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Mathematical modelling of drying kinetics of paddy in sun drying and air inflated solar dryer

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Abstract
A solar powered air inflated grain dryer was developed at Indian Agricultural Research Institute, New Delhi. The developed dryer works on principle of greenhouse effect. The thin layer drying experiments were carried out by drying the freshly harvested paddy in the developed dryer and sun drying. The time required for drying of paddy up to milling moisture content of 14% in the developed dryer ranged from 7.5-9 hours and 11-12.8 hours in sun drying respectively. The drying curves obtained from the experiments were fitted to eight commonly used thin layer drying models. The selected models were compared based on coefficient of determination (R^2) and Root mean square error (RMSE). The page model (R^2=0.9954 and RMSE = 0.007245) had the best fit for the drying of paddy in the developed dryer. Wang and Singh model (R^2=0.995 and RMSE = 0.0064) followed by approximation of diffusion model were other models which suitably described the drying kinetics of paddy in the dryer. Sun drying of paddy was found to yield similar results with page model (R^2=0.9990 and RMSE = 0.0007) and Wang and Singh model (R^2=0.998 and RMSE= 0.01035)) as two best fit models.

Keywords: thin layer drying, paddy, solar dryer, modelling

Introduction
Drying of agricultural products is done either to preserve them for later use or as an integral part of production process (Ertekin and Yaldiz, 2004) [6]. Sundrying of grains is the most commonly used practice across the globe but the final quality of dried product in sun drying is comparatively inferior. Sun dried of grains also leads to infestation probabilities and losses by insects, birds. Moreover the drying process is uncontrolled. Solar drying system is one of the most attractive and promising applications of solar energy systems in tropical and subtropical countries. The technical development of solar drying systems can proceed in two directions. Firstly, simple, low power, short life, and comparatively low efficiency-drying system. Secondly, high efficiency, high power, long life expensive drying system. Simulation modelling of dryers used in agriculture are necessary in order to predict the outflow and achieve a control over the drying process.

Modelling of a dryer enables to predict then drying behaviour of the product and optimise the entire drying operation. The aim of this work is to study the drying kinetics of paddy dried under sun and then developed solar powered air inflated grain dryer respectively and find the best fit model for the drying process.

Materials and Methods
A solar powered air inflated dryer was fabricated with base of drying chamber made up of thick low density black polyethylene sheet of 350 micron thickness. Black colour of the sheet allowed it to absorb the solar radiations falling and hence assist to increase the temperature within the dryer. Top of the drying chamber UV stabilized transparent low density poly ethylene sheet of two variable thicknesses (200 micron and 300 micron) was used. The transparent sheet allowed most of the radiations to pass through it and enter the dryer. Higher flexibility of the top transparent sheet allowed the drying chamber to inflate smoothly and hence form a quonset tunnel while the air is blown through the chamber. A fan capable of blowing air to retain the structure and not allowing it to collapse was selected. A solar power operated 12V DC fan (40 cm) diameter with 3 blades and high speed copper motor was selected. The frame for the blowing unit was made of angle iron (40×40×6 mm) due to its resistance to vibration, better stability and easy availability.

Table 1: Specifications of the developed solar powered air inflated grain dryer

Parameters	Specifications
Length of drying chamber	5m
Depth of grain bed	4 cm
Width of drying chamber	2m
Drying bed dimensions	4.2 × 1.4 m
Blowing unit	DC fan
Maximum height of inflation	81 cm
Drying area (m²)	5.88 m²
Capacity (kg)	100 kg
Diameter of axial fan (mm)	40
Inlet air velocity	3 m/s
Air flow rate (m³/h)	1356.48

The comparative performance evaluation of the developed solar inflated grain dryer with respect to sun drying was done at Energy laboratory, division of Agricultural Engineering, Indian Agricultural Research Institute, New Delhi.

In the experiments, 100 kg of Paddy (PB-1121) with initial moisture content 22±0.3% was dried in solar powered air inflated grain dryer and sun drying on the concrete floor simultaneously. 4 cm grain bed depth was maintained during the entire process of drying. Equal amount of samples were collected at every 30 minutes time interval from the dryer and sun drying which was used for determination of moisture content and the drying rate. The sun drying process occurred at ambient temperature.

Fig 1: Developed solar powered air inflated grain dryer

The moisture content of the paddy sample was determined by hot air oven method following AOAC standards (Jindal *et al*., 1987). The samples collected at every half hour interval were kept in properly labelled aluminium boxes and weighted using Mettle Toledo weighting balance of least count 0.001 gram. The aluminium boxes were kept in the hot air oven for 16 hours maintaining a temperature of 130° Celsius. The samples were re weighted after 16 hours and difference in the weight gave the amount of moisture in the sample.

Weight of aluminium container (g) = W_1
Initial Weight of the grain sample collected = W_2
Initial Weight of the grain = W_2- W_1
Final weight of the sample = W_3
Final weight of the grain = W_3- W_1

$$\text{Moisture content of the grain (wb)} = \frac{(W_2-W_1)-(W_3-W_1)}{W_2-W_1} \times 100$$

$$\text{(db)} = \frac{(W_2-W_1)-(W_3-W_1)}{W_3-W_1} \times 100$$

The moisture content obtained after 30 minutes time interval was plotted against time (Fig. 2). Moisture ratio was calculated and plotted against time. Fitting for various thin layer drying models was checked for various thin layer drying models. Curve fitting tool of MATLAB (2014 b) was used for checking the fit to various models. Various model constants and statistical parameters were obtained (Table 2).

Table 2: Thin layer models evaluated in the study

Model	Equation	References
Newton	M.R = exp(-kt)	O'Callaghan et al. (1971)
Henderson and Pabis	M.R = a exp(-kt)	Agrawal and Singh (1977)
Page	M.R = $\exp(-kt^n)$	Chhinman (1984)
Modified page	M.R = $\exp(-kt)^n$	Chandra and Singh (1995)
Wang and Singh	M.R = $M_0 + at + bt^2$	Wang and Singh (1978)
Two terms	M.R = $a \exp(-K_1t) + b \exp(-K_2t)$	Henderson (1974)
Verma *et al.*	M.R = $a \exp(-K_1t) + (1-a) \exp(-K_2t)$	Chandra and Singh (1995)
Approximation of diffusion	M.R = a exp(-Kt) + (1-a) exp(-Kbt)	Kassem (1998)

Various statistical parameters such as coefficient of correlation (R^2), Error sum of square (SSE), and root mean square of error (RMSE) values were also found with the help of same tool to decide the quality of fit.

Results and Discussion

Drying rate for paddy grain in the developed dryer and sun drying

Values of amount of moisture removed per hour while drying paddy (PB 1121) with initial moisture content 22 ± 0.3 % was compared for the developed dryer and sun drying. The drying rate of paddy in the developed dryer was found to be significantly different (P=0.0019) as compared to sun drying. The average time consumed for drying of paddy up to milling moisture content of 14% in the developed dryer ranged from 7.5-9 hours and 11-12.5 hours in the developed dryer and sun drying respectively, thus saving an apprehensive amount of time. The rise of temperature of the drying air and forced convection flow which carries away the moisture at a desirable rate was the major reasons behind increased rate of drying. The time saved in the operation is crucial as it allows more quantity of the grain to be dried in short time preventing their spoilage.

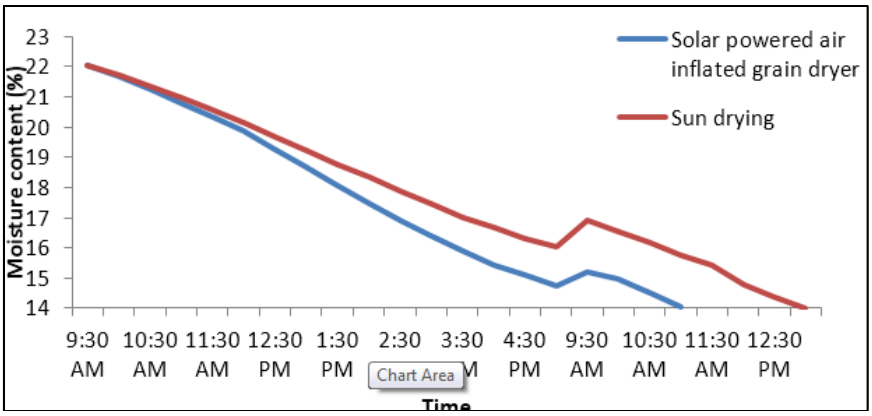

Fig 2: Drying curves of paddy dried in selected methods

Validation of thin layer drying models for paddy dried under Sun

The values of various model constants obtained and statistical parameters such as coefficient of determination (R^2), Error sum of square (SSE), and root mean square of error (RMSE) values obtained The coefficient of determination values was highest and RMSE was found to be lower for Page model for sundried paddy. The page model was found to have the best fit for the obtained experimental data followed by Wang and Singh model and approximation of diffusion model.

Table 3: Selected thin layer drying model constants and statistical parameters for paddy dried in sun drying models

Model name	R^2	SSE	RMSE	K (h^{-1})	K_1	K_2	A	B	N
Page	0.999	0.0007	0.00749	0.069					1.418
Wang &singh	0.998	0.0015	0.01035				-0.09	-0.06	
Approximation of diffusion	0.998	0.00095	0.0085	0.315			-10.5	0.924	
Verma *et al*.	0.998	0.00099	0.00873		0.323	0.28	-5.67		
Newton	0.96	0.0330	0.04691	0.134					
Henderson and pabis	0.975	0.02034	0.03811	0.149			1.065		
Modified page	0.96	0.03301	0.04856	1.234					0.108
Two terms	0.991	0.0070	0.0241		0.256	0.25	-30.1	31.21	

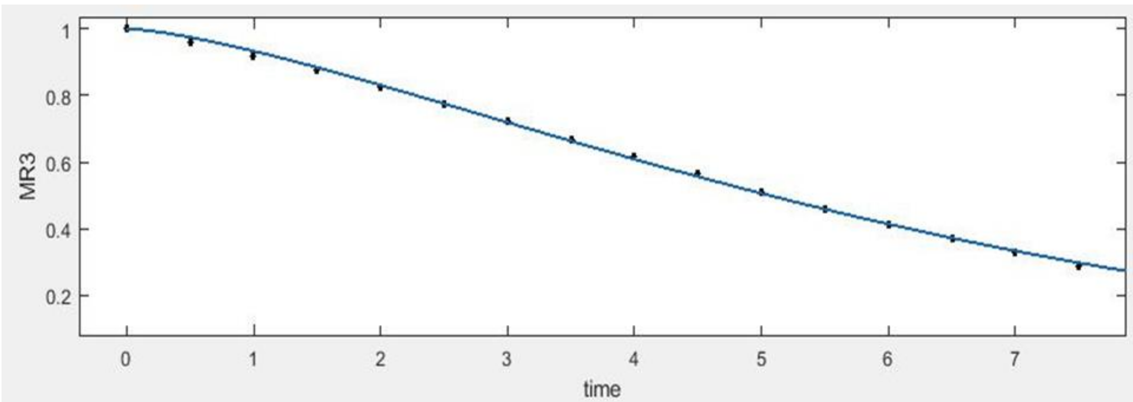

Fig 3: Fitting curve of Page model for paddy dried under sun

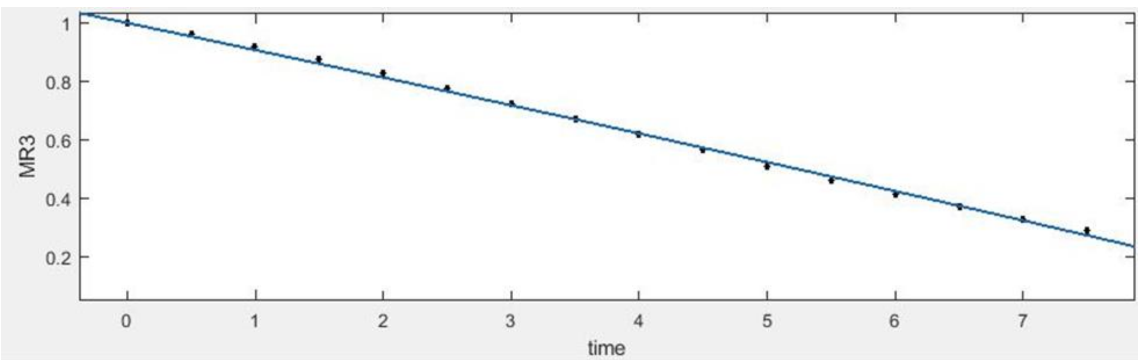

Fig 4: Fitting curve of Wang and Singh model for paddy dried under sun

Validation of thin layer drying models for developed solar powered air inflated grain dryer

The validation of various selected models for paddy dried in the developed solar powered air inflated grain dryer showed that the page model had the best fit for the obtained experimental data followed by Wang and Singh model and approximation of diffusion model

Table 4: Selected thin layer drying model constants and statistical parameters for paddy dried in the developed dryer

Model Name	R^2	SSE	RMSE	K (h^{-1})	K_1	K_2	A	B	N
Page	0.995	0.007245	0.0022	0.056					1.806
Wang &singh	0.995	0.0214	0.0064				-0.10	-0.002	
Approximation of diffusion	0.9854	0.02125	0.04043	0.4737			-55.8	0.980	
Verma *et al*.	0.9855	0.02116	0.04034		0.4571	0.4607	139.8		
Newton	0.9063	0.1364	0.09537	0.1917					
Henderson and pabis	0.9327	0.09794	0.08364	0.2203			1.12		
Modified page	0.9063	0.1364	0.09872	4.023					0.04766
Two terms	0.9867	0.01934	0.04015		0.4839	0.4603	-23.1	24.07	

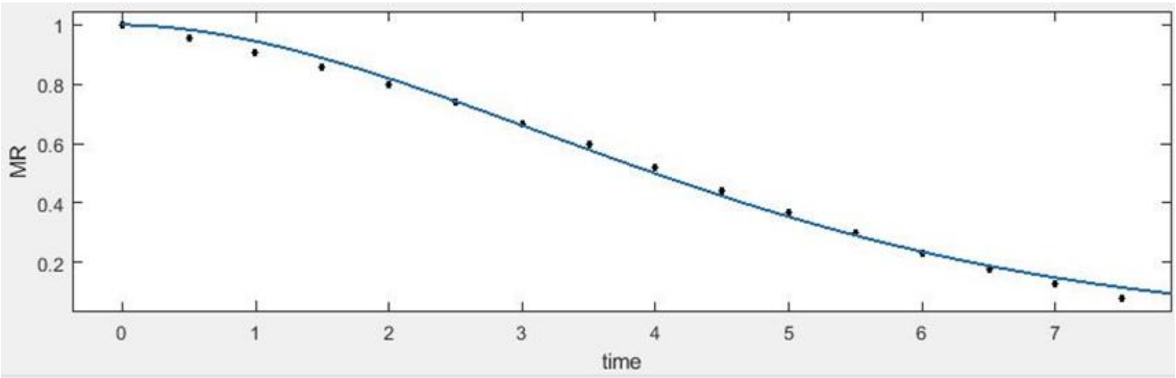

Fig 5: Fitting curve of Page model for paddy dried in the developed drier

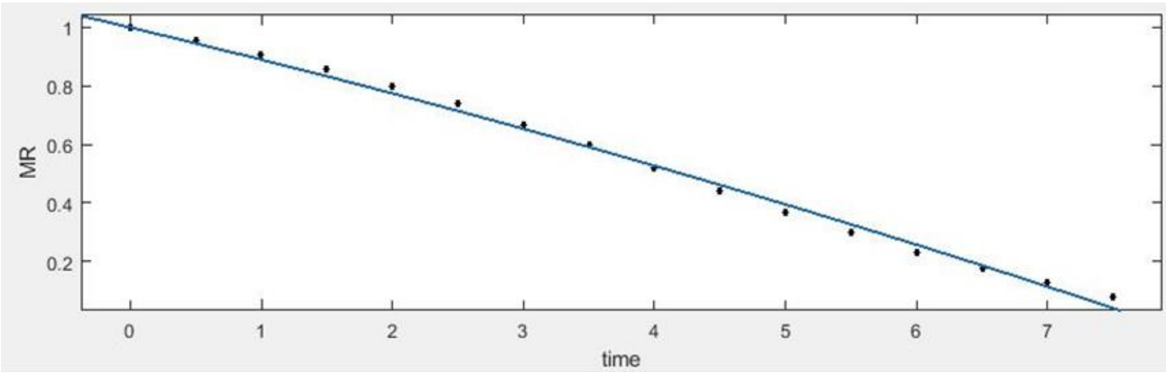

Fig 6: Fitting curve of Wang and Singh model for paddy dried in the developed drier

The study of drying kinetics of paddy is of immense importance in order to optimise the performance of the dryer. In both the drying methods the Page model of thin layer drying was found to have the highest value of coefficient of determination and lowest value of root mean square error. The values of R^2 and RMSE for Page model was found (0.999, 0.0007) and (0.9954,0.007245) for the developed dryer and sun drying respectively. Thus this model explains the drying behaviour of selected paddy grains in most accurate manner. This modelling study allows optimization of operating parameters and performance improvements of the drying system. Page model as suitable model for drying of various agricultural commodities has been found earlier by Basunia & Abe (2005) [3] and Das *et al.* (2005) [5]. Wang and Singh model was found to produce the second best results for model fitting in the drying data obtained for the developed dryer and sun drying. The simplicity of operation of these model adds to their utility in explaining the drying kinetics of paddy in the developed solar powered air inflated grain dryer and sun drying.

Conclusion

The time required for drying of paddy up to milling moisture content of 14% in the developed solar dryer ranged from 7.5-9 hours and 11-12.8 hours in sun drying respectively. Eight commonly used thin layer drying models were validated for drying data obtained and it was found that page model (R^2=0.9954 and RMSE = 0.007245) had the best fit for the drying of paddy in the developed dryer. Wang and Singh (R^2=0.995 and RMSE = 0.0064) model followed by approximation of diffusion model were other models which suitably described the kinetics. The validation was conducted for paddy which was sun dried paddy and it was found to yield similar results with page model (R^2=0.999 and RMSE = 0.0007) and Wang and Singh model (R^2=0.998 and RMSE= 0.01035) as two best fit models. Thus using these models the drying behaviour can be suitably predicted for paddy dried in sun drying as well as the developed solar powered air inflated grain dryer.

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