisture content of cucumber slices was 22.20 g-water/ g-solid cucumber. The drying processes were stopped when a moisture content of about 0.11 g-water/ g-solid cucumber was reached. At water bath temperatures of 65°C, 75°C, and 85°C, the total drying times taken to reach a moisture content of approximately 0.11 g-water/ g-solid was 115, 50, and 40 minutes respectively. The drying time for the 3.0 mm cucumber slices decreased when the water temperature in the Refractance Window™ dryer was increased. Also, the aforementioned times are considerably shorter times than the 4 - 8 hours experienced using the Excalibur Dehydrator designed by Discount Juicers (1998).

3.2 Fitting of Mathematical Models to the Drying Curves

For the three sets of experiments performed, the initial moisture content of cucumber slices was 22.20 g-water/ g-solid cucumber. The drying processes were stopped when a final moisture content of about 0.11 g-water/ g-solid cucumber was reached. The experimental moisture content data, on a dry basis, obtained during the drying experiments were converted into the moisture ratio (MR) and fitted to the 8 thin-layer drying models listed in Table 1. Presented in Tables 2, 3 and 4 are the statistical parameters of the tested models fitted to the experimental data.

Table 2: Statistical Parameters of the Models Fitted to the Experimental Data at 65°C

S/N	Model	R^2	SSE	RSME
1	Haghi and Ghanadzadeh model	0.9923	0.0140	0.0316
2	Midili and Kucuk model	0.9840	0.0302	0.0434
3	Henderson and Pabis model	0.9840	0.0302	0.0421
4	Page Model	0.9800	0.0377	0.0458
5	Modified Page II model	0.9800	0.0377	0.0458
6	Diffusion Approach Model	0.9792	0.0393	0.0481
7	Logarithmic Model	0.9722	0.0525	0.0556
8	Newton Model	0.9623	0.0713	0.0612

Table 3: Statistical Parameters of the Models Fitted to the Experimental Data at 75°C

S/N	Model	R^2	SSE	RSME
1	Haghi and Ghanadzadeh model	0.9993	0.0010	0.0110
2	Midili and Kucuk model	0.9991	0.0011	0.0107
3	Henderson and Pabis model	0.9989	0.0014	0.0113
4	Page Model	0.9989	0.0014	0.0108
5	Modified Page II model	0.9989	0.0014	0.0108
6	Diffusion approach model	0.9985	0.0019	0.0131
7	Logarithmic model	0.9840	0.0208	0.0435
8	Newton model	0.9801	0.0259	0.0446

The model chosen to best fits the drying kinetics of the cucumber slices must have R^2 closest to unity, SSE and RSME closest to zero. While all the models fit the experimental data with an accuracy better than 96%, the Haghi and Ghanadzadeh (2005), thin-layer drying model is observed to be best fit the experimental data in all 3 cases. The R^2, SSE and RSME values are 0.9923, 0.0140, 0.0316 when the bath water was 65°C, 0.9993, 0.0010, 0.0110 when the bath water was 75°C, and 1.0000, 0.0000, 0.0011 when the bath water was 85°C. The constants obtained for each model are presented in Table 5.

Table 4: Statistical Parameters of the Models Fitted to the Experimental Data at 85°C

S/N	Model	R^2	SSE	RSME
1	Haghi and Ghanadzadeh model	1.0000	0.0000	0.0011
2	Midili and Kucuk model	0.9996	0.0004	0.0076
3	Henderson and Pabis model	0.9992	0.0008	0.0100
4	Page Model	0.9992	0.0008	0.0095
5	Modified Page II model	0.9992	0.0008	0.0095
6	Diffusion Approach model	0.9670	0.0345	0.0657
7	Logarithmic model	0.9684	0.0330	0.0643
8	Newton model	0.9670	0.0345	0.0587

Table 5: Constants Obtained by Fitting Experimental Data to Thin-layer Models

Model Name	65°C	75°C	85 °C
Haghi and Ghanadzadeh	a = 0.4864	a = 1.113	a = 0.9683
	b = 0.0003137	b = 0.01127	b = 0.002098
	c = 2.047	c = 1.434	c = 2.474
	d = 2.075e-05	d = -1.217e-05	d = 2.824e-06
	e = -0.00603	e = 0.002462	e = -0.0005553
	f = 0.4288	f = -0.1139	f = 0.03173
Midili and Kucuk	a = 0.9153	a = 0.9982	a = 1
	b = 3.103e-06	b = 5.762e-05	b = 0.0001023
	k = 0.001605	k = 0.009943	k = 0.003103
	n = 1.629	n = 1.496	n = 2.294
Approximation of diffusion	a = -16.72	a = -8.25	a = 0.6634
	b = 0.9576	b = 0.8932	b = 1
	k = 0.04067	k = 0.1052	k = 0.088
Newton Model	k = 0.02241	k = 0.04875	k = 0.08819
Page Model	k = 0.005113	k = 0.01037	k = 0.003217
	n = 1.366	n = 1.482	n = 2.277
Modified Page II	k = 0.02099	k = 0.0458	k = 0.08037
	n = 1.365	n = 1.482	n = 2.276
Henderson and Pabis	a = 0.9156	a = 0.9987	a = 1
	k = 0.001619	k = 0.01027	k = 0.003218
	n = 1.27	n = 1.484	n = 2.277
Logarithmic Model	a = 1.083	a = 1.064	a = 1.037
	c = -0.0607	c = -0.01782	c = -0.009881
	k = 0.01977	k = 0.04834	k = 0.08755

Further validation that the Haghi and Ghanadzadeh (2005) thin-layer drying model best fit the drying kinetics was done by plotting the values of experimental and predicted moisture contents (Figure 2). The lines obtained, had a slope of 0.9961, 0.9847 and 1.000, and R^2 values of 0.99. 1.00 and 1.00 for the 65°C, 75°C, and 85°C respectively. The implication is that the experimentally determined moisture content of the 3.0 mm thick cucumber slices does not vary significantly from the predicted data.

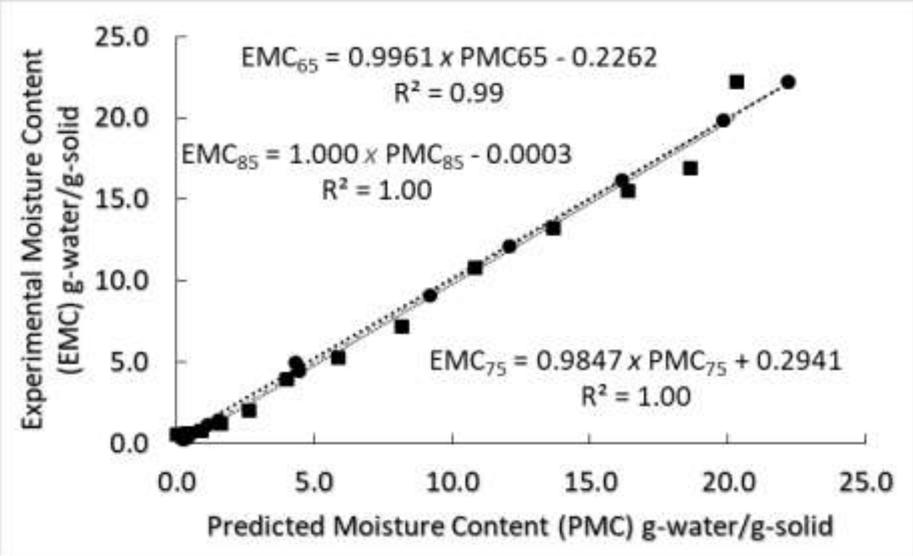

Figure 2. Experimental and predicted moisture content at different temperatures

3.3 Drying Curve

The drying curve, moisture content verses drying time is shown in Figure 3. The drying curves show that moisture ratio decreases continuously with drying time. At bath water temperatures of 65°C, 75°C, and 85°C, the total drying times taken to reach a moisture content of approximately 0.11 g-water/ g-solid was 115, 50, and 40 minutes respectively.

The drying time for the 3.0 mm cucumber slices decreased when the water temperature in the Refractance Window^{TM} dryer was increased. This is expected as an increase in temperature increases the speed at which moisture move through in interstice of the cucumber slices. It is observed that by increasing the temperature 10°C, from 65°C to 75°C, the drying time was more than halved. Yet, when the temperature is further increased by another 10°C, i.e. from 75°C to 85°C, the drying time for the 3mm thick slices did not change much.

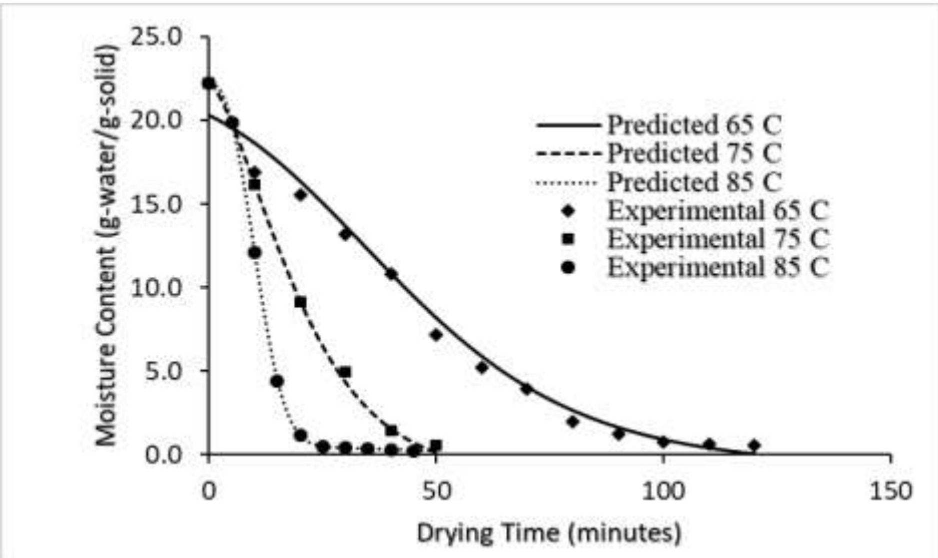

Figure 3: Experimental and predicted moisture content changes with drying time at different temperatures

3.4 Drying Rate Curve

Plots for the drying rate vs. drying time plot (drying rate curve) for the 3.0 mm thick cucumber slices with water temperatures of 65°C, 75°C, and 85°C in the Refractance Window™ dryer is shown in Figure 4.

The plots are line plots that were obtained by differentiating respective Haghi and Ghanadzadeh (2005) model that fit the experimental data points. Figure 4 shows that the drying rate rises initially; this is the initial drying rate period. In this period, sensible and latent heat of evaporation is transferred to the moisture. The drying rate then reaches a peak value and then starts to fall. Clearly, when the drying rate falls, this is the falling rate period. In the falling rate period, moisture migrates from the inner spaces of each slice to the outer surface before being released. The peak drying rate occurs at about 35, 11 and 10 minutes after drying commenced for the slices dried the dryer with water temperatures of 65°C, 75°C, and 85°C respectively. As observed in the Figure 4, most of constant rate drying period is relatively short.

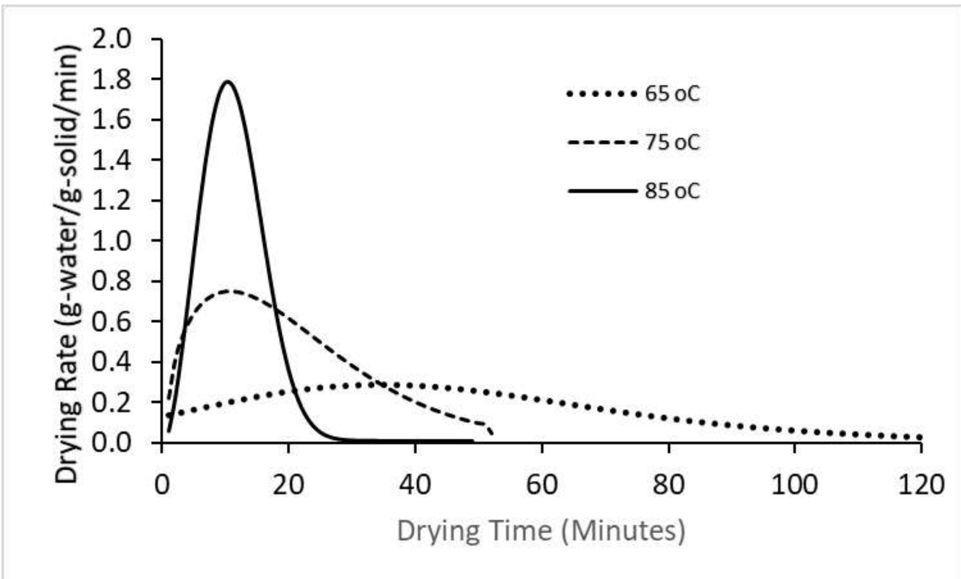

Figure 4: Drying rate changes with drying time at different temperatures

3.5 Krischer Curve

The Krischer curve, (i.e. the drying rate vs. moisture content plot) for the cucumber slices is shown in Figure 5. The plot is a combination of the drying curve and the drying rate curve. Figure 5 shows that the drying rate (right to left) increases, it reaches a peak value and then drops (falling rate period). The peak drying rate reached was observed when the moisture content was about 0.28, 0.75 and 1.79 g-water/g-solid/min operated at 65°C, 75°C, and 85°C respectively.

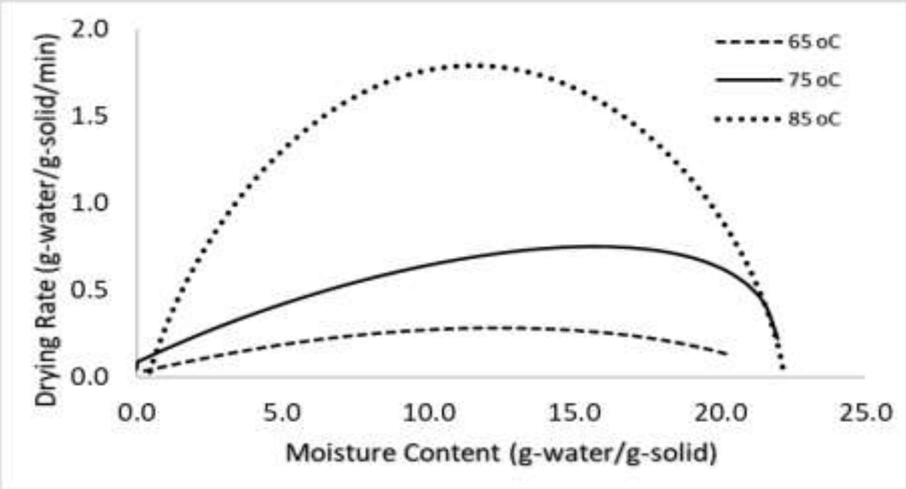

Figure 5: Drying rate changes with moisture content at different temperatures

3.6 Rehydration Ratio

The Rehydration ratio curve, i.e., Rehydration ratio *vs.* Rehydration time plot for the cucumber slices 3.0 mm thick at 27^{o}C, is shown in Figure 6. There is a rapid increase in the rehydration ratio in the first 60 minutes to a value of about 4.46. After that, the rehydration ratio steadily increases to a value of 5.12 after 260 minutes, 5.23 after 280 minutes and 5.25 after 300 minutes. This increase was less than a 1% in the rehydration ratio value in the last 20 minutes preceding the entire 300 minutes of rehydration. The moisture content of the cucumber slices after 300 minutes of rehydration was 11.50 g-water/g-cucumber (92% wet basis).

The Rehydration data and time was fitted with a two-term exponential model (Eqn. 4) and a second order polynomial (Eqn. 5). The constants and regression data obtained from the statistical analysis is present in Table 5.

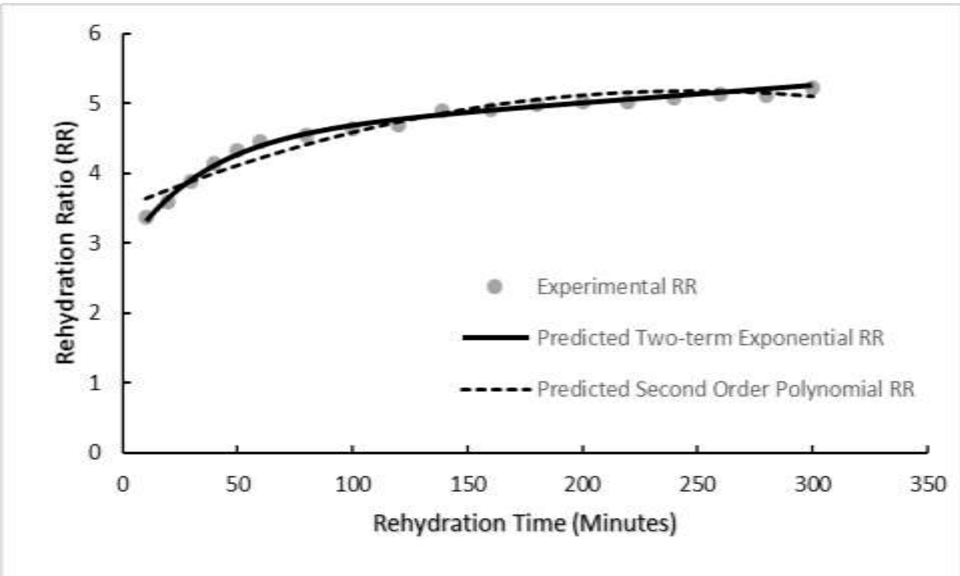

Figure 6: Rehydration ratio *vs.* Drying time

Table 6. Results of Statistical Analysis of the Rehydration Data

Two-Term Exponential Model	Second Order Polynomial Model
Coefficients (with 95% confidence bounds)	Coefficients (with 95% confidence bounds)
p_1 = 4.559 (4.42, 4.697)	p_4 = -2.746 x10^{-5} (-3.784 x10^{-5}, -1.709 x10^{-5})
p_2 = 0.0004791 (0.0003479, 0.0006103)	p_6 = 0.01356 (0.01037, 0.01676)
p_3 = -1.681 (-1.853, -1.509)	p_7 = 3.514 (3.322, 3.705)
p_4 = -0.02921 (-0.03612, -0.02231)	
Goodness of fit:	Goodness of fit:
R^2: 0.9941	R^2: 0.9428
SSE: 0.03194	SSE: 0.3116
RMSE: 0.04776	RMSE: 0.1441

Singh and Pandey, (2011), had fitted rehydration data (rehydration ratio and rehydration time) for cubed sweet potatoes to a second order polynomial of the form in equation 6. The result of fitting the experimental rehydration data to a second order polynomial is also presented in Table 6. Clearly, there is a better fit of the rehydration data to the two-term exponential equation than the second order polynomial equation. This is because the former has a coefficient of variance (R^2) closer to unity and both the sum of square-error (SSE) and root-square-mean error (RMSE) values are closer to zero than the latter.

3.7 Estimating the Ascorbic Acid Content

The ascorbic acid content of the 3.0 mm thick cucumber slices was determined before and after the dehydration experiments. The determined values are shown in Figure 7. Clearly, there is a reduction in the ascorbic acid content of the cucumber slices as the heating temperature increases. As shown in Figures 7, for the slices dehydrated at 65^{o}C, 75^{o}C, and 85^{o}C, a decrease in the ascorbic acid content of 7.93%, 24.28%, and 38.94% respectively were observed.

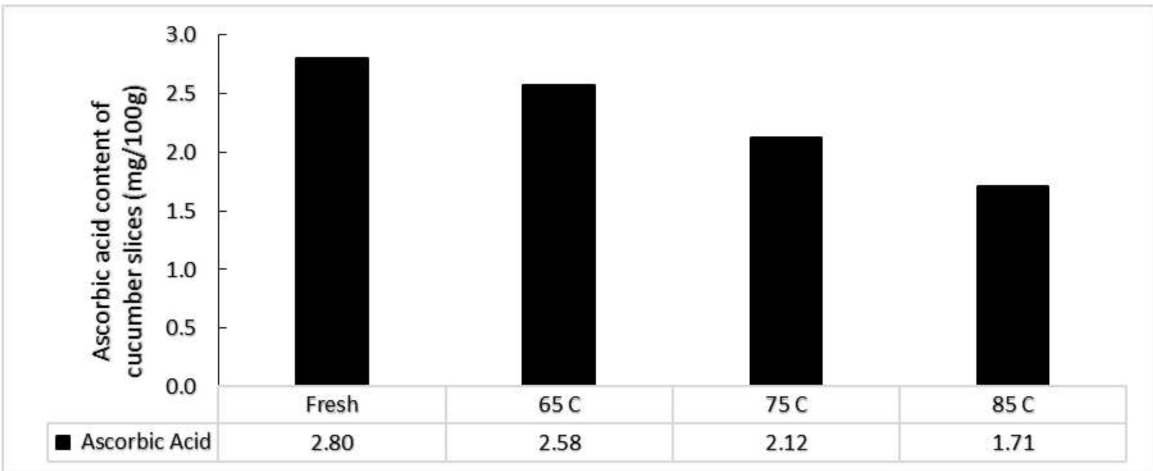

Figure 7: Ascorbic acid content of cucumber slices (mg/100g) at different conditions

4.0 CONCLUSION

Cucumber (*Cucumis sativus*) slices 3.0 mm thick, with an initial moisture content of 22.20 g-water/g-solid were dehydrated to a moisture content below 0.11 g-water/g-solid cucumber using a Refractance Window^{TM} dryer in which the flume water temperature was 65^{o}C, 75 ^{o}C, and 85^{o}C. Also, rehydration of 3.0 mm thick cucumber slices, was performed at room temperature, 27^{o}C.The following conclusion can be made, the 3.0 mm thick cucumber slices dried to a moisture content of 0.11 g-water/g-solid in 115, 50, and 40 minutes at 65 ^{o}C, 75 ^{o}C, and 85 °C respectively is considerably shorter times than using an Excalibur Dehydrator (Discount Juicers, 1998). The drying rate of cucumber slices increased with an increase in the water temperature in the Refractance Window™ dryer. This drying rate increase is expected as heat is one of the factors known to increase the rate of evaporation (Lewis, 1921). The rehydration ratio determined for the dehydrated cucumber slices increased to 5.25 after 300 minutes in which the moisture content of the cucumber slices reached 11.50 g-water/g-cucumber (92% wet basis). Also, for rehydration times less than 300 minutes, a two-term rehydration model could be used to predict the rehydration ratios with excellent accuracy. Finally, as dehydration was performed at higher temperatures, the amount of Ascorbic acid decreased with temperature A decrease in the ascorbic acid content of 7.93%, 24.28%, and 38.94% were observed for slices dehydrated at 65°C, 75°C, and 85°C, respectively.

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