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Dehydration Characterization of Carrot *(Daucus Carota)* Slices Dried Using the Refractance Window™ Drying Technique

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ABSTRACT

The drying characteristics of yellow carrots (Daucus Carota) were studied using a laboratory scale batch Refractance Window™ (RW) dryer. This study was performed to facilitate the understanding of the design on a continuously operating RW dryer, by studying the drying characteristics of a batch RW drying process. A dryer was constructed by modifying a laboratory water bath. The bath is covered with a transparent Polyethylene terephthalate (PET) plastic film that has a drying area of 10 cm by 10 cm. 3 mm thick slices of carrots were dried on the Refractance Window™dryer, and the variation of the moisture content of the slices was measured during the drying process. The water temperature beneath the plastic film was maintained at 60 °C. From the experimental data the drying curves, the drying rate curves and the Krischer curves were plotted. The thin layer mathematical drying model that describes the drying kinetics of the drying data was determined. The bulk density of the powdered carrots and the variation of the rehydration ratio of the carrot slices with time was determined. The effective moisture diffusivity of the carrots is also estimated. Observations indicate that the carrot slices dried to below 10% moisture content on a dry basis in about 200 minutes. Regression analysis suggests that the Haghi and Ghanadzadeh model best describes the drying behaviour for the 3 mm thick slices with a coefficient of determination (R^2) value of 0.999 for the 17 models studied. The Rehydration Ratio of the carrot samples varied from 2.457 to 4.126 with rehydration times of 10 to 60 minutes. An average bulk density value of the carrot powder samples was 0.8625 grams/ml. The effective moisture diffusivity of the 3 mm thick carrot slices was determined to be 7.29513×10^{-8} m^2/s.

Keywords: Carrots, Refractance Window™ Drying, Drying Curves, Rehydration Ratio, Thin Layer Dying Models.

1. INTRODUCTION

Carrots, a root vegetable, are grown world-wide. Among vegetables, carrots have been ranked very high in nutritional value, potatoes and broccoli being more nutritious (USFDA, 2008). Carrots are rich in vitamin A and vitamin K, high in fiber and are also a good source of potassium. Carrots also have valuable amounts of antioxidant nutrients including traditional antioxidants like vitamin C and phyto-nutrient antioxidants like beta-carotene. The health benefits of carrots include reducing cholesterol and the signs of premature aging, preventing heart attacks, warding off of certain cancers and improving vision (da Silva Dias, 2014). Furthermore, carrots have the ability to increase the health of human skin, boost the immune system, improve digestion, increase cardiovascular health, detoxify the body, and boost oral health in a variety of ways.

Nutritionists' advice eating carrots in moderation because they contain more sugar than any other vegetable and it is believed that over ripe carrots, have high levels of sugars (da Silva Dias, 2014). Other than this, it is obvious that consuming carrots is beneficial. In many parts of the world, carrots are dried, turned into powder and used to make bread, cakes, soups, stews, curries and pies (Gupta, 2001). They are sometimes eaten raw or eaten as a snack. The Chinese make carrot soup (Chapman, 2009), the Africans make carrot porridge (Amagloh et al, 2012), and the Europeans among other things make carrot puree for their babies (Rubatzky, Quiros and Simon, 1999). A post-harvest preservation method is therefore needed to ensure that carrots are available throughout the year. Drying is a common method used to preserve carrot. Grishin et al. (1973) studied the kinetics of dehydrating vegetables and changes in the main chemical constituents (ascorbic acid, carotenes, essential oils, total sugars) due to drying process. It was recommended that diced carrots (cubes 5-8 mm) should be dried at 160°C. Carrots and onions were suggested to be used as basic ingredients of the snacks.

Reyes et al. (2002) analyzed the drying curves for 3 kg batches of carrot dice (9 x 9 x 3 mm) in a mechanically agitated fluidized bed drier operated at temperature of 70 - 160°C, air velocities of 1.1 - 2.2 m/s and stirring rates of 30 - 70 rpm. Loss of carotenes was minimal when drying was carried out at about 130°C with a drying time below 12 min. Machewad et al. (2003) studied the drying properties of carrots and their suitability for producing various value added products. Chemical properties of carrots indicated their suitability for drying and the feasibility of using carrot shreds for further processing. Leaching losses were observed in reducing sugars and total sugars during pre-treatments and an adverse effect was seen on beta-carotene content in all samples. Reconstitution ratio of dried carrot shreds was higher in pre-treated samples than untreated. Carrot shreds dried in open air had a lower reconstitution ratio. It was suggested that dried carrot shreds could be used as a base material for preparation of carrot *halwa*. Upadhyay et al. (2008) studied the characterization and dehydration kinetics of carrot pomace in open sun and in tray drier at 60, 65 70, 75 and 80º C. Observation indicated that increasing temperature from 60 to 75ºC., β-carotene retention (db) was increased from 9.86 to 11.57 mg/100g and ascorbic acid retention decreased from 22.95 to 13.53 mg/100g. Optimal drying was observed at 65º C on the basis of β-carotene and ascorbic acid retention. On the basis of the correlation coefficient (R^2), Upadhyay et al. (2008) claimed that the Page thin layer drying model rendered a better prediction of drying data than the Lewis model.

In this study, the dehydration kinetics and rehydration characteristic of carrot slices is investigated using the Refractance Window^{TM} drying techniques. An understanding of the dehydration kinetics using this novel technology will enable the design of equipment that operates continuously, thereby reducing the production time of dehydrated products.

2. MATIRIALS AND METHODS

2.1 The Equipment

A schematic diagram of the Refractance Window^{TM} type dryer used in this study is shown in Fig. 1. An electrically heated water bath was modified to construct the equipment. A transparent Polyethylene terephthalate (PET) plastic film replaced the bath's metal cover and the film was secured in place with metal angle brackets. The brackets were placed so that the lower side of the plastic film is always in contact with the water in the bath. The PET plastic film had a thickness of 0.15 mm. A 2.5kW electric immersion heater with a temperature controller heated the water bath. A current of air was maintained above the Refractance Window using a fan; this is to ensure that the vapour above the window did not inhibit the drying process.

2.2 Preparation of Carrot Slices

The carrot tubers used in this study were obtained from a local market. The tubers were washed, peeled and cut into 3 mm thick slices using a Mandolin type slicer. The moisture content of the fresh carrot slices was determined using a MB45 OHAUS Moisture Analyser. The experiment was repeated three times.

2.3 The Experimental Process

The water in the bath was heated to a temperature of 60^{o}C and the bath controller maintained this temperature throughout the experiment. With the plastic film secured in place, carrot slices are placed on the plastic film to dry. At specific time intervals, as the experiment progresses, some carrot slices were removed and the moisture content determined, using the moisture analyzer. The drying process is stopped when the moisture content of the sample was about 5% on a wet basis.

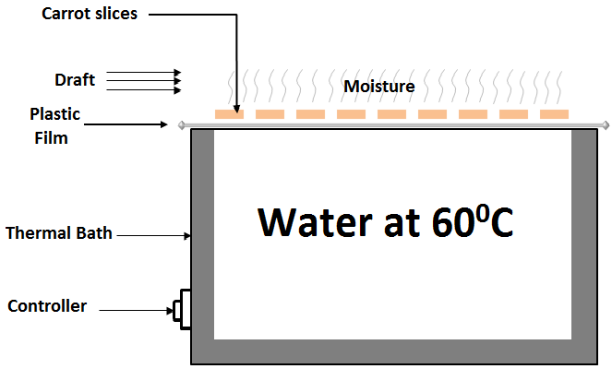

Fig. 1 Set up of the Apparatus Used

The drying experiments are repeated three times for each drying period and the average moisture content values for each time period taken.

Measurements

A MB45 OHAUS Moisture Analyser was used to measure the moisture content and weight of the carrot slices. The mass and % moisture contents readings were determined to an accuracy of 0.01g and 0.01% respectively. The thickness of the carrot slices was measured using a digital Vernier caliper.

2.4 Processing Experimental Kinetics Data

The experimental kinetic data was processed by first calculating the moisture ratio. The moisture ratio is calculated using equation 1 (Pala et al., 1996) and Doymaz, 2004),

$$MR = MC_t / MC_i \quad [1]$$

Where MC_t is the moisture content of carrot after drying for time t and MC_i is the initial moisture content of fresh carrot all in the unit of g of water removed/g of solids.

The moisture ratio (MR) is then fitted to the thin layer drying models list in Table 1. The parametric coefficients of each model are determined using Datafit 9.1 data regression software developed by Oakdale Engineering, Oakdale, (2014) PA USA. The software uses the Levenberg-Marquardt Method for Nonlinear Least Square Problems in determining its solution, (Gavin, 2013).The thin layer drying models that best fits the drying data is obtained by performing a Regression analysis using the drying data and the models listed in Table 1. The thin layer drying model that best fits the drying data has a value of the Coefficient of determination (R^2) close to unity and Chi-square (χ2) and Root Mean Square Error (RMSE) values that are minimal. (Akpinar, 2010; Tunde-Akintunde and Afon, 2010; El-Mesery and Mwithiga, 2014; John et al, 2014).

The value of correlation coefficient (R^2) is determined using equation 2

$$R^2 = \frac{\sum_{i-1}^{N}(MR_i - MR_{prev,i}).\sum_{i=1}^{N}(MR_i - MR_{\exp,i})}{\sqrt{\left[\sum_{i-1}^{N}(MR_i - MR_{pre,i}{}^2)\right]\left[\sum(MR_i - MR_{\exp,i}{}^2)\right]}} \quad [2]$$

The Root Mean Square Error (RMSE) is determined using equation 3

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^2\right]^{1/2} \quad [3]$$

Chi-square (χ2) is determined using equation 4

$$\chi 2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N-n} \quad [4]$$

Where,

N is the total number of observations, n is the number of model parameters, MR denotes the moisture ratio; $MR_{pre,i}$ and

$MR_{\exp,i}$ is the predicted and experimental moisture ratio at *i*th observation respectively.

After obtaining the best thin layer drying model that fits the drying data, the drying curve: moisture content – time plot, the drying rate curve: drying rate – time plot, and the Krischer curve: drying rate – moisture content plot, were obtained.

2.5 Bulk Density (ρ_b) Determination

The bulk density of the dried carrot is determined using the procedure described by Abdul-Fadl and Ghanem (2011). About 3 grams of the dried carrot powder was poured into a 10 ml graduated measuring cylinder and then tapped to reduce inter-particle pore spaces. The volume occupied was recorded. The bulk density was calculated using equation 5.

$$\rho_b = M_s / V_s \qquad [5]$$

Where ρ_b is bulk density, M_s is mass of sample used in grams and V_s is volume in ml occupied by sample in the measuring cylinder.

2.6 Rehydration Ratio (RR) Determination

The ability of the dried product to rehydrate is an important quality. The rehydration ratio was determined by soaking a known weight of dried carrot in water with a weight ratio greater than 1 to 6 as recommended by Baron Spices and Seasonings (2014). The experiments were repeated by increasing the soaking time. In each instance the mass of the rehydrated solid was then measured and the rehydration ratio determined using equation 6.

$$RR = M_r / M_d \qquad [6]$$

Where, M_r is the mass of the rehydrated solid and M_d is the mass of the dry sample.

Table 1 Thin Layer Drying Models

/N	Model	S/N	Model
1	MR = exp (-k.t) Newton Model (Ayensu, 1997).	10	MR = a.exp (-k.t) + (1-a).exp (-k.b.t) Diffusion Approach (Demir et al., 2007)
2	MR = exp (−k.t^n) Page Model (Page, 1949)	11	MR = a.exp (-k.t) + (1-a).exp (-g.t) Verma et al. (Verma el al. (1985)
3	MR = exp (−(k.t)^n) Modified Page(Ozdemir and Devres, (1999),	12	MR = exp (-k$_1$.t/1+k$_2$.t) Aghbashlo et al. (Aghbashlo et al. (2009)
4	MR = a.exp (-k.t) Henderson and Pabis (Henderson and Pabis, 1961)	13	MR = a.exp (−k.t^n) + b.t Midilli et al. (Midilli et al., 2002)
5	MR = a.exp (-k.t)+ b.exp (-g.t)+ c.exp (-h.t) Modified Henderson and Pabis Model (Karathanos ,1999)	14	MR = a.exp (-b.t^c) + d.t^2 + e.t + f Haghi and Ghanadzadeh (Haghi and Ghanadzadeh (2005).
6	MR = a.exp (-k.t) + c Logarithmic (Togrul and Pehlivan, 2003)	15	MR = a.exp[-ct/L^2] Simplified Fick's diffusion (SFFD) eqn. Diamente and Munro (1991)
7	MR = a.exp (−k$_0$.t) + b exp (−k$_1$.t) Two term (Madamba, 1996)	16	MR = exp[-k(t/L^2)^n] Modified Page equation –II (Diamente and Munro ,1993)
8	MR = a.exp (-k.t) + (1-a) exp (-k.a.t) Two term exponential (Sharaf-Elden et al. (1980)	17	MR = exp(-(t/a)^b) Weibull (Corzo et al.,(2008)
9	MR = 1+ a.t + b.t^2 Wang and Singh Model (Wang and Singh, 1978)		

2.7 Effective Moisture Diffusivity Determination

The Effective moisture diffusivity (D_{eff}) will be determined using Fick's second equationof diffusion which is as presented in Equation 7 (Crank, 1975).

The slice is considered to be of constant moisture diffusivity, infinite slab geometry, and a uniform initial moisture distribution (Crank 1975). The Crank equation for slabs which involved a series of exponents can be simplified to Equation 8 because the first term is used for long drying times (Lopez et al., 2000). Further detailed discussions can be found in Jena and Das (2007) and Taheri-Garavand, Rafiee and Keyhani (2011).

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-\frac{(2n-1)^2\pi^2 D_{eff}t}{4L^2}\right) \quad [7]$$

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

Where,

MR is the moisture ratio, D_{eff} (m^2s^{-1}) is the effective moisture diffusivity, L (m) is the sample thickness and t is the drying time (s).

A plot of $\ln(MR)$ against time gives a slope k_d from which D_{eff} can be obtained according to the equation 9

$$k_d = \frac{\pi^2 D_{eff}}{4L^2} \quad [9]$$

3. RESULTS AND DISCUSSIONS

Carrot slices 3 mm thick, with an initial moisture content of 663 % on a dry basis was dried until the moisture content was less than 10%. The moisture ratio for each drying time was calculated using equation 1. The moisture ratio data obtained were fitted to the seventeen (17) thin layer drying models presented in Table 1. Table 2 presents the details of the constants obtained from fitting the moisture ratio data to the drying models. The results suggested that the Haghi and Ghanadzadeh model best describes the drying kinetics for the 3 mm thick carrot slices with the coefficient of determination (R^2) value of 0.999.

3.1 The Drying Curve

The drying curve, (i.e. moisture content – time plot), for the carrot slices is shown in Fig. 2. The plot displays the experimentally data points and also the line plot obtained from the Haghi and Ghanadzadeh model. Fig. 2 shows that in about 200 minutes the 3 mm thick carrot slices dried to below 10 % moisture content.

3.2 The Drying Rate Curve

The drying rate curve, (i.e. drying rate – time plot) for the 3 mm thick carrot slices is shown in Fig. 3. The plot in Fig. 3 is a line plot which is obtained by differentiating the Haghi and Ghanadzadeh model equation obtained from the experimentally data points. The drying rate initially increases and reaches its maximum values at about 10 minutes and then falls. In the falling rate period, the rate initially falls very quickly and then slower thereafter.

3.3 The Krischer Curve

The Krischer curve, i.e. the drying rate – moisture content plot for the carrot slices is shown in Fig. 4. The plot is a combination of the Drying curve and the Drying rate curve. Fig. 4 shows that the drying rate (right to left) increases from its initial value when the carrot slice is fresh, it reaches a peak value (constant rate period) when the moisture content is about 580% (dry basis) and then falls (falling rate period). As illustrated, the constant rate period is just for a few minutes.

3.4 Rehydration Ratio (RR)

The Rehydration ratio - time plots for the 3 mm thick carrot slices is shown in Fig. 5. The rehydration ratio varies from 2.457 to 4.126 as the rehydration varies from 10 to 50 minutes.

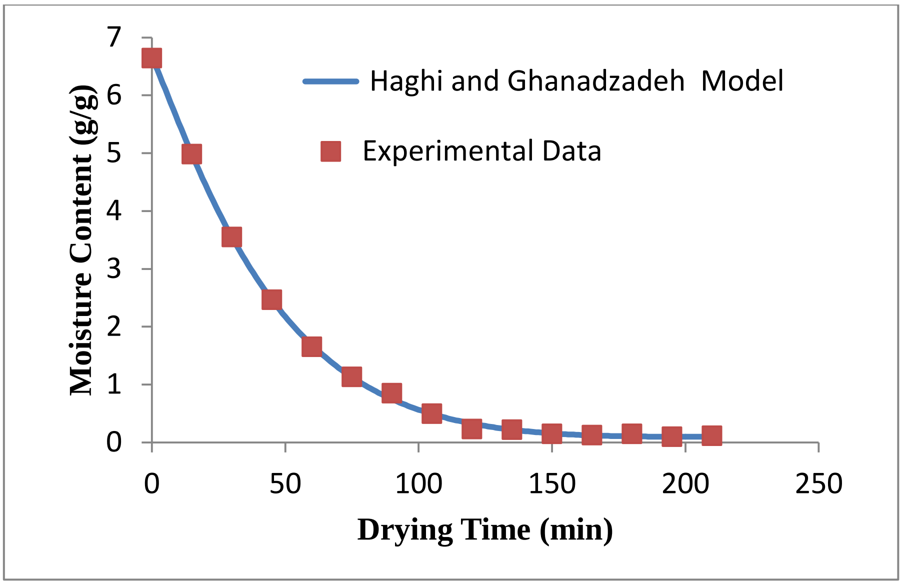

Fig. 2 Drying Curve – Moisture content-drying time plot for 3 mm thick carrot slices

3.5 Effective Moisture Diffusivity

A plot of $\ln(MR)$ against drying time is shown in Fig. 6. The line and the linear relationship that best fits the data are also shown on the figure. From the slope, k_d of the line, the effective moisture diffusivity D_{eff} is obtained, according to equation 9. For 3 mm thick carrot slices, a value of 7.29513 × 10^{-8} m^2s^{-1} is obtained as the effective moisture diffusivity.

4. CONCLUSIONS

Carrot slices with an initial moisture content of about 663 % (dry basis) was dried until the moisture contents was less than 10% using a Refractance Window dryer. The Haghi and Ghanadzadeh drying model was observed to best fit the drying kinetics of the carrot slices with the experimental data fitting the model with a coefficient of determination (R^2) value of 99.9%. The carrot slices dried to a moisture content of less than 10% within 200 minutes. The drying rate for the carrot slices reach a maximum value after about 10 minutes after drying begins. Finally, as the rehydration time varies from 10 to 60 minutes, the rehydration ratio for the carrot slices varies from 2.457 to 4.126. The bulk density of carrot was determined to be 0.8625 g/ml. The effective moisture diffusivity was found to be 7.29513×10^{-8} m^2/s.

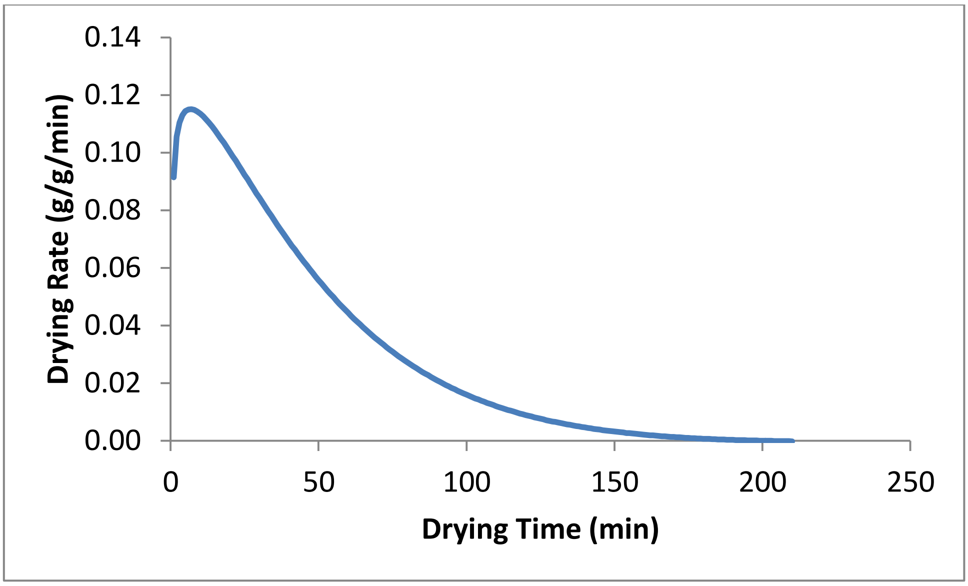

Fig. 3 Drying Rate Curve – Drying rate - drying time plot for 3 mm thick carrot slices

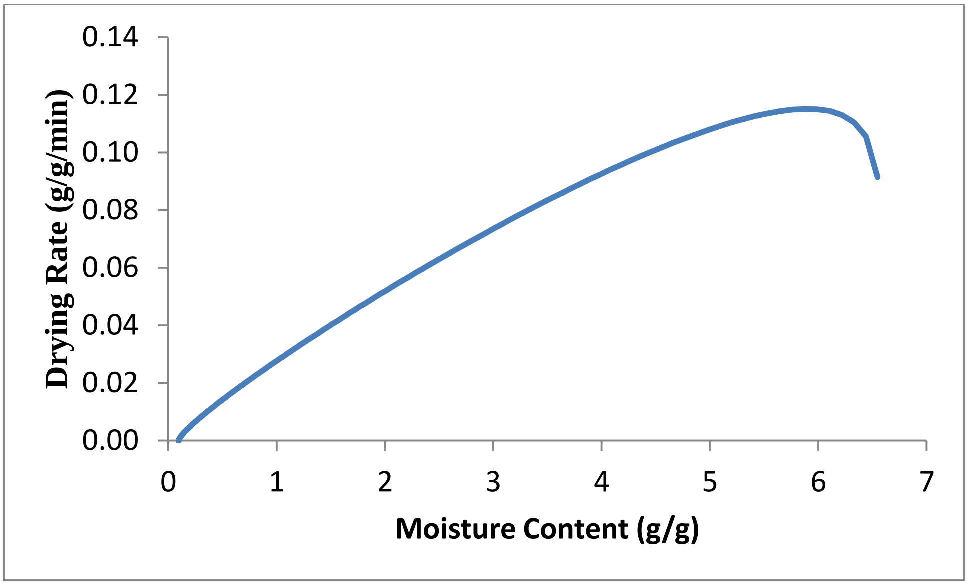

Fig. 4 Krischer curve – Drying rate - Moisture plot for 3 mm thick carrot slices

Table 2: Constants and Coefficients for the Models Obtained by Fitting Data to the 17 Thin Layer Models for 3 mm Thick Carrot slices

No.	Model Name	Polymath Constants		R^2	MBE	χ2	RMSE
1	Newton	k= 0.02265		0.997258	-0.00349	0.000237	0.014788
2	Page	k= 0.022075	n= 1.118216	0.998391	-0.04139	0.005027	0.065223
3	Modified Page	k= 0.022075	n= 1.118216	0.998391	-0.00628	0.000152	0.011326
4	Henderson and Pabis	a= 1.008633	k= 0.022814	0.997335	-0.00294	0.000251	0.014578
5	Modified Henderson and Pabis	a= 0.000433 g= 0.022931 b= 0.50327	c= 0.505564 h= 0.022931 k= -0.00992	0.997836	0.001046	0.00032	0.013137
6	Logarithmic / Yagcioglu et al.	a= 1.004429 c= 0.005356	k= 0.023192	0.997533	2.2E-07	0.000256	0.014026
7	Two term	a= 1.008834 b= 0.000433	k_0= 0.022931 k_1= -0.00992	0.997836	0.001046	0.000249	0.013137
8	Two term exponential	a= 1.613842	k= 0.028415	0.998414	-0.00623	0.000149	0.011246
9	Wang and Singh	a= -0.00951	b= 2.01E-05	0.768802	0.033022	0.021788	0.13578
10	Diffusion Approach	a= 0.999614 b= -0.44991	k= 0.022749	0.997747	0.000364	0.000234	0.013405
11	Verma et al.	a= 3.091106 g= 0.017591	k= 0.019047	0.997496	-0.00536	0.00026	0.014132
12	Aghbashlo et al.	k_1= 0.020349	k_2= -0.00159	0.998126	-0.00726	0.000177	0.012226
13	Midilli et al.	k= 0.012586 n= 1.149347	a= 0.9998825 b= 4.43E-05	0.9993773	-0.00018	7.172E-05	0.007046
14	Haghi and Ghanadzadeh	a= 1.088222 c= 1.113747 e= 0.00073	b= 0.013406 d= -1.28E-06 f= -0.08824	0.9994914	6.384E-06	7.533E-05	0.006369
15	Simplified Fick's diffusion (SFFD) equation	a= 1.008633	c= 0.205328	0.997335	-0.00294	0.000251	0.014578
16	Modified Page equation -II	k= 0.16416	n= 1.118098	0.998391	-0.00627	0.000152	0.011326
17	Weibull	a= 45.29976	b= 1.118216	0.998391	-0.00628	0.000152	0.011326

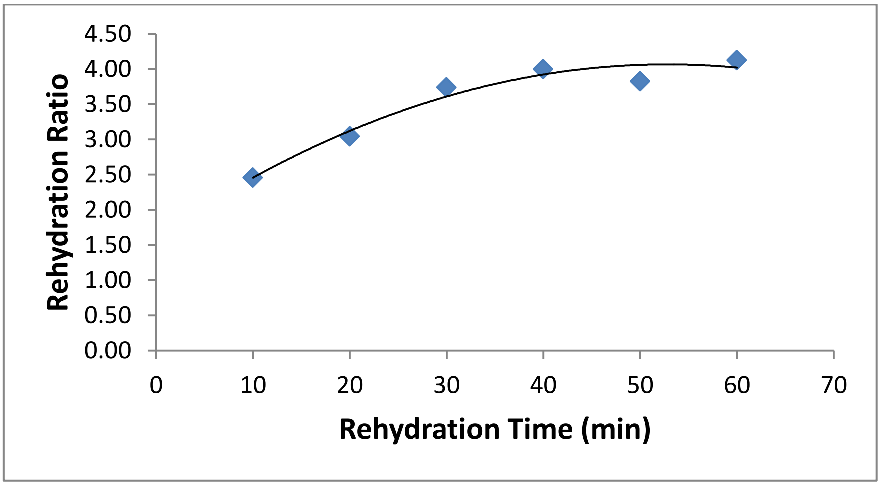

Fig. 5 Plot of Rehydration Ratio against Rehydration Time

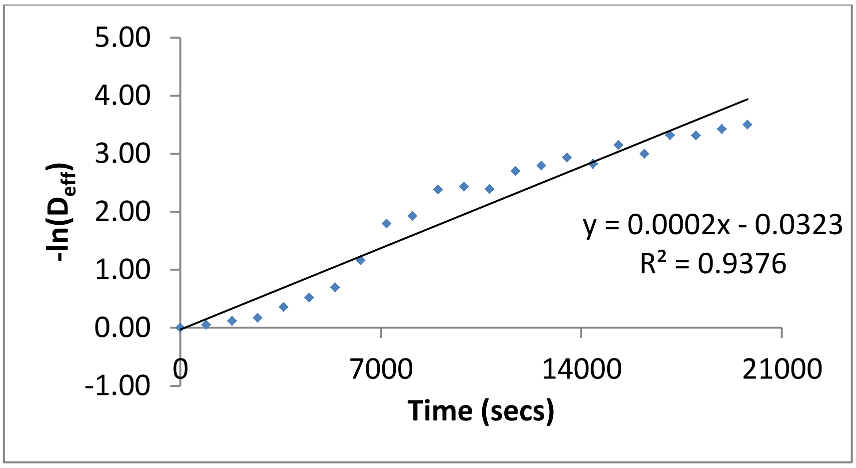

Fig. 6 – $\ln(MR)$ **vs time plot - Estimation of Moisture Diffusivity Coefficient**

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