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Mathematical modelling of paddy drying in hybrid greenhouse dryer

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Abstract
During paddy growing seasons, paddy drying experiments were performed on three separate bed thicknesses (5, 10 and 15 cm) in hybrid greenhouse dryer. Paddy-drying continued until a moisture content of 12 percent (d.b) was achieved, moisture content converted to a moisture ratio (MR). Moisture ratio MR of paddy during drying was fitted to the eleven thin layer drying models. The most fitting models was the logarithmic model to explain the drying characteristics of paddy dried during Rabi season in thin layer. Logarithmic model gave R^2 = 0.9891, χ^2 = 0.00689, RMSE = 0.024477 and MBE = 4.02×10-8. Midilli model was the best one that can describe the drying behavior of the *Kharif* Paddy thin-layer drying. Midilli model gave R^2 = 0.9953, χ^2 = 0.0000408, RMSE = 0.019042 and MBE = -1.3×10-5.

Keywords: Solar drying, greenhouse drying, mathematical modeling, moisture ratio

Introduction
India, after China, is the second largest rice producer in the world (*Oryza sativa L*.). In India, both area and production are predominated by paddy. Rice production in India was 115.6 MT during the year 2018-19 which was higher than the previous year's production of 111.01 MT (Anonymous, 2019) [1]. The drying of farm products is carried out either for preservation or as it as part of the production process. Grain drying using solar energy is the most commonly used process in the world, but the final dried product quality in sun drying is comparatively lower. Sun-drying of grains often contributes to the possibility of infestation and extinction of birds and insects. In fact, the drying process is unregulated. Solar drying is one of the most interesting and feasible applications in tropical and subtropical countries.
For the optimization of the operational parameters and improvements in efficiency of drying systems, mathematical drying modeling is essential. Solar drying must be examined and modeled in order to understand the different needs of each farm product and forecast the solar drying system's effectiveness (Steinfeld and Segal, 1986 [2]). The sample must be mathematically modeled based on the drying conditions obtained from the experimental investigation. The thin layer drying includes several critical parameters to obtain drying characteristics of the product. Many researchers have studied the drying characteristics of paddy (Basunia and Abe, 1998 [3]; Noomhorm and Verma, 1986[4]; Wang and Singh, 1978[5]; Agrawal and Singh, 1977 [6]; Verma *et al*., 1985 [7]) under natural convection at variable temperature and humidity of air (Basunia and Abe, 2001 [8]) and various models have been applied with more or less effectiveness for the drying rate prediction. Mathematical simulation equations have been used in a variety of studies involving primarily thin-layer drying simulation. Five of the studies refer to the drying with variable air temperatures and humidity of paddy in forced convection. Hence the present study was taken up to study the mathematical modeling of paddy drying process under forced ventilated conditions.

Materials and Methods
Drying Procedure
Paddy drying experiments were conducted during paddy growing seasons namely *kharif* and *Rabi at* three different bed thicknesses (5, 10 and 15 cm) between 9:00 AM and 5 PM using hybrid solar greenhouse dryer by Madhava *et al*, 2017 [9]. The paddy harvested in the fresh (Variety: BPT 5204) has been packed with 18 trays and place in the hybrid greenhouse dryer.

The drying process continued until the moisture content of 12 percent (d.b.) was reached. Four 40 watt DC fans were installed for forced ventilation. The DC exhaust fans were powered by two no-150-watt photovoltaic panels, with 18.5 V rated voltage and 8.10 a rated current.

Mathematical Modeling

Selected models of the thin layer drying are fitted with drying data obtained by thin layer hybrid greenhouse drying of paddy during Kharif and Rabi seasons to evaluate the drying behavior of the paddy. Empirical models developed from the fundamental diffusion models are suitable for food grains in general. Eleven mathematical models were tested for the best model to explain the drying behavior of the paddy in the present study. The drying data involving moisture content versus drying time were transformed into a dimensionless parameter called moisture ratio versus time in order to normalize drying curves.

In order to establish the best paddy drying model that performs adequately under forced-convection greenhouse drying, eleven empirical or semi-empirical models, as outlined in Table 1. The following assumptions are taken in establishing a mathematical model for polyhouse dryers (Janjai *et al*., 2011 [10])

(a) There is unidirectional airflow and no air stratification inside the dryer.

(b) The paddy dried in thin layers and computation is based on the thin layer drying model.

(c) The specific heat of the air, the cover and the products are constant.

Of the eleven drying models as shown in Table 2, the drying data as the moisture ratio (MR) versus drying time were used. The non-linear regression analysis was performed using the SPSS16.0 software package to establish the model constants and to get the best fit model. The best model to explain paddy drying behavior was selected based on high coefficient of determination (R2) and low chi-square ($\chi 2$), mean bias error (MBE) and root mean square error (RMSE) values (Togrul and Pehlivan 2002 [11]; Diamante and Munro, 1991 [12]; Erenturk *et al*., 2004 [13]).

Moisture Ratio

In order to compare the experimental results, the moisture content (M) of the sample converted into a moisture ratio (MR). The paddy moisture ratio (MR) has been determined using the following equation during drying.

$$MR = \frac{M - Me}{M_0 - Me}$$

Where

M = Instantaneous moisture content, %, d.b

Mo = Initial moisture content, %, d.b.

Me = Equilibrium moisture content (EMC) of the material, %, d.b.

The modified Henderson equation and the Chung-Pfost equation are two of the best scientific moisture equations. The modified Henderson equation was used to determine the moisture content in accordance with the following equation and paddy constants (ASAE standards: ASAE D245.4).

$$M_e = \frac{1}{100}\left[\frac{\ln(1 - RH)}{-K(T + C)}\right]^{\frac{1}{N}}$$

RH = Relative Humidity, decimal

T = Temperature, °C

For paddy K=1.9187×10^{-5}, N=2.4451, C= 51.161; Standard error=0.0097

Statistical Analysis

The statistical computer software program was used to perform regression analysis, the key criteria to pick the best equation to interpret the drying curve equation was correlation coefficient (R^2). The computation of the validity of fitness was augmented by the calculation coefficient (R^2) (Thompson *et al*., 1979 [14]), Reduced chi-square ($\chi 2$), total square error (SSE) and a mean square root error (RMSE) Hagan *et al*., 1996 [15] ; Principe *et al*., 2000 [16]. These parameters are defined as follows

Coefficient of determination (R^2) draws a distinction between the predicted (MRpre) and the experimental (MR exp) values, and it is essential to obtain the best fit model.

$$R^2 = \frac{\sum_{i=1}^{N}[(\text{MRexp})(\text{MRpre})] - \frac{1}{N}\sum_{i=1}^{N}(\text{MRpre})}{\sqrt{\left[\left[(\text{MR}_{\text{exp}})^2 - \frac{1}{N}(\sum_{i=1}^{N}(\text{MRexp})^2\right]\left[(\text{MRexp})^2 - \frac{1}{N}(\sum_{i=1}^{N}(\text{MRexp})^2\right]\right]}}$$

Reduced chi-square $\chi 2$ is used to establish the goodness of the fit, lower value of the $\chi 2$ gives the best fit.

$$\chi 2 = \frac{\sum_{i=1}^{N}(\text{MRexp} - \text{MRpre})^2}{N - n}$$

N = Total number of observations

n = Number of constants

Root mean square error provides guidance on the short-term performance of the correlations by allowing a term-by-term comparison of the actual deviation between the predicted (MR pre) and the experimental (MR exp) values. RMSE is always positive, but a null value is ideal. When the RMSE is lower, the calculation is more reliable.

$$RSME = \sqrt{\frac{\sum_{i=1}^{N}(MRexp - MRpre)}{N}}$$

Mean bias error (MBE) gives the mean deviation between predicted (MRpre) and experimental (MR exp) values, it must be equal to zero at ideal conditions. A positive value of MBE indicates an over-estimate while a negative value indicates an under-estimate. The MBE can be computed by an equation as follows.

$$MBE = \frac{\sum_{i=1}^{N}(MRexp - MRpre)}{N}$$

The drying equations generally used for thin layer greenhouse drying of food grains are given in Table 1. The primary criterion for selecting the best equation know variations of drying curves of dried samples was the reduced χ-square, root mean square error (RMSE) and mean biased error (MBE). Reduced χ-square is the mean square of the differences between the experimental and estimated values for the models and has been used to determine the fit's goodness. The lower the χ-square value, the better the performance. The RMSE varies between the predicted and the experimental values and is required to achieve zero

Results and Discussion

Results of the paddy drying experiments conducted in hybrid greenhouse dryer were fitted to the eleven empirical or semi-empirical models in order to establish the best paddy drying model that performs adequately under forced-convection greenhouse drying, the results are reported below.

Mathematical Modeling

Figure 1 and Figure 2 indicates the moisture ratio for paddy drying under various seasons and various bed thicknesses. It was clear that, the moisture ratio has decreased continuously with the drying time. The constant rate period was clearly absent, and paddy drying was completed through the entire time in the falling rate period. The falling rate period during drying showed that, the internal mass transfer has occurred by diffusion. The drying process produces moisture gradients within the grain and hence the drying rate retarded. The removal of moisture from the paddy slows down and gets closer to the equilibrium moisture content. The drying of paddy has been recorded with similar observations (Manikantan *et al*., 2014 [17], Khanali, *et al*., 2012[18], Akin *et al*., 2014 [19] and Omid, *et al*., 2006 [20])

Grain bed thickness also affected the drying rate, with a bed thickness of 5 cm; the drying rate was high due to higher grain temperature and air flow rates compared to 10 cm and 15 cm of bed thickness. Increased drying air temperature, air flow rate and decreased air humidity increases the drying capacity (Hacıhafızoglu, 2008[21]). The air flow rate has the effect of moving moisture from the surface and therefore the drying potential increased considerably. Higher air temperature, air flow and lower relative humidity were observed during *Rabi* season and, consequently, the drying rate was higher in Rabi season than in *Kharif* season.

Table 2 and Table 3 provide the results of the statistical analysis carried out on these greenhouse drying models of Kharif and Rabi paddy, the drying model coefficients, and the other comparison criteria used to evaluate goodness of fit namely R2, Chi-square, RMSE, MBE. The logarithmic model was found to be the most appropriate model for depicting the drying curve of the thin drying layer of Rabi paddy. The logarithmic model gave R2 = 0.9892, χ2 = 0.000689, RMSE = 0.024477 and MBE = 4.02X10-8. Logistical model and Newton models are other appropriate models to characterize the experimental results in addition to logarithmic model.

The Midilli model was found to be the best model in the Kharif season to explain the thin layer drying performance paddy in greenhouses under forced ventilation. Midilli model gave R2 = 0.995523, χ2 = 0.0000408, RMSE = 0.019042 and MBE= -1.3X10-5. Other appropriate models for describing experimental data are the Wang & Singh, and logarithmic models. Experimental data and predicted data using these models are shown in Figure 5.76. The findings obtained are well in line with the findings, of Omid, 2006 [20]; Oktay *et al*., 2008 [22]; Manikantan *et al*., 2014 [17]; Konan *et al*., 2014 [23]; Basunia and Abe, 2001 [8] and Khanali *et al*., 2012 [24].

Table 1: Mathematical models given by various authors for drying curves

Norms	Model	References
Newton	$MR = exp(-kt)$	O'Callaghan *et al*.(1971)
Page	$MR = exp(-kt^n)$	Agrawal and Singh (1977) [6]
Modified page	$MR = exp(-kt)^n$	Diamante and Munro (1993) [12]
Henderson & Paris	$MR = aexp(-kt)$	Chhinman (1984)
Logarithmic	$MR = a_0 + aexp(-kt)$	Chandra and Singh (1995)
Logistic	$MR=\frac{a_0}{1+aexp(-kt)}$	Chandra and Singh (1995)
Two-term	$MR = a_0 + aexp(-k_0t)+ bexp(-bt)$	Henderson (1974)
Geometric	$MR = at^{-n}$	Chandra and Singh (1995)
Wang& Singh	$MR = 1 + a_1t + a_2t^2$	Wang and Singh (1978) [5]
Diffusion approach	$MR = aexp(-kt) + (1-a)exp(-kbt)$	Kassem (1998)
Midilli	$MR = aexp(-kt) + bt$	Midilli *et al*, (2002)

Table 2: Mathematical modeling of solar greenhouse dryer during *Rabi* S20eason

Model Name	Model Coefficients	R2	RMSE	MBE	χ-square
Newton	K=0.060911	0.9888	0.036458	0.006644	0.006946
Page	k=0.038508 n=1.176874	0.9875	0.026528	0.001542	0.001688
Modified page	k= -0.050670 n= 1.202117	0.9888	0.036458	0.006644	0.001456
Henderson	a=1.076026 k=0.067306	0.9879	0.02585	0.000688	0.000732
logarithmic	a_0= -0.12174 a = 1.175896 k = 0.054827	0.9892	0.024477	4.02E-08	0.000689
Logistic	a_0= 3.951308 a = 2.763762 k = -0.07922	0.9887	0.024957	0.000133	0.000716
Two-term	a=-0.04804 b=1.116448 k=0.087997 g=0.066728	0.9882	0.024322	0.003768	0.000716
Geometric	a=1.146416 n=0.331726	0.8468	0.072835	0.038343	0.00581
Wang & Singh	a_1=-0.0477057 a_2=0.00047589	0.9824	0.02501	-0.01137	0.000686
Diffusion approach	a=-0.07049 b=0.022546				

	k=2.928041	0.9882	0.02435	0.004064	0.000682
Midilli	a=1.042437 b=-0.00582 k=0.05183	0.9881	0.02274	0.00487	0.000595

Table 3: Mathematical modeling of solar greenhouse dryer during *Kharif* Season

Model Name	Model Coefficients	R2	RMSE	MBE	χ-square
Newton	K=0.06694	0.9762	0.069784	0.004756	0.004939359
Page	k=0.020983 n=1.431555	0.9839	0.036492	-0.00565	-0.0061
Modified Page	k= -0.05584 n=1.198813	0.9762	0.069784	-0.00476	0.005259
Henderson	a=1.129239 k=0.075763	0.9679	0.054402	0.010737	0.003196
Logarithmic	a_0=-1.04998 a= 2.074701 k= 0.024358	0.9891	0.019363	-4.7E-06	0.000422
Logistic	a_0= 1.25638 a= 0.278394 k= -0.14332	0.9866	0.033447	0.003003	0.001259
Two-term	a=-9.31593 b=10.29381 k=0.144336 g=0.131581	0.9821	0.039041	0.004414	0.001789
Geometric	a=1.264466 n=0.453295	0.7450	0.745002	0.011933	0.023138
Wang & Singh	a_1=-0.0455896 a_2=0.00034478	0.9949	0.020712	-0.0017	0.000463
Diffusion approach	a=-12.4893 b=0.935878 k=0.13998	0.9818	0.039211	0.005172	0.00173
Midilli	a=1.027964 b=-0.01278 k=0.037978	0.9955	0.019042	-1.3E-05	0.000408

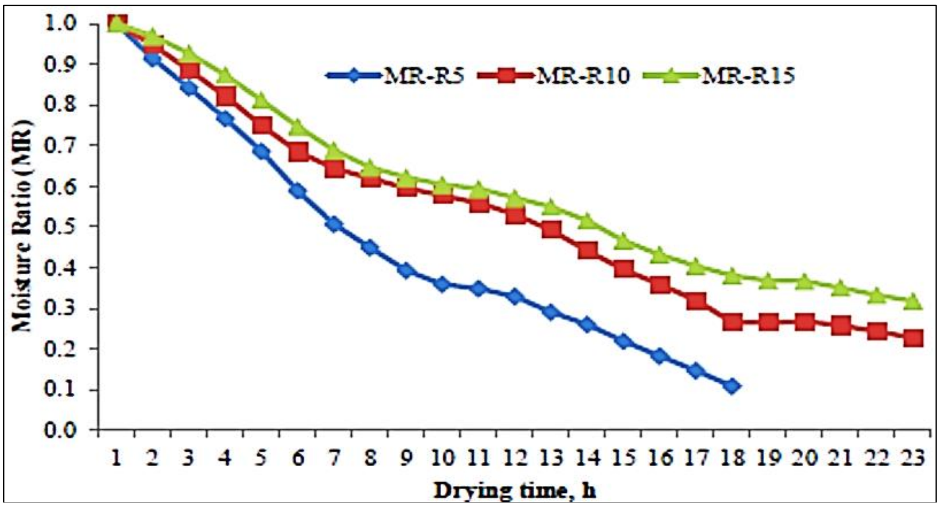

Fig 1: Variation of moisture ratio with drying time during *Kharif* season

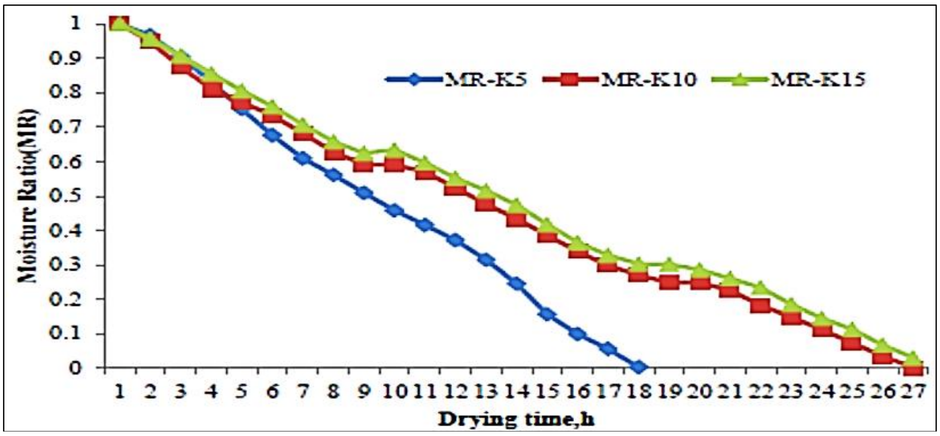

Fig 2: Variation of moisture ratio with drying time during *Rabi* season

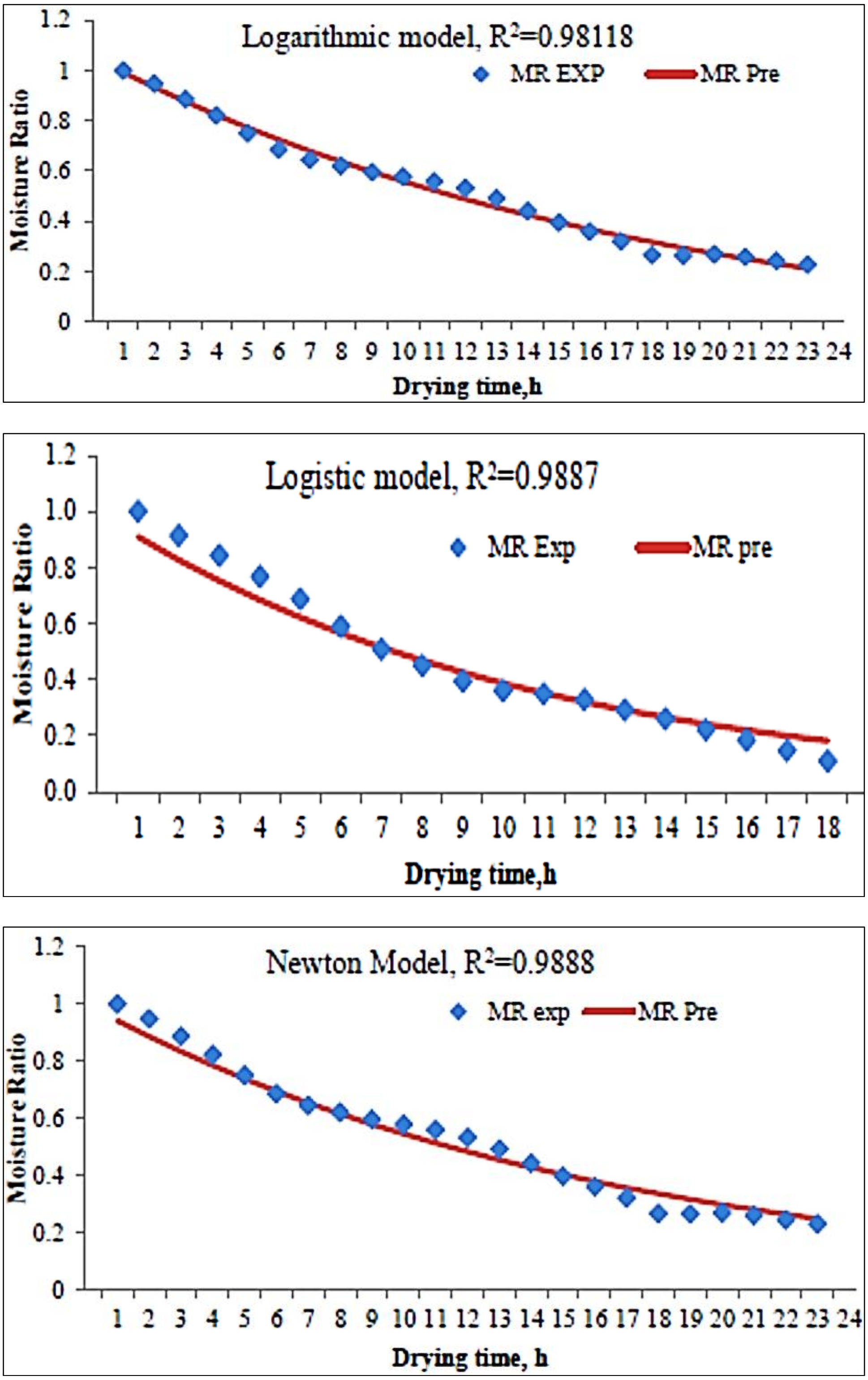

Fig 3: Comparison of experimental and predicted moisture ratios with drying time by different models during *Rabi* season

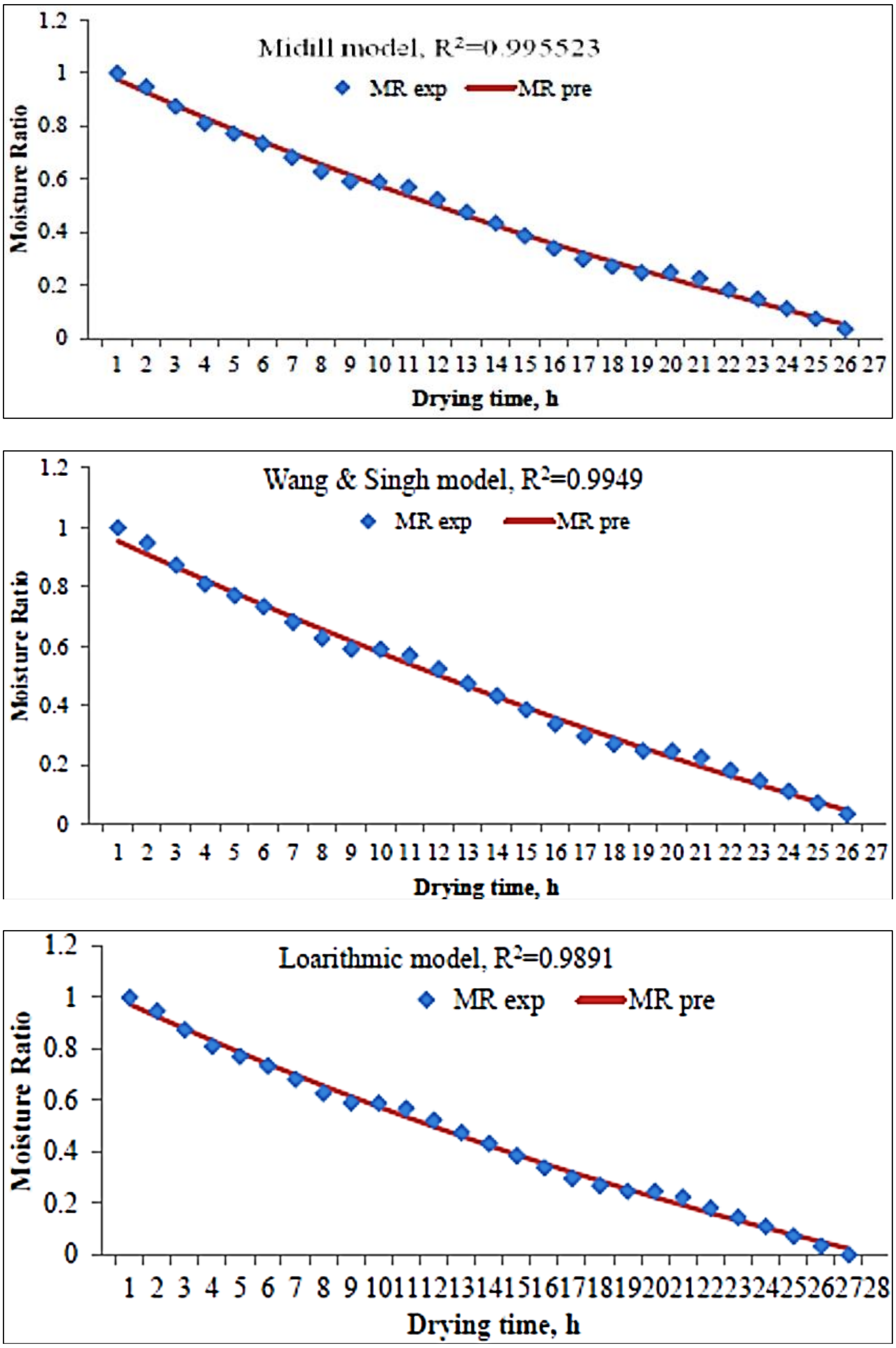

Fig 4: Comparison of experimental and predicted moisture ratios with drying time by different models during *Kharif* season

Conclusion

The logarithmic model has been found to be the best model to describe the drying characteristics of Rabi paddy among eleven thin-layer drying models. It was also found that the Midilli model was best able to explain the drying behavior of Kharif paddy with thin layer drying.

References

1. Anonymous. Annual Report 2014-15, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India. 2015.
2. Steinfield A, Segal I. A simulation model for solar thin layer drying process. Drying Technology. 1986; 4:535-542.
3. Basunia MA, Abe T. Thin-layer drying characteristics of rough rice at low and high temperatures. Drying Technology. 1998; 16:579-595.
4. Noomhorm A, Verma LR. Deep-bed rice drying simulation using two generalized single-layer models. Trans ASAE. 1986; 29(5):1456-1461.
5. Wang CY, Singh RP. Single layer drying equation for rough rice. American Society of Agricultural Engineers, 1978, 78-3001.
6. Agrawal YC, Singh RP. Thin-layer drying studies on short-grain rice. American Society of Agricultural Engineers, 1977, 77-3531.
7. Verma LR, Bucklin RA, Endan JB, Wratten FT. Effects of drying air parameters on rice drying models. Trans. ASAE, 1985, 296-301.

8. Basunia MA, Abe T. Thin layer solar characteristics of rough rice under natural convection. Journal of Food Engineering. 2001; 47:295-301.
9. Madhava M, Kumar S, Bhaskara Rao D, Smith DD, Hema kumar HV. Performance evaluation of photovoltaic ventilated hybrid greenhouse dryer under no-load condition.2017. Agric. Eng. Int. CIGR. 2017; 19(2):93-101.
10. Janjai S, Intawee P, Kaewkiewa J, Sritus C, Khamvongsa VA. Largescale solarbgreenhouse dryer using polycarbonate cover: modelling and testing in a tropical environment of Lao People’s Democratic Republic. Renewable Energy. 2011; 36:1053-1062.
11. Toğrulİ T, Pehlivan D. Mathematical modelling of solar drying of apricots in thin layers. Journal of Food Engineering. 2002; 55:209-216.
12. Diamante LM Munro PA. Mathematical modelling of the thin layer solar drying of sweet potato slices. *Solar Energy*. 1993; 51:271-276.
13. Erenturk S, Gulaboglu MS, Gultekin S. The thin layer drying characteristics of rosehip. Journal of Bio systems engineering. 2004; 89(2):159-166.
14. Thompson M, Walton SJ, Wood SJ. Statistical appraisal of interference effects in the determination of trace elements by atomic absorption spectro photometry in applied geochemistry. Analys. 1979; 104:299-312.
15. Hagan MT, Demuth HB, Beale MH. Neuronal Network Design. PWS Publishing, Boston, MA. USA, 1996.
16. Principe JC, Euliano NR, Lefebvre WC. Neuronal and adaptive systems: Fundamentals through simulation. John Wiley and Sons, New York, 2000.
17. Manikantan MR, Barnwa P, Goyal RK. Drying characteristics of paddy in an integrated dryer. Journal of Food Science and Technology. 2014; 51(4):813-819.
18. Khanali M, Rafiee S, Jafari A, Hashemabadi SH, Banisharif A. Moisture- dependent physical properties of rough rice grain. Elixer Mechanical Engineering. 2012; 52:11609-11613.
19. Akin A, Gurlek G, Ozbalta N. Mathematical model of solar drying characteristics for pepper (capsicum annuum). Journal of Thermal Science and Technology. 2014; 34(2):99-109.
20. Omid M, Yadollahinia AR, Rafiee S. A thin-layer drying model for paddy dryer. Proceedings of the international conference on Innovations in Food and Bioprocess Technologies, 2006, 12-14.
21. Hacıhafızog O, Ahmet C, Kamil K. Mathematical modelling of drying of thin layer rough rice. Food and Bio Products Processing, 2006, 268-275.
22. Oktay H, Ahmet C, Kamil K. Mathematical modelling of drying of thin layer rough rice. Food and Bio Products Processing. 2008; 86:268-275.
23. Konan A, Assidjo NE, Kouame P, Benjamin Y. Modelling of rough rice solar drying under natural convection. European Scientific Journal. 2014; 10(3):141-156.
24. Khanali M, Rafiee S, Jafari A. Hashemabadi SH, Banisharif A. Mathematical modeling of fluidized bed drying of rough rice (*Oryza sativa* L.) grain. Journal of Agricultural Technology. 2012; 8(3):795-810.