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Statistical Modelling of Drying Characteristics of Unripe Plantain (*Musa Paradisiaca*) Slices

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ABSTRACT

This work is designed to carry out the statistical modelling of the drying characteristics of unripe plantain (*Musa paradisiaca*) slices and to study the effect of drying temperature and slice thickness on drying characteristics. The test samples were dried in a laboratory scale oven dryer at varying temperatures of 70^0C, 80^0C and 90^0C, and different slice thicknesses of 2mm, 3mm and 4mm.The result obtained indicated that drying temperature and slice thickness had significant effect on drying rate and hence moisture profile. The moisture ratio – drying time data obtained were fitted to ten thin layer drying models. The fit quality obtained with each model was evaluated using statistical tests namely; coefficient of determination (R^2), root mean square error (RMSE), reduced chi-square (X^2), and standard error of estimate (SEE). Although most of the models fitted quite well to the experimental data, Page and Modified Page models showed the highest average R^2 and the lowest average RMSE, X^2 and SEE values. Page and modified Page models were selected and found suitable to represent the drying characteristics of unripe plantain slices and predict drying times.

Keywords-- Drying, Slice Thickness, Temperature, Thin-Layer Models, *Musa Paradisiaca*

I. INTRODUCTION

Drying is a mass transfer process consisting of the removal of water or another solvent by evaporation from a solid, semi-solid or liquid. This process is often used as a final production step before selling or packaging products. To be considered ''dried'', the final product must be solid, in the form of a continuous sheet, long pieces, particles or powder. A source of heat and an agent to remove the vapour produced by the process are often involved. Unripe plantain (*Musa paradisiacal*) is a very nutritive food crop cultivated in the tropics and is an important staple food in Sub-Sahara Africa. It is a rich source of carbohydrate, vitamins, and other food supplements. The medical importance of the food crop cannot be overemphasized (Eklou *et al*., 2006; Hahou *et al*., 2003). It is abundant in a particular period, when it is in season and scarce during the off season. Since this food crop is highly perishable after harvest, drying is a common practice for preserving it in order to make it available throughout the year.

A number of drying models have been applied in characterizing the drying kinetics of unripe plantain of different species. Satimehin *et al.* (2010) presented a study on the experimental determination of the thin-layer drying rates of plantain chips as a function of drying air temperature. The plantain chips were fully exposed to convective air at constant temperatures of 40, 50, 60 and 75 °C, and velocity of 2.2 m/s. The drying data obtained were fitted to the thin-layer drying model of Fick's diffusion equation. Results showed that plantain drying is a diffusion-controlled process. The rate of drying increased with temperature; and the characteristic drying constant also increased linearly with the product's temperature. Ayim *et al.* (2012) investigated the effects of pretreatment and temperature on the air-drying of two plantain varieties, namely French horn and False horn, in a hot air drier at temperature range of 50^oC to 80^oC. Sliced samples from each variety were thoroughly mixed and divided into four groups of which one portion was dipped in citric acid, another in sodium metabisulphite all for one minute and a third steam blanched for 10 minutes. The fourth portion was not pretreated and it served as the control. Drying took place entirely in the falling rate period. Effective moisture diffusivity increased with increased drying air temperature and varied significantly ($p < 0.05$) with pretreatment. Temperature dependency of moisture on diffusivity was illustrated by the Arrhenius relationship. Over the range of temperature, effective moisture diffusivity varied from 7.54×10^{-10} to 2.37×10^{-9} and 5.17×10^{-10} to 3.11×10^{-9} for French horn and False horn respectively. Activation energy for drying ranged from 11.88kJ/mol to 33.10kJ/mol and 26.76kJ/mol to 44.50kJ/mol for French and False Horn respectively. The effects of variety and pretreatment were significant ($p < 0.05$) on activation energy. The results suggest that citric acid and sodium metabisulphite pretreatment had a significant impact on the drying and were effective as temperature decreased. Famurewa and Adejumo (2015) studied the thin layer drying behavior of unripe plantain slices using charcoal fuelled cabinet dryer. The dryer's optimum operating temperature was in the range 50^{o}C - 70^{0}C. Fourteen different thin layer drying models were fitted to experimental data to enable the selection of a suitable drying model. Midilli and Kucuk, Modified Henderson, and Wang and Singh models were most suitable to describe the drying behavior of the unripe plantain at 5, 10 and 15 mm thicknesses respectively. In a study by Ashaolu and Akinbiyi (2015), the effects of varying chips sizes of plantain varieties (Dwarf Cavendish and *Musa sapientum*) at different drying conditions were investigated. The drying was carried out at 50, 60, 70 and 80^{0}C using convective air flowing at a velocity of 2.2 m/s. The plantain samples were cut into equal sizes of thicknesses: 2cm, 3cm, 4cm, and 5cm for the two varieties used in the experiment. The results showed that drying rate was higher at 80^{0}C than 50^{0}C and that the entire drying process took place in the falling rate period. The study also indicates that the method of drying is more efficient on 2cm thickness than 5cm especially for *Musa sapientum* variety of the banana. The *Musa sapientum* variety had the highest drying rate than Dwarf *Cavendish* variety in almost all temperatures and treatment variations. Oforkansi and Oduola (2016) presented a study which focused on the selection of the appropriate thin-layer models that best describe the drying characteristics of the French horn plantain. The drying of the 5mm thickness size plantain samples occurred at 40^{O}C, 50^{O}C, 60^{O}C and 70^{O}C temperatures until the equilibrium condition was attained. The experimental moisture ratio values at each temperature were fitted to Lewis, Page and Modified-page thin-layer models. The results showed that Page model best described the drying characteristics of the plantain sample within the temperature range of the analysis.

The major objectives of this study were to investigate the effect of drying temperature and slice thickness on drying characteristics of unripe plantain slices and to establish suitable drying model to describe the drying behaviour.

II. MATERIALS AND METHOD

Fresh fingers of unripe plantain, procured from a local market, in Owerri, Nigeria were used in this study. They were stored at room temperature (about 25^{o}C) until the drying process. The storage time did not exceed two days for each batch procured.

The fresh unripe plantains were peeled and cut into thin slices of 2mm, 3mm, and 4mm thicknesses with a kitchen knife. The measurement was done with the aid of venier caliper for thickness accuracy.

To determine the initial moisture content M_0, 30g sample each of 2mm, 3mm, and 4mm thicknesses were dried in the oven at 90^{o}C till constant mass was achieved. The initial moisture content was then determined for each slice thickness.

Another 30g sample each of the same thicknesses (2mm, 3mm and 4mm) was introduced into the oven at 70^{o}C. The samples were dried in the oven at the intervals of 10mins for about 30mins, 20mins interval for 1hour and 30mins interval till constant mass was attained. After each drying process, the samples were removed and cooled in desiccators for a period of 5mins before weighing. The moisture content was determined after each time interval using the following formula for weight loss;

$$\text{Moisture loss } M_c = \frac{M_1 - M_2}{M_2} \times 100 \quad (1)$$

where M_c is the moisture content at time, t, M_1 and M_2 are the initial and final mass of a given sample in grams.

The same procedure was carried out for 80^{0}C and 90^{0}C oven temperature respectively. The moisture content that corresponded to the time at which constant mass was achieved was the equilibrium moisture content M_e for that run. The moisture content was then converted to moisture ratio using the formula;

$$M_R = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

whereM_R is the moisture ratio, M_t the moisture content at time, t, the drying time, M_o the initial moisture content and M_e the equilibrium moisturecontent.The moisture ratio versus drying time data obtained from the drying experiment were fitted to ten thin layer drying models using MATLAB 7.9. These models are shown in Table 1. The coefficient of determination (R^2), root mean square error (RMSE), reduced chi square (X^2) and sum of errors of estimate (SEE) were used as criteria for adequacy of fit. The model with the highest R^2 and lowest RMSE, X^2 and SEE values was chosen as the best model that describes the thin layer drying characteristics of the plantain slices.

III. RESULTS AND DISCUSSION

Drying characteristics

The change in moisture profile with respect to time for various thicknesses and drying temperatures for unripe plantain is presented in terms of moisture ratio versus time data shown in Tables 2 – 4. It can be observed that for a constant drying temperature, drying rate increased for

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lower thickness of material and higher temperature. Thus, drying temperature and slice thickness had significant effect on drying behaviour of unripe plantain slices, though the effect of temperature was more pronounced. The increase in temperature and decrease in slice thickness resulted in a decrease in drying time. As the thickness of the slices increased, time required to dry the sample to the equilibrium or safe moisture content also increased, because moisture had to travel relatively a longer path in case of thick sample to come to the surface from the inside of the slice. As the drying proceeded, the surface moisture receded gradually and the moisture inside the product tried to diffuse to the surface. The same drying behaviour has been reported by earlier researchers (Akgun and Doymaz, 2005; Jena and Das, 2007). Similarly, as temperature increased, vapour pressure inside the sample also increased and in turn the pressure gradient between the surface and inner side of the sample increased resulting in a higher drying rate and consequently lesser drying time. This behaviour of decreasing time with increasing drying temperature has also been reported for different foodstuffs (Sarsavadia *et al.*, 1999; Jain and Pathare, 2004; Sharma *et al.*, 2005; Doymaz, 2007; Nkwocha *et al.*, 2015a; Nkwocha *et al.*, 2015b).

Table1: Mathematical models used to fit the drying kinetics of unripe plantain.

Model /No	**Model name**	**Model equation**	**References**
1	Lewis model	$MR = \exp(kt)$	Lewis (1927)
2	Page model	$MR = exp(-kt^n)$	Page (1947)
3	Henderson & Pabis	$MR = aexp(-kt)$	Overhults et al. (1973)
4	Logarithmic model	$MR = aexp(-kt) + c$	Diamente and Munro.(1993)
5	Modified page	$MR = aexp[(-kt)^n]$	Henderson and Pabis (1961)
6	Wang and Singh	$MR = 1 + at + bt^2$	Karathanos and Belessiotis(1999)
7	Two-term model	$MR = aexp(-k_0t) + bexp(-k_1t)$	Yagcioglu *et al.* (1999)
8	Two-term exponential model	$MR = aexp(-kt) + (1-a)exp(-kat)$	Wang and Singh (1978)
9	Modified Henderson & Pabis	$MR = aexp(-kt) + bexp(-gt) + cexp(-ht)$	Henderson (1974)
10	Modified page model 11	$MR = exp(-(kt)^n)$	Sharaf-Elden et al. (1980)

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Table 2: Drying at 70°C for different sample thicknesses

Drying time, t (min)	Moisture Ratio, M_R Sample thickness		
	2mm	3mm	4mm
0	1	1	1
10	0.88856	0.8361	0.9039
20	0.7505	0.7596	0.8177
30	0.6604	0.6261	0.7454
50	0.4600	0.4324	0.5876
70	0.2390	0.1949	0.4506
90	0.0979	0.0796	0.3448
120	0.0276	0.0262	01948
150	0.0113	0.0079	0.0895
180	0.0095	0.0076	0.0270
210	0.0061	0.0061	0.0106
240	0.0033	0.0012	0.0064
270	0.0015	0.0010	0.0044
300	0.0008	0.0001	0.0012
330	0	0	0

Table 3: **Drying at 80°C for different sample thicknesses**

Drying time, t (min)	Moisture Ratio, M_R Sample thickness		
	2mm	3mm	4mm
0	1	1	1
10	0.8252	0.8996	0.8819
20	0.7024	0.7932	0.7893
30	0.5453	0.6981	0.7029
50	0.3226	0.5040	0.5270
70	0.1014	0.2221	0.3029
90	0.0344	0.0867	0.1687
120	0.0137	0.0457	0.0657
150	0.0004	0.0268	0.0383
180	0	0.0247	0.0305
210	0	0.0022	0.091
240	0	0	0.0060
270	0	0	0.0013
310	0	0	0

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Table 4: Drying at 90°C for different sample thicknesses

Drying time, t (min)	Moisture Ratio, M_R Sample thickness		
	2mm	3mm	4mm
0	1	1	1
10	0.7532	0.8226	0.8758
20	0.5149	0.6841	0.7436
30	0.1754	0.2804	0.4686
50	0.0270	0.0424	0.2190
70	0.0158	0.0285	0.0819
90	0.0064	0.0205	0.0317
120	0.0063	0.0078	0.0106
150	0.0033	0.0054	0.0099
180	0.0023	0.0034	0.0013
210	0.0014	0.0013	0.0007
240	0.0007	0.0011	0.0004
270	0	0	0

Mathematical Modelling

The statistical results of the different models, including the comparison criteria used to evaluate goodness of fit are presented in Tables 5 and 6. R^2 values varied from 0.8131 to 0.9974, whereas the RMSE values ranged from 0.01223 to 0.15220. Chi-square values were found to be varying from 6.8879E-14 to 6.6100E-2, with SEE ranging from 0.0011 to 0.4319. All the models investigated recorded $R^2 > 0.97$ and RMSE ≤ 0.06 with the exception of Wang and Singh (model No. 6) and Modified Henderson & Pabis (model No. 9). Although most of the models fitted quite well to the experimental data, Page and Modified Page models showed the highest average $R^2$and the lowest average RMSE, chi-square and SEE values. Page and modified Page models (referred to as Page models) were therefore selected as suitable models to represent the drying characteristics of unripe plantain slices. Figs 1 – 6 depict the suitability of Page models to predict the experimental moisture ratio values with drying time at different drying temperatures for different slice thicknesses. These figures impress very good agreement between experimental and predicted moisture ratio values. Thus, it can be confirmed that the Page models are appropriate for describing the drying kinetics of unripe plantain slices. Page model has been selected by earlier researchers to predict the drying behaviour for various food products (Nkwocha et al., 2015a; Nkwocha etal., 2015b; Therdthai and Zhou, 2009; Doymaz and Ishmail, 2011; Mitra et al., 2011).

IV. CONCLUSION

The drying kinetics of unripe plantain of 2mm, 3mm, and 4mm thick slices in a laboratory convective dryer at temperatures – 70, 80, and 90^0 C was studied. The study showed that drying temperature and slice thickness had significant effect on drying rate and hence moisture profile variation within the slices. Increase in the drying temperature and decrease in slice thickness caused a decrease in drying time. Based on non-linear regression analysis, Page model and Modified Page model were found suitable and selected to predict the drying pattern of unripe plantain slices.

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Table 5: Statistical Results obtained from the different thin layer models for different slice thicknesses and temperatures

	70°C -2mm				80°C -2mm				90°C -2mm			
No	SEE	R^2	RMSE	X^2	SEE	R^2	RMSE	X^2	SEE	R^2	RMSE	X^2
1	0.0143	0.9803	0.05193	2.0478×10^{-4}	0.1838	0.9783	0.05659	3.3800×10^{-2}	0.0089	0.9723	0.05648	8.0060×10^{-5}
2	0.0121	0.9970	0.02118	1.4750×10^{-4}	0.0190	0.9959	0.02621	3.6266×10^{-4}	0.0048	0.9957	0.02314	2.2720×10^{-5}
3	0.0412	0.9844	0.04788	1.7000×10^{-3}	0.0451	0.9817	0.05512	2.0000×10^{-3}	0.0273	0.9750	0.05607	7.4412×10^{-4}
4	0.0019	0.9864	0.04651	3.4408×10^{-12}	0.0011	0.9873	0.04915	6.8879×10^{-14}	0.0015	0.9757	0.05787	2.9144×10^{-14}
5	0.0563	0.9970	0.02118	3.2000×10^{-3}	0.0306	0.9959	0.02621	9.3648×10^{-4}	0.0678	0.9957	0.02314	4.6000×10^{-3}
6	0.0899	0.9246	0.1054	8.1000×10^{-3}	0.0211	0.9860	0.04825	4.4632×10^{-4}	0.2571	0.5808	0.22940	6.6100×10^{-2}
7	0.0323	0.9962	0.02567	1.0000×10^{-3}	0.0380	0.9880	0.05149	1.2000×10^{-3}	0.0080	0.9749	0.06203	6.3780×10^{-5}
8	0.015	0.9956	0.02552	2.2391×10^{-4}	0.0201	0.9945	0.03027	4.0521×10^{-4}	0.0094	0.9930	0.02968	8.8705×10^{-5}
9	0.0355	0.8911	0.1522	1.3000×10^{-3}	0.0463	0.9970	0.03135	2.1000×10^{-3}	0.0108	0.9902	0.04395	1.1558×10^{-4}
10	0.0126	0.9970	0.02205	1.5836×10^{-4}	0.0203	0.9959	0.02802	4.1262×10^{-4}	0.0050	0.9957	0.02420	2.5051×10^{-5}

	70°C -3mm				80°C -3mm				90°C -3mm			
No	SEE	R^2	RMSE	X^2	SEE	R^2	RMSE	X^2	SEE	R^2	RMSE	X^2
1	0.0184	0.9812	0.04983	3.3809×10^{-4}	0.0052	0.9652	0.07327	2.7473×10^{-5}	0.0058	0.9527	0.07893	3.0872×10^{-5}
2	0.0165	0.9853	0.02581	2.7252×10^{-4}	0.0047	0.9944	0.03085	2.2522×10^{-5}	0.0098	0.9920	0.03384	9.5178×10^{-5}
3	0.0395	0.9839	0.04783	1.6000×10^{-3}	0.0460	0.9727	0.06806	2.2100×10^{-3}	0.0350	0.9584	0.07735	1.2000×10^{-3}
4	0.0026	0.9857	0.04688	1.1581×10^{-12}	0.0040	0.9772	0.06558	1.6079×10^{-13}	0.0084	0.9596	0.07990	7.0054×10^{-13}
5	0.0165	0.9953	0.02581	2.7066×10^{-4}	0.0047	0.9944	0.03085	2.2341×10^{-5}	0.0098	0.9920	0.03384	9.5480×10^{-5}
6	0.1127	0.9038	0.11690	1.2700×10^{-2}	0.0015	0.9754	0.06446	2.2822×10^{-6}	0.1840	0.7284	0.19750	3.3900×10^{-2}
7	0.0412	0.9877	0.04544	1.7000×10^{-3}	0.0486	0.9820	0.06177	2.4000×10^{-3}	0.0367	0.9867	0.04828	1.3000×10^{-3}
8	0.0192	0.9942	0.02877	3.6798×10^{-4}	0.0056	0.9915	0.03796	3.1708×10^{-5}	0.4318	0.9851	0.04621	1.8640×10^{-1}
9	0.0082	0.9978	0.02122	6.7102×10^{-5}	0.1150	0.8131	0.07123	1.3200×10^{-2}	0.0570	0.9993	0.01223	3.2000×10^{-3}
10	0.0163	0.9953	0.03468	2.6622×10^{-4}	0.0033	0.9944	0.03323	1.1068×10^{-5}	0.0101	0.9920	0.03549	1.0114×10^{-4}

No = Model number

Table 6: Statistical Results obtained from the different thin layer models for different slice thicknesses and temperatures

	70°C -4mm				80°C -4mm				90°C -4mm			
No	SEE	R^2	RMSE	X^2	SEE	R^2	RMSE	X^2	SEE	R^2	RMSE	X^2
1	0.0239	0.9858	0.04466	5.7340×10^{-4}	0.0125	0.9814	0.05131	1.5685×10^{-4}	0.3225	0.9715	0.06324	1.0400×10^{-1}
2	0.0259	0.9974	0.02059	6.7064×10^{-4}	0.0077	0.9968	0.02307	5.9935×10^{-5}	0.0109	0.9957	0.02314	1.1987×10^{-4}
3	0.0496	0.9887	0.04131	2.5000×10^{-3}	0.0394	0.9853	0.04752	1.6000×10^{-3}	0.0374	0.9780	0.05797	1.4000×10^{-3}
4	0.0015	0.9939	0.03170	2.2329×10^{-12}	0.0040	0.9879	0.04502	4.5081×10^{-12}	0.3500	0.9797	0.05850	1.2250×10^{-1}
5	0.0277	0.9974	0.02059	7.6942×10^{-4}	0.0077	0.9968	0.02307	5.9695×10^{-5}	0.0110	0.9957	0.02314	1.1994×10^{-4}
6	0.0281	0.9915	0.03589	7.8968×10^{-4}	0.0444	0.9681	0.06986	2.0000×10^{-3}	0.1064	0.8769	0.13720	1.1300×10^{-2}
7	0.0466	0.9807	0.05863	2.2000×10^{-3}	0.0321	0.9608	0.04392	1.0000×10^{-3}	0.0077	0.9832	0.05600	5.9027×10^{-7}
8	0.0249	0.9968	0.02189	6.2241×10^{-4}	0.0130	0.9960	0.02461	1.6849×10^{-4}	0.0050	0.9974	0.02011	2.4784×10^{-5}
9	0.0337	0.9911	0.04416	1.1380×10^{-1}	0.0361	0.9895	0.04910	1.3000×10^{-3}	0.0329	0.9926	0.04291	1.1000×10^{-3}
10	0.0251	0.9974	0.02059	6.2845×10^{-4}	0.0079	0.9968	0.02307	6.1818×10^{-5}	0.0115	0.9957	0.01975	1.3174×10^{-4}

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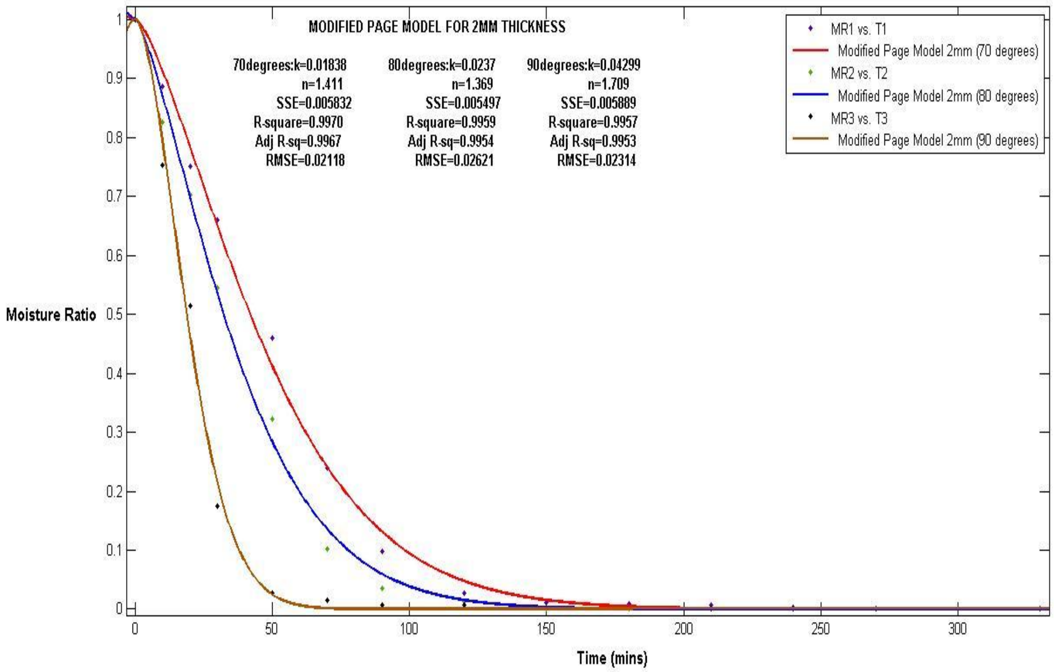

Fig. 1: Page Model fits for 2mm thickness at the three drying temperatures

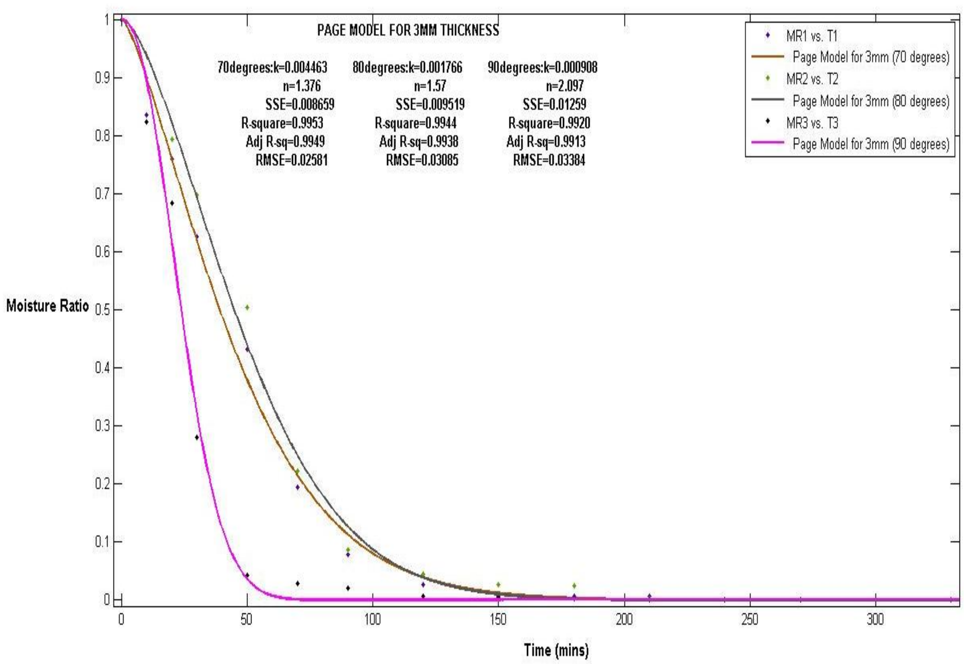

Fig.2: Page Model fits for 3mm thickness at the three drying temperatures

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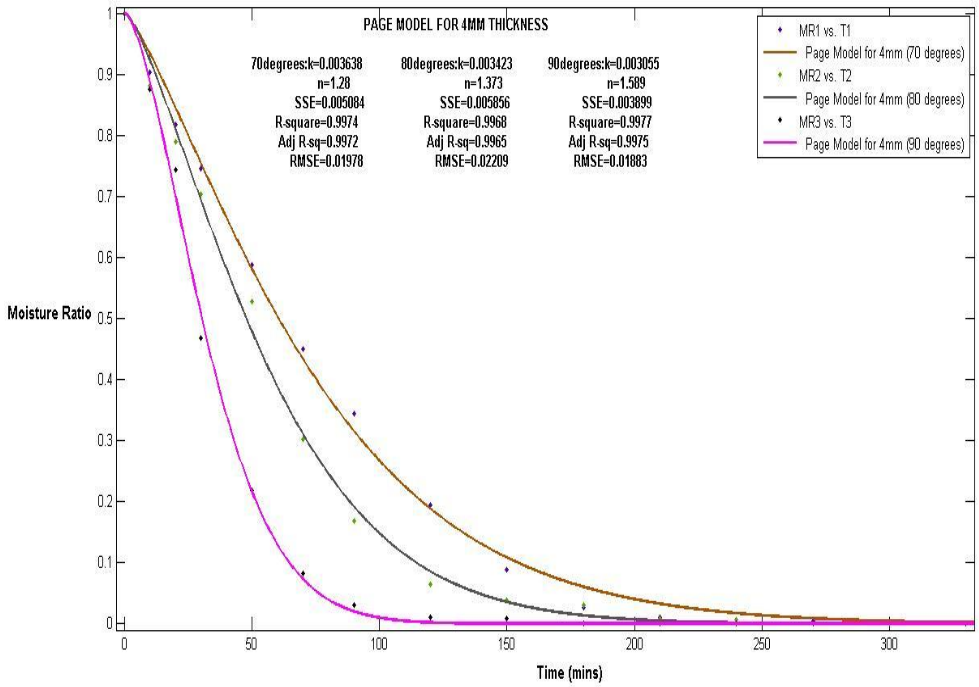

Fig. 3: Page Model fits for 4mm thickness at the three drying temperatures

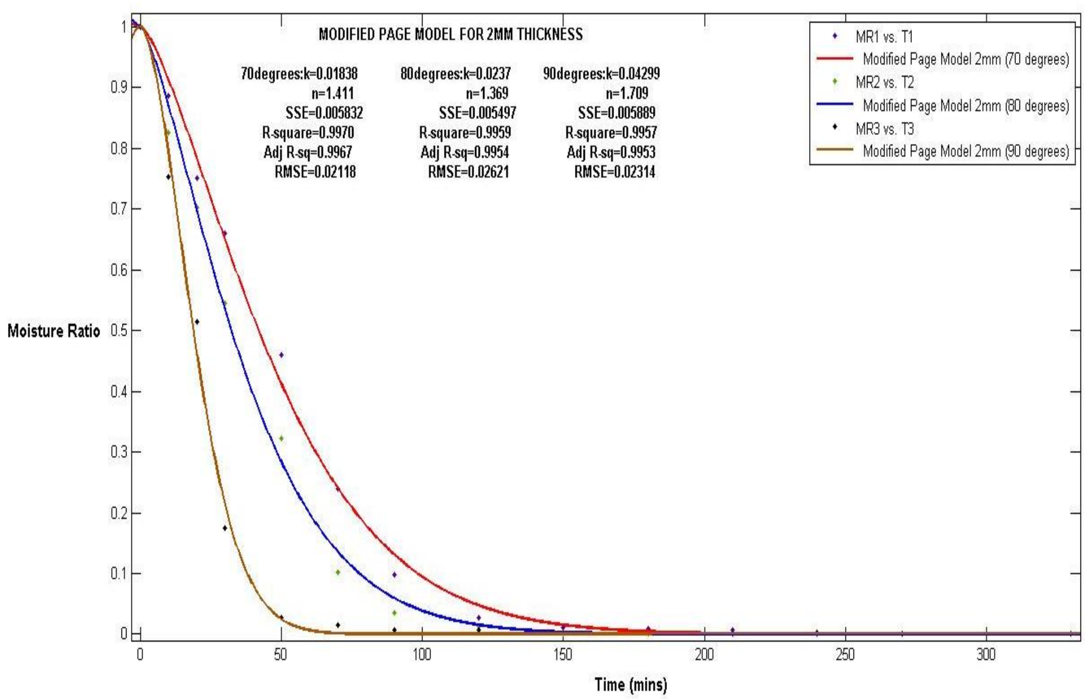

Fig. 4: Modified Page model fits for 2mm thickness at the three drying temperatures

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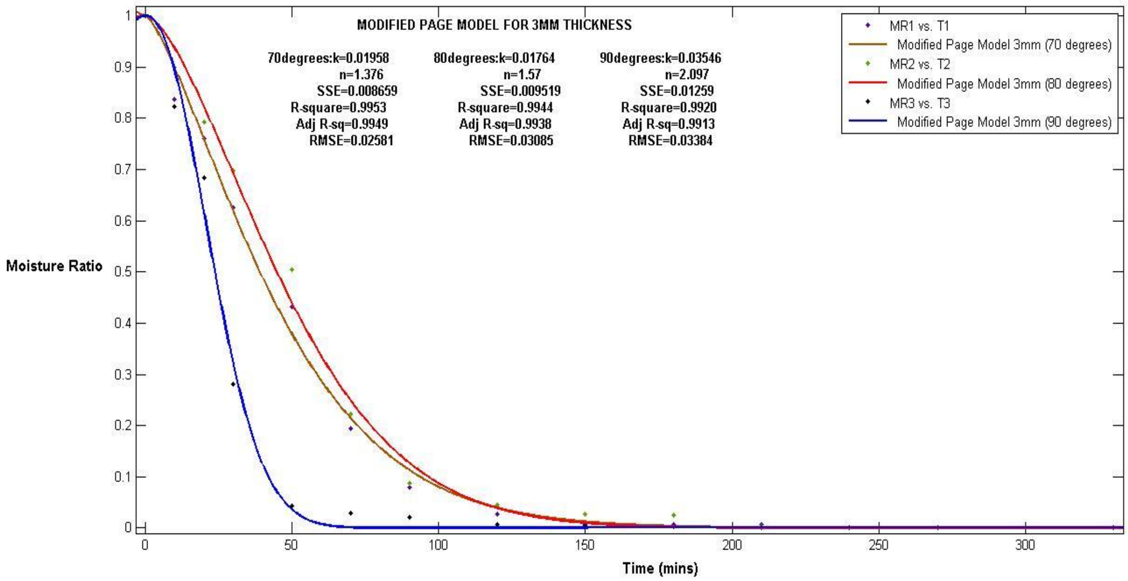

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Fig. 5: Modified Page model fits for 3mm thickness at the three drying temperatures.

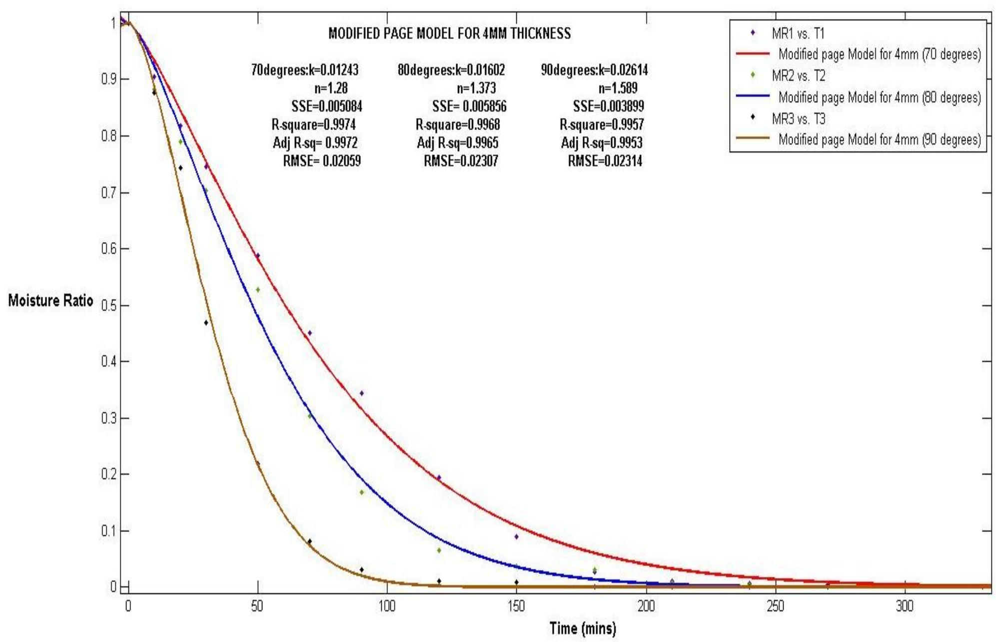

Fig. 6: Modified Page Model fits for 4mm thickness at the three drying temperatures

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