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Thin-layer drying of some Sri Lankan paddy varieties under low humid conditions

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ABSTRACT

Thin-layer drying characteristics of paddy were examined within the relative humidity range from 30% to 60%. A test chamber has been constructed with Perspex and continuously flushed with low humid air to control the inside relative humidly at required levels and several homogeneous thin layer paddy samples were dried inside the chamber. BG 300, BG 352 and BG 357 paddy varieties developed by Rice Research and Development Institute, Bathalegoda, Sri Lanka have been used in this study. Normalized drying data was transformed into dimensionless parameter called Moisture Ratio, and fitted with four semi-theoretical models. Correlation coefficients, standard errors and residual plots were used as criteria for evaluating the goodness-of-fit. Of the models used the two-term exponential model was found to fit well with the experimental data and is recommended as the thin-layer drying model for paddy. Drying constant of the dominant drying process of BG 300 varies from 9.31×10^{-5} s^{-1} to 8.41×10^{-5} s^{-1}, BG 352 varies from 8.81×10^{-5} s^{-1} to 7.99×10^{-5} s^{-1} and BG 357 varies from 1.22×10^{-4} s^{-1} to 1.01×10^{-4} s^{-1} over the RH range 30 - 60%. Investigations revealed that the magnitudes of the drying constants increase linearly with the decrease of the relative humidity level of the ambient atmosphere. Results further indicate that the two drying constants can be attributed to two diffusion processes, one which occurs within the seed and the other across the husk.

Nomenclature:

A, B	drying coefficients	MC_i	initial moisture content (% db)
db	dry basis	MR	moisture ratio
D_{eff}	effective diffusivity ($m^2\,s^{-1}$)	R	average radius of paddy seed (m)
k, k_1, k_2	drying constants (s^{-1})	RH	relative humidity (%)
MC	moisture content at time t (% db)	T	temperature (^{o} C)
MC_e	equilibrium moisture content	t	drying time (s)

1. INTRODUCTION

The moisture content of Sri Lankan paddy after harvesting may vary from 18 % db to over 30 % db and it is necessary to dry the paddy to lower moisture contents (13-14 % db) for safe storage [1]. Open-air sun drying has been used by farmers since time immemorial to dry paddy and other agricultural products as a means of preservation [2]. In certain paddy producing areas, weather conditions during harvest are not favorable for complete sun drying of paddy. In addition to this, sun drying which normally takes place in open air has many disadvantages such as mixing with dust, insect infestation, high labor costs, large area requirement, losses due to birds and possibility of microbial cross-contamination [3]. All these factors call for artificial drying of paddy after harvesting to allow safe storage and retail distribution.

High humidity levels (75 %- 85 %) prevailing in Sri Lanka is a severe problem when it comes to storing of agricultural products. Biological degrading of food under high humid conditions is a well known effect. Each year authorities have to destroy tons of paddy as they become unsuitable for human consumption due to bad storage conditions. The conditions of stored grains are determined by the complex interactions between the grain and the macro and micro-environment, and a variety of organisms including micro-organisms, insects, mites etc. which can give rise to such deterioration [4]. If the relative humidity level can be reduced and controlled inside warehouses it is possible to prolong the shelf-life of grains including paddy.

Chen and Wu investigated the drying characteristics of paddy under different temperatures and relative humidity ranges and they identified the two term model as the best model for describing thin layer drying of rough rice [5]. Basunia and Abe studied thin layer solar drying of paddy under natural convection. They used the Page model to simulate the drying behavior of paddy [2]. There are extensive studies which have been done on drying of paddy in other countries; however to our knowledge only one study was found which was related to the drying and the mathematical modeling of the drying of Sri Lankan paddy varieties [4].

The objectives of this study are to identify a suitable thin layer drying model for Sri Lanka paddy varieties under low humid conditions and to validate it by statistical comparison with experimental data, and evaluate the effects of relative humidity of drying air on the drying constants. BG 300, BG 352 and BG 357 paddy varieties locally developed by the Rice Research and Development Institute, Bathalegoda, Sri Lanka were used to investigate drying characteristics of paddy under ambient air temperature 30^{o} C and relative humidity ranges from 30 % to 60 %.

2. THEORETICAL BACKGROUND

In order to describe the single layer drying behavior of paddy and to predict it under different drying conditions, it is necessary to model the drying process. It has been accepted that drying phenomenon of biological products during the falling rate condition is controlled by the mechanism of liquid and/or vapour diffusion. Thin-layer drying models that describe the drying phenomenon of these materials mainly fall into three categories namely, theoretical, semi-theoretical and empirical [6].

The semi-theoretical models are generally derived by simplifying general series solutions of Fick’s second law or modification of simplified models. Equation 1 represents the Fick’s second law [7].

$$\frac{\partial(MC)}{\partial t} = D_{eff}\frac{\partial(MC)^2}{\partial r^2} \qquad (1)$$

The initial and boundary conditions may be expressed as follows

At $t = 0$, $MC = MC_i$, for $0 < r < R$
At $t > 0$, $MC = MC_e$, for $r = R$ (top, evaporating surface)
At $t > 0$, $\frac{\partial(MC)}{\partial r} = 0$, for $r = 0$ (bottom, non – evaporating surface)

There are several analytical solutions of Fick's second law for regularly shape bodies such as rectangular, cylindrical and spherical. Drying of many food products such as rice [8, 9], carrots [10] and tea [7] has also been successfully predicted using analytical solutions Fick's second law. General series solution of Fick's second law in spherical coordinates given below is

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\,exp\left(\frac{-n^2 D_{eff}\,\pi^2}{R^2}\;t\right) \qquad (2)$$

For long drying times (and neglecting the higher order terms by setting n = 1), it has been demonstrated that equation 2 can be further simplified as follows [11].

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{R^2}\right)t \qquad (3)$$

Effective diffusivity can be calculated from the gradient form the linear regression of the "ln MR vs t". R is the radius of paddy seed. Effective diffusivity depends on the drying air temperature besides variety and composition of the material [7].

The different semi theoretical models based on the equation 1 are indicated below [3, 7]. In this research, experimental data were fitted in to following mathematical models to find the best model for drying of Sri Lankan paddy varieties.

Henderson and Pabis	$MR = A.\exp(-kt)$	(4)
Page	$MR = \exp(-kt^n)$	(5)
Lewis	$MR = \exp(-kt)$	(6)
Two Term Exponential	$MR = A.\exp(-k_1 t) + B.\exp(-k_2 t)$	(7)

3. METHODOLOGY

3.1 Preparation of Samples

Paddy samples of 50 g were soaked 24 h in a water bath. After 24 h the samples were removed from water and kept to evaporate the surface water. When the sample attained 55 g they were put in air tight polyethylene bags and kept at room temperature for 12 h so as to let the samples reach homogeneous moisture content within the kernels.

3.2 Drying Chamber

The drying chamber is schematically shown in figure 1. It was designed and constructed in order to control and maintain the internal relative humidity at different levels between 25 % and 75 % at 30^0 C. This was done by injecting ambient air with RH~75 % into the chamber by DC fans, and was allowing it to mix with dry air with RH~25 % produced by an air compressor. Relative humidity inside the chamber was controlled by adjusting the speed of the inlet fans. To sustain uniform condition inside the chamber, air was mixed by another 12 V DC fan. The Sensirion SHT75 digital sensor was used to measure the inside RH and Temperature. The sensor was interfaced to a PIC16F877A microcontroller based system and the RH and temperature were displayed on a Seven Segment Display (SSD) panel.

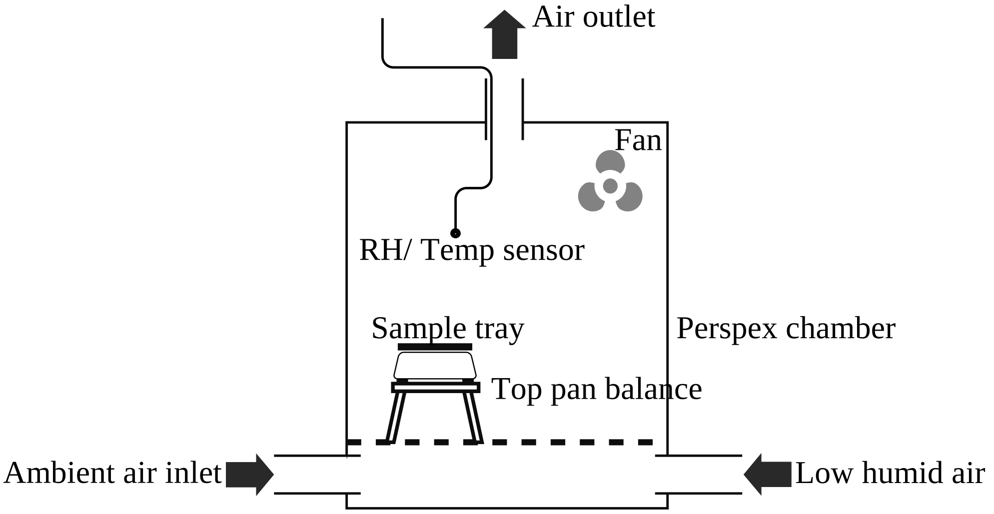

Figure 1: Schematic diagram of the drying chamber

3.3 Experimental Procedure

An electronic balance was placed inside the dryer chamber. At first the air in the chamber was humified to a required value by injecting dry air and the ambient air and the system was allowed to settle for 30 minutes. A sample of approximately 50 g was evenly spread on a Perspex tray to form a single seed layer. The sample was placed over the electronic balance and the test was started. The mass of the paddy sample was recorded at 5 min intervals throughout the drying period. Ambient air temperature and relative humidity of the drying air were recorded continuously using the SHT75 sensor with an accuracy of ± 1° C and ± 1 % RH. After the drying procedure was completed, samples were placed in an oven kept at 110° C for 8 h. After that the mass was measured and this mass was used to calculate the moisture content of the paddy.

3.4 Moisture Ratio

In order to normalize the drying curves, the data involving moisture contents of paddy during the thin-layer drying experiments were transformed to a dimensionless parameter called moisture ratio.

$$MR = \frac{MC - MC_e}{MC_i - MC_e} \tag{8}$$

3.5 Equilibrium Moisture Content

Under the given drying condition the minimum moisture content to which the grain can be dried is called the equilibrium moisture content. Basunia and Abe proposed that the Modified - Chung - Pfost equation is the most appropriate equation for expressing the equilibrium moisture content of paddy [2].

$$MCe = 29.394 - 4.6015 \ln[-(T + 35.703)\ln(RH)] \tag{9}$$

4. RESULTS AND DISCUSSION

4.1 Drying Curves

The effect of relative humidity on drying of paddy variety BG 357 is illustrated in figure 2. A lower air relative humidity produced a higher drying rate and consequently the moisture ratio decreases fast.

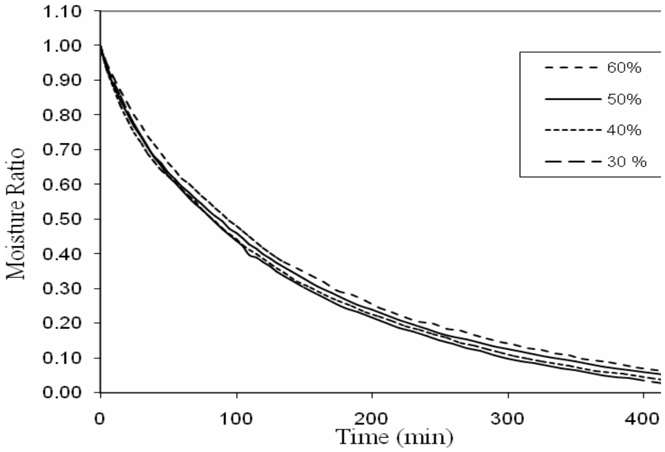

Figure 2: Variation of the moisture ratio of BG 357 with time

4.2 Effective Diffusivity

Effective diffusivity was investigated from the gradient derived form the linear regression of the graph of ln (MR) against time. Figure 3 represents that the effective diffusivities depend on the drying air relative humidity and variety.

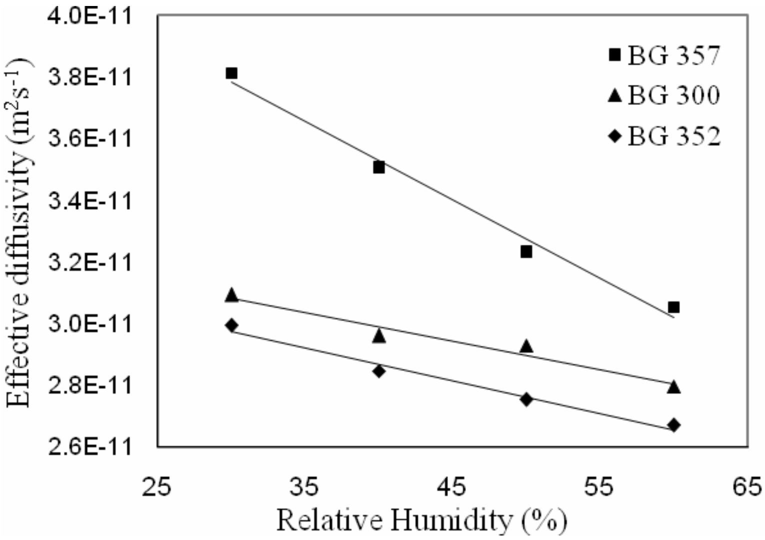

Figure 3: Effective diffusivity variation with Relative Humidity

4.3 Selecting Best Mathematical Model

The thin-layer drying equations in 4, 5, 6, and 7 were tested to select the best model for describing the drying behavior of paddy. The correlation coefficient (R^2), standard error and residual plots were the parameters to select the best equation to account for the variation in the drying curves of dried paddy samples. The results of the statistical computations carried out to evaluate four drying models for BG 352 variety are presented in table 1.

Table 1: Results of regression analysis and drying constants for BG 352

Mathematical Model	Relative Humidity	R^2	Standard Error	k_1 (s^{-1})	k_2 (s^{-1})
Henderson & Pabis	30	0.9978	0.017	9.5E-05	NA
	40	0.9970	0.018	8.9E-05	
	50	0.9980	0.015	8.6E-05	
	60	0.9986	0.013	8.3E-05	
Page	30	0.9994	0.009	2.3E-04	NA
	40	0.9987	0.012	2.7E-04	
	50	0.9990	0.011	2.2E-04	
	60	0.9993	0.009	1.8E-04	
Lewis	30	0.9922	0.031	1.1E-04	NA
	40	0.9872	0.038	1.0E-04	
	50	0.9907	0.033	9.6E-05	
	60	0.9940	0.027	9.1E-05	
Two Term	30	0.9999	0.004	8.8E-05	9.7E-04
	40	0.9999	0.004	8.4E-05	1.4E-03
	50	0.9999	0.003	8.1E-05	1.4E-03
	60	0.9999	0.004	8.0E-05	1.3E-03

Among the considered mathematical drying models, the two term model was found to be more suitable for predicting the behavior of drying of paddy with the highest value for R^2 and lower value of standard error than the other models. Besides the two term model, the other models had the clear pattern of residual distribution. The randomly scattered pattern of the residual data for the two term model indicated good fitting agreement of this model.

Table 2: Drying constants obtained from two term exponential model

RH %	BG 300		BG 352		BG 357	
	k_1 (s^{-1})	k_2 (s^{-1})	k_1 (s^{-1})	k_2 (s^{-1})	k_1 (s^{-1})	k_2 (s^{-1})
30	9.3E-05	1.3E-03	8.8E-05	9.7E-04	1.2E-04	1.1E-03
40	8.9E-05	1.0E-03	8.4E-05	1.4E-03	1.1E-04	1.4E-03
50	8.8E-05	1.2E-03	8.1E-05	1.4E-03	1.1E-04	1.3E-03
60	8.4E-05	1.5E-03	8.0E-05	1.3E-03	1.0E-04	5.6E-04

According to the simplified solution for the Fick's 2nd law of diffusion through a homogeneous media can be expressed as equation 3 or in the form $MR = \exp(-kt)$. According to the table 1, drying of paddy best fits to a two term equation like $MR = A\exp(-k_1 t) + B\exp(-k_2 t)$. By making the coefficients $A+B$ unity, the equation can be interpreted as a collective result of two types of diffusion processes taken place in the sample, and A and B become weights and k_1 and k_2 becomes drying for each diffusion. According to table 2, it is evident that $k_1 << k_2$, hence, of the two drying processes, the second drying process is rapid compared to the first. For BG 352, *A* and *B* coefficients was 0.87 and 0.13 respectively at 40 % RH level.

The two diffusion processes in paddy seed may be considered to be due to the diffusion from, the rice seed to the environment and diffusion from the husk to the environment. Husk is highly porous; hence, the moisture in the paddy husk diffuses rapidly to the surrounding, while moisture in the rice seed diffuses to the surrounding slowly. Hence the lower drying constant k_1 can be attributed to the diffusion of moisture from the rice seed and k_2 is due to the diffusion of moisture from the husk.

The drying constant k_1 is very much close to the drying constant obtained by the other one term models, because the first drying process is dominant. It was revealed that this constant was a function of relative humidity. As shown in figure 4 it can be identified that drying constant k_1 decrease linearly with increasing of relative humidity.

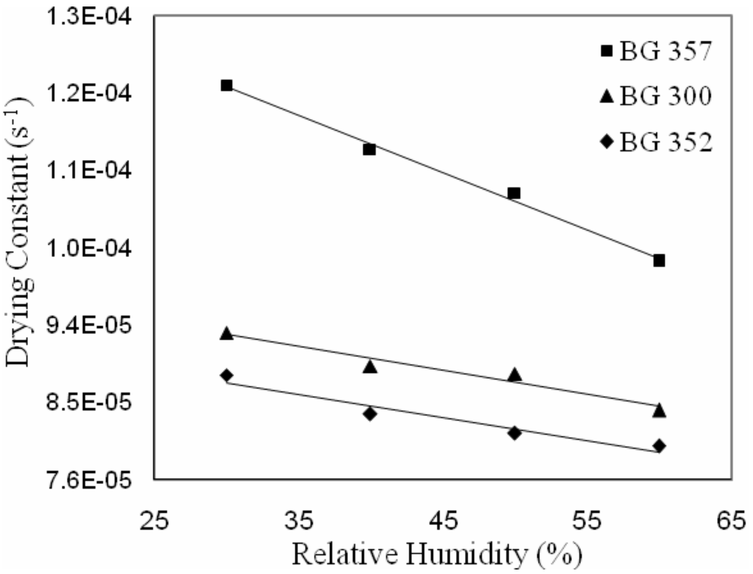

Figure 4: Variation of drying constant (k_1) with relative humidity

4.4 Comparison of Drying of BG 300, BG 352 and BG 357

It was found that the drying rate of BG 357 was higher than that of the BG 352 and BG 300 under the same drying conditions. Figure 5 represent the drying behavior of these three varieties under same drying conditions. Of the paddy varieties considered, the highest drying constant k_1 was shown by the BG 357, and the lowest drying constant was shown by the BG 352. According to the table 3 the radius and surface area of the paddy varieties are different. The greater the equivalent radius of the seed the lower the drying constant (k_1).

Table 3: Radius and surface area of paddy varieties

Paddy variety	Radius (m)	Surface Area (m^2)
BG 300	0.00179	0.0040
BG 352	0.00181	0.0041
BG 357	0.00169	0.0036

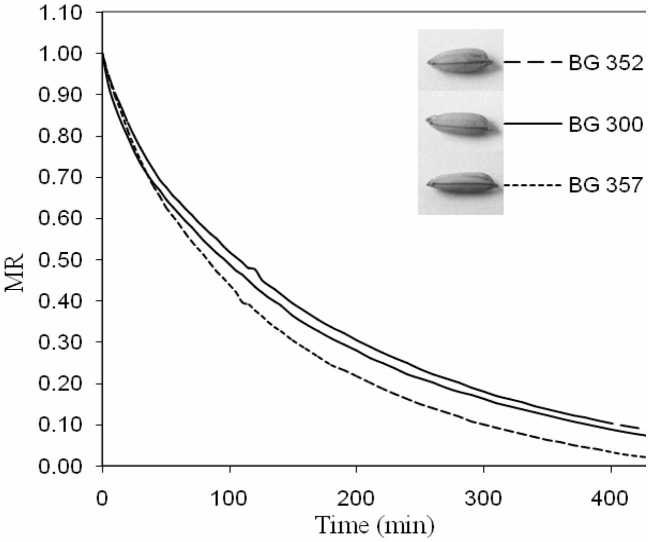

Figure 5: Comparison of drying curves of BG 300, BG 352 and BG 357 at RH= 30%

5. CONCLUSIONS

Thin layer drying characteristics of paddy were investigated under relative humidity ranges from 30 % to 60% and identified the two term exponential model as the best model for describing thin layer drying of paddy. Drying constant of the dominant drying process of BG 300 varies from 9.31×10^{-5} s^{-1} to 8.41×10^{-5} s^{-1}, BG 352 varies from 8.81×10^{-5} s^{-1} to 7.99×10^{-5} s^{-1} and BG 357 varies from 1.22×10^{-4} s^{-1} to 1.01×10^{-4} s^{-1} over the RH range 30 - 60 %. Drying constant and effective diffusivity linearly decreased with increase of relative humidity level of the ambient atmosphere. Results further indicate that the two drying constants can be attributed to two diffusion processes, one which occurs within the seed and the other across the husk.

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