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Evaluation and Selection of Thin-layer Drying Models for Paddy Dried in Static Flat-bed Batch Dryer

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A Static flat-bed batch dryer was developed for drying paddy from harvesting moisture content (20 – 22%) to 12% for safe storage. The dryer mainly consisted of Blower, Heating chamber, Plenum chamber and drying chamber. Twenty kg paddy was dried in the developed dryer at two different inlet air flow rate (1 m^3/min. and 1.26 m^3/min). The machine has a capacity of 20 kg and temperature of drying air was 60 and 55°C respectively. The moisture content was recorded at every 15 minutes interval and moisture ratio plots were generated. The experimental data were fit in 8 different thin-layer drying models and statistical parameters along with the model constants were obtained. It was found that the Wang and Singh model with the highest values for R^2 and the least values of RMSE in selected drying conditions has the best fit. Henderson & Pabis and Newton models were also found suitable for describing the drying kinetics of paddy in the developed dryer.

Keywords: Static flat-bed batch dryer; thin layer drying; curve fitting; mathematical modelling.

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ABBREVIATIONS

a, b, c drying coefficients
n exponent, a constant
M instantaneous moisture content, decimal dry basis
M_0 initial moisture content, decimal dry basis
M_t moisture content at time t, decimal dry basis
RMSE root mean square error
R^2 coefficient of determination
dt time of successive measurements, min;
k_0,k_1,k_2 drying constants
Me equilibrium moisture content, decimal dry basis
M. R moisture ratio = $(M- M_e)/(M_0 – M_e)$, decimal
χ^2 chi-square

1. INTRODUCTION

India comprises of one third for the total paddy cultivated area (83 million hectares). Northeastern, southern India and river valleys are the major regions in which the production of paddy is centred in the country. The per capita consumption of rice worldwide has remained remarkably stable since the year 2000 and amounted to about 53.9 kilograms per year in 2018-2019 [1]. In India, the states of *West Bengal, Orissa, Andhra Pradesh, Tamil Nadu* and *Bihar* are the major cultivators of paddy. The harvesting operation of paddy is done at the higher moisture content of 24%, to minimise the shattering losses after harvest. Drying of agricultural materials such as grains is a non-linear process with long-time delay and considerable complexity. Therefore, it is very difficult to establish a precise mathematical model for grain drying control [2]. Various researches have been conducted for the development of thin-layer drying models and evaluating their accuracy for prediction in various dryers. Golmohammadi *et al.* [3] studied the intermittent drying characteristics of various Iranian rice varieties to determine the drying kinetics and effective moisture diffusivity. Yadollahinia [4] conducted experiments on the drying kinetics of paddy at five different air temperatures ranging from 30 to 70°C and air velocity from 0.25 to 1m/s. Drying curves obtained from the experimental data, fitted to eight thin layer models and compared with three statistical parameters, showed that two terms model can predict moisture change with greater accuracy than other models. Similar results were reported by Hasan et al. [5] in which five thin-layer drying equations were fitted to the experimental data and the Midilli equation was found to be the best followed by the two-term exponential equation. Model drying behaviour of different agricultural products often requires various statistical methods of regression and correlation analysis. This study was conducted to study the drying kinetics of paddy in the static flatbed batch dryer and evaluate the various thin layer models to find the most suitable model for the process.

2. MATERIALS AND METHODS

A static flat-bed batch dryer was developed and evaluated at the Department of Agricultural Engineering, University of Agricultural Sciences, GKVK Bengaluru. The static flat-bed dryer is a type of on-farm dryer was designed and developed based on the anthropometric data for agricultural workers for easy operation of the dryer. In the fabrication process, the plenum chamber was fabricated first. The drying chamber was designed to hold a capacity of 20 kg paddy in a batch drying process. The electric heating coils were assembled in the heating chamber of the dryer and connections were arranged. The maximum capacity of the blower was about 1.47m^3/min., it was placed at ground level to blow the air to the heating chamber. The air flows in cross direction to the heating coils and flows underneath the drying chamber.

Drying experiments were conducted in the developed dryer by drying 20 kg of freshly harvested paddy at 22-24% initial moisture content. The experiments were conducted at two different airflow rates of 1 and 1.26 m^3/min. the temperature developed in the dryer was correspondingly 60 and 55°C in the dryer.The decline in moisture content was recorded at every 15 minutes interval. Moisture ratio was calculated for the corresponding change in moisture and plot of moisture ratio and time was generated. The drying chamber was mixed uniformly after every 15 minutes interval so that all the grain gets uniform exposure to the drying air.

The obtained moisture ratio was plotted against time and its fitting for various thin layer drying models was checked for different treatment combinations. Curve fitting tool was used for checking the fit to various models. Values of various constants were found for 8 different thin-layer drying models (Table 1).

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 the same tool to decide the quality of fit. Linear and non-linear regression models are important tools to find the relationship between different variables. The goodness of fit of the tested models to the experimental data is the coefficients of determination (R^2) and root mean square error (RMSE) [6]. Model studies help us to identify the best-suited equation for the drying kinetics of a particular commodity dried in a dryer and hence predict its drying parameters such as drying rate.

Fig. 1. Top view of the developed dryer

Fig. 2. Profile view of the developed dryer

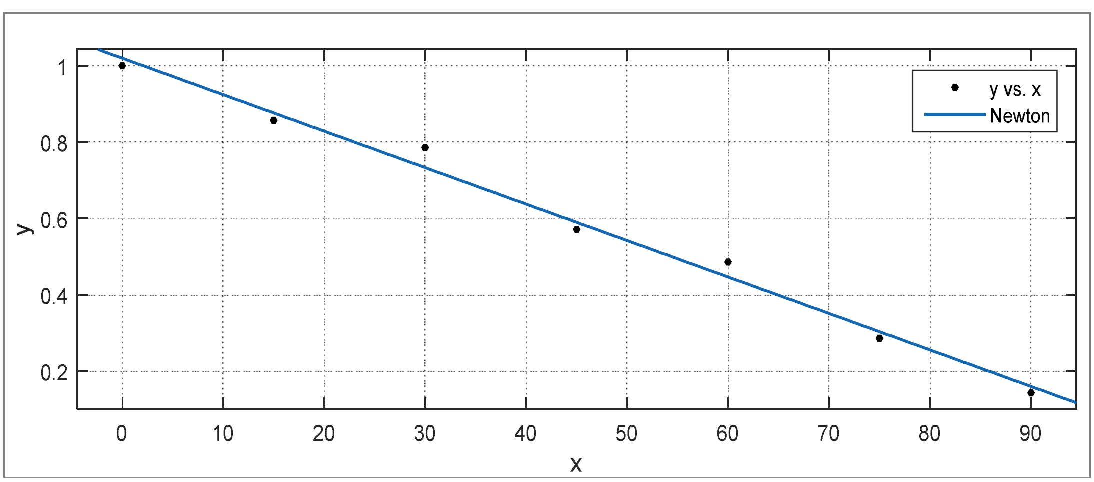
Fig. 3. Front view of the developed dryer

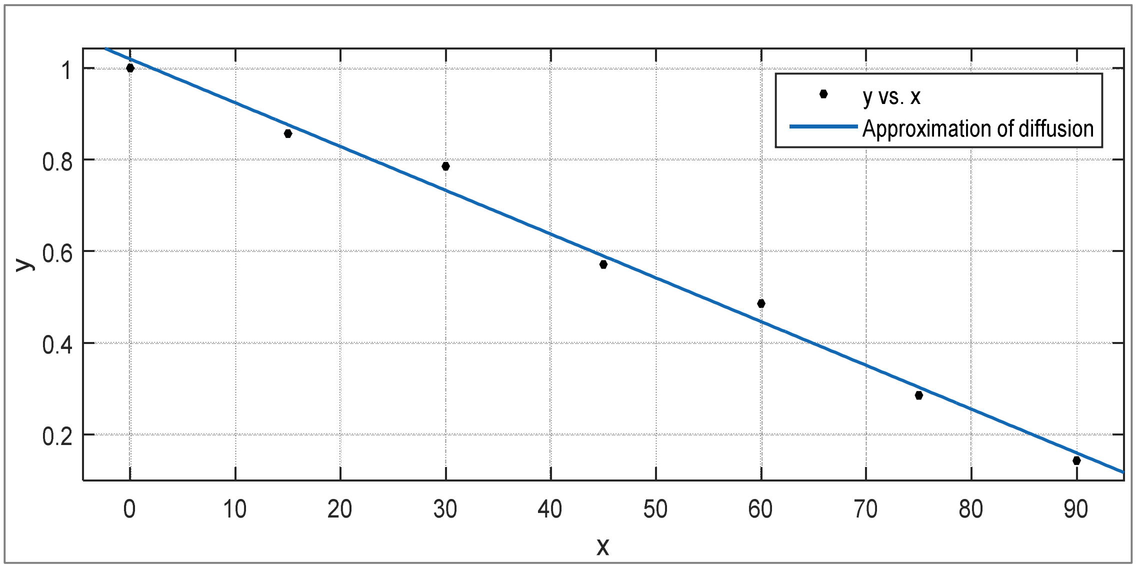
Table 1. Thin layer models evaluated in the study

Model	Equation	References
Newton	$M.R = \exp(-kt)$	[7]
Henderson and Pabis	$M.R = a\exp(-kt)$	[8]
Page	$M.R = \exp(-kt^n)$	[9]
Modified page	$M.R = \exp(-kt)^n$	[10]
Wang and Singh	$M.R = 1 + at + bt^2$	[11]
Two terms	$M.R = a\exp(-K1t) + b\exp(-K2t)$	[12]
Verma *et al.*	$M.R = a\exp(-K1t) + (1-a)\exp(-K2t)$	[13]
Approximation of diffusion	$M.R = a\exp(-Kt) + (1-a)\exp(-Kbt)$	[14]

3. RESULTS AND DISCUSSION

The curve fitting approach helped to calculate various statistical parameters for various thin layer drying models and hence obtain the best fit model for drying characteristics of paddy in the developed dryer. In the drying experiments, it was found that the Wang and Singh model has the best fit for the experimental results (Table 2).




y vs. x
Approximation of diffusion
y
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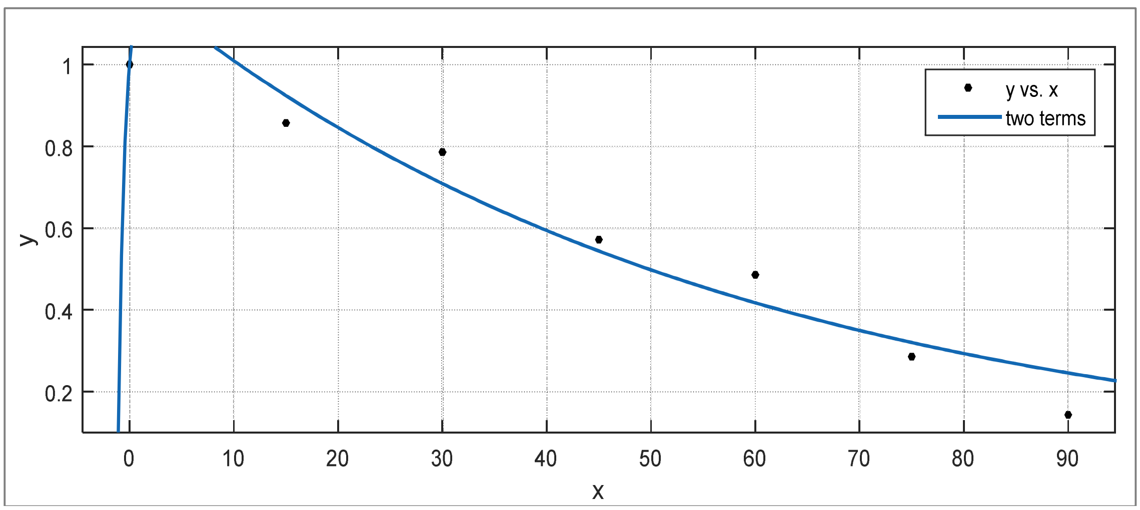
y vs. x
two terms
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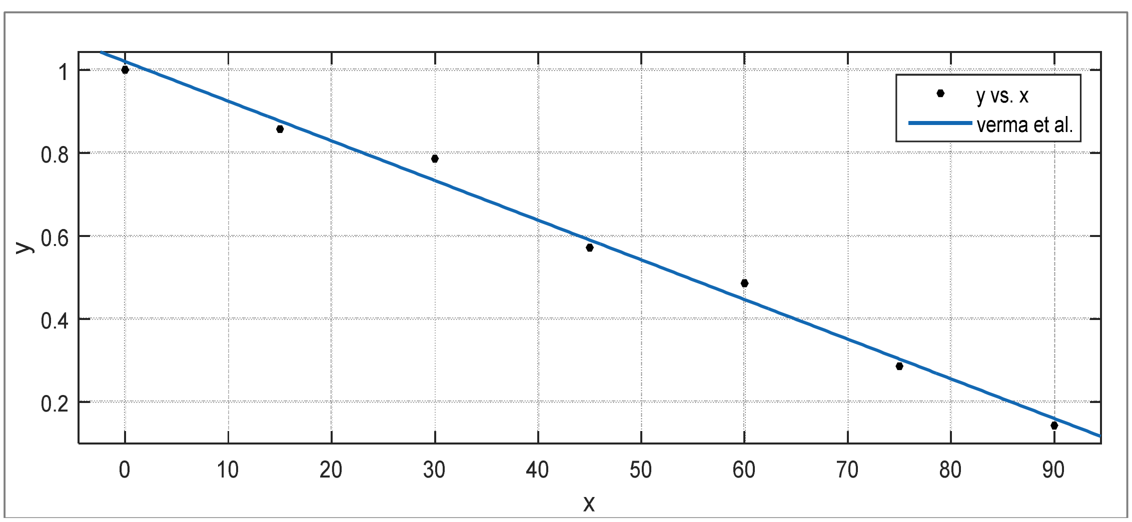
y vs. x
verma et al.
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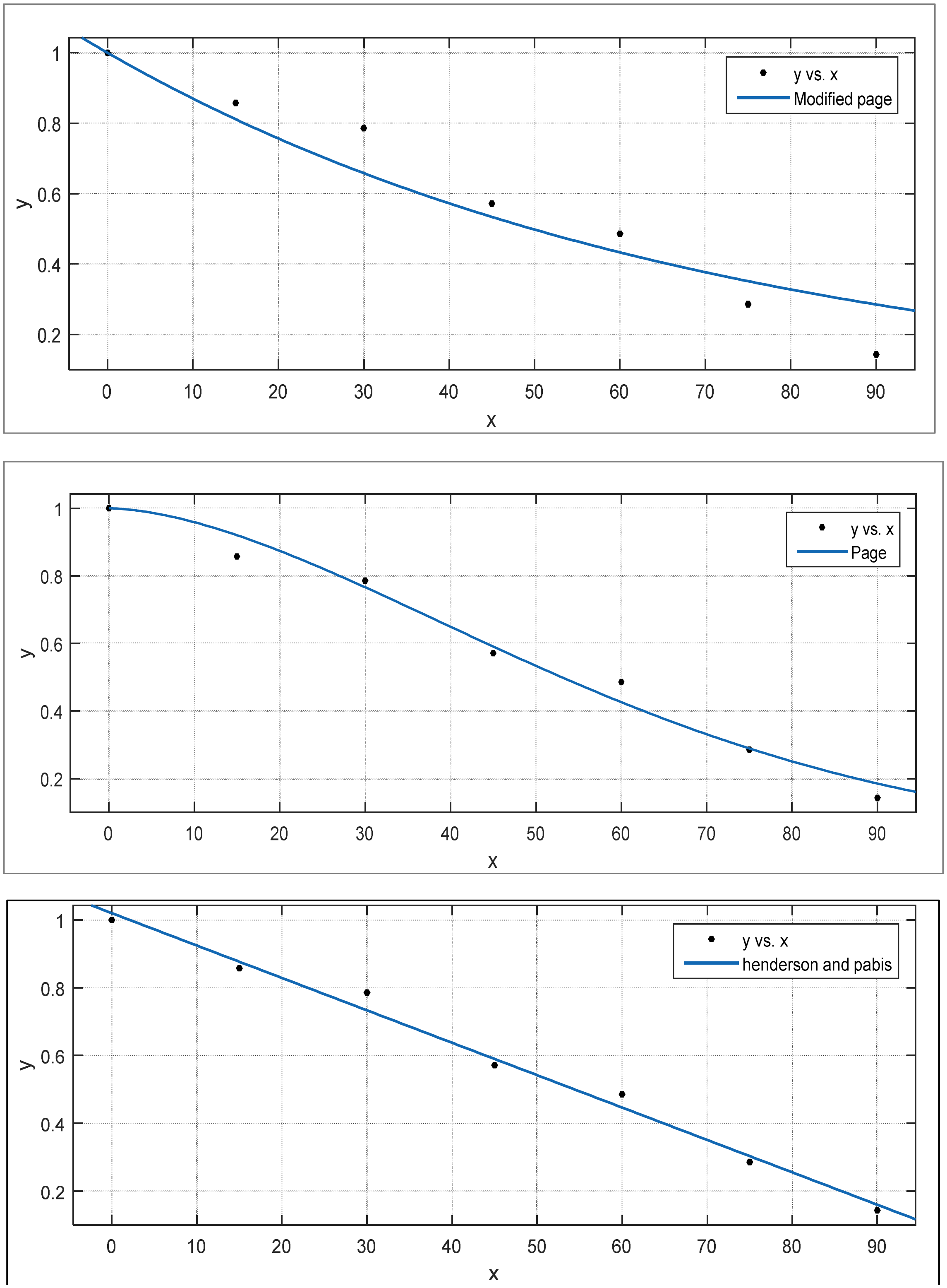
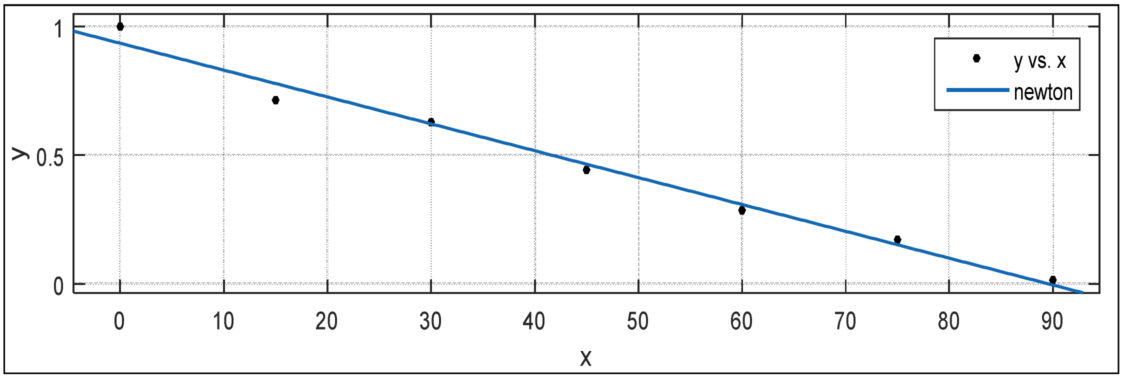


Fig 4. Curve fitting of the experimental data and thin layer drying models in the developed dryer. Inlet air velocity: 1.26 m^3/min. drying air temperature: 55°C


y vs. x
newton
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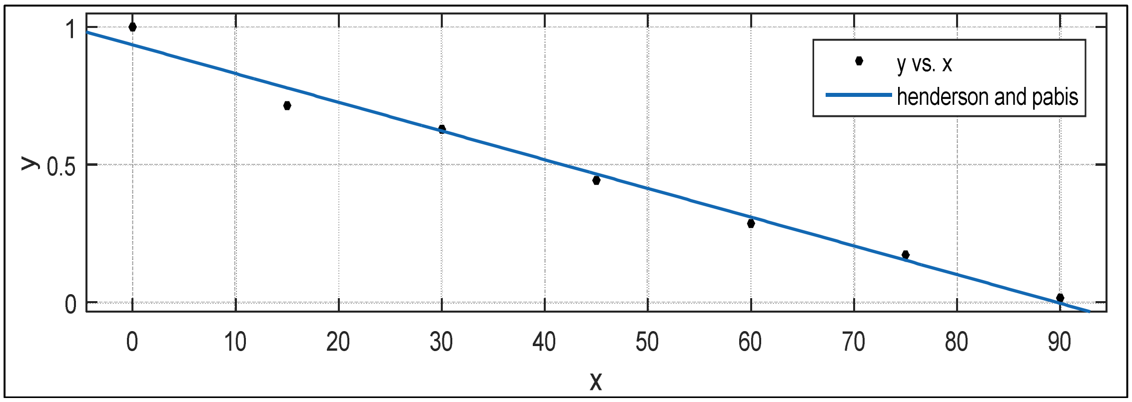
y vs. x
henderson and pabis
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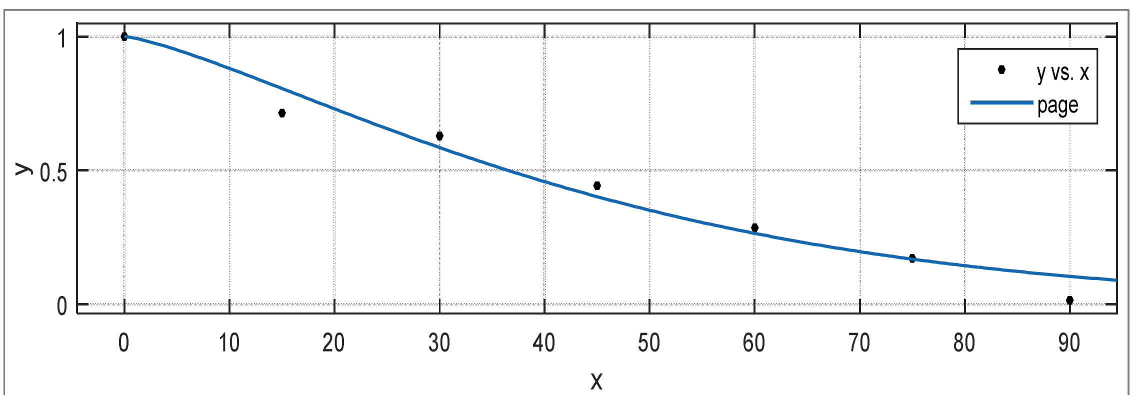
y vs. x
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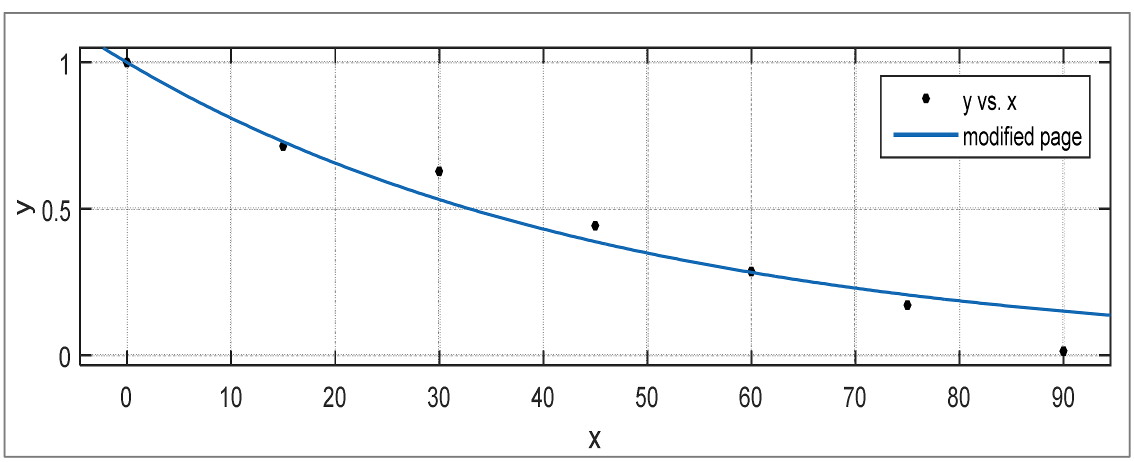
y vs. x
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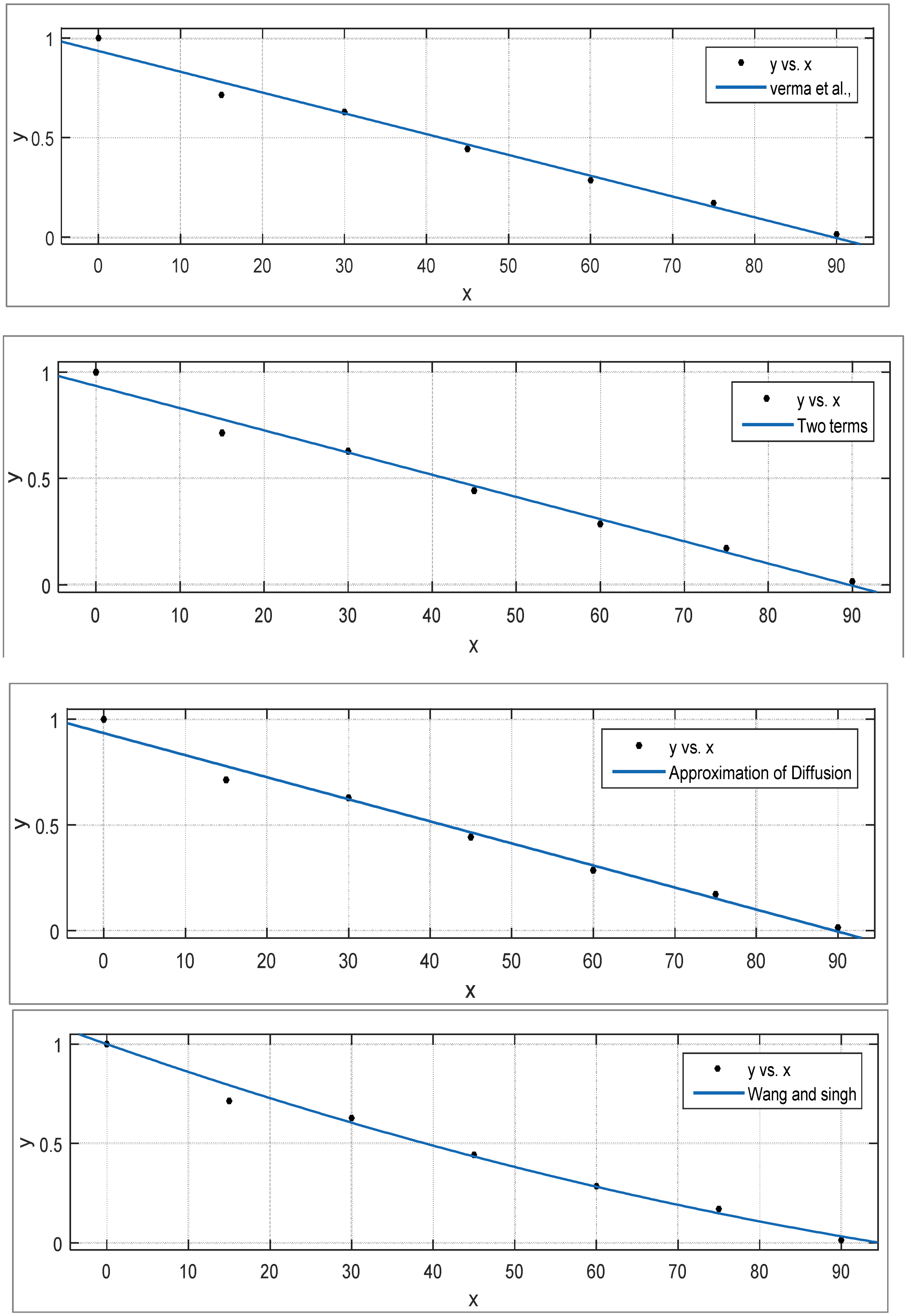

Fig 5. Curve fitting of the experimental data and thin layer drying models in the developed dryer. Inlet air velocity: 1 m^3/min. drying air temperature: 60°C

Table 2. Model constants and statistical parameters for drying of paddy at inlet air flow rate 1.26 m^3/min and 55°C

Model name	R^2	SSE	RMSE	K (h^{-1})	K_1	K_2	a	B	n
Page	0.9826	0.01011	0.04496	0.0008798					1.679
Wang & Singh	0.9927	0.00424	0.02912				-0.007845	1.935e-05	
Approximation of diffusion	0.9897	0.005999	0.04472	-0.0441			-2.735	-1.217	
Verma et al.	0.9897	0.005999	0.04472	-0.0441	0.01729	0.02684	0.5586		
Modified Page	0.919	0.04709	0.09705	0.8905					0.01567
Two terms	0.9526	0.02756	0.09584		0.01767	1.574	1.204	-0.2045	
Henderson and Pabis	0.9897	0.005999	0.03873	0.009558			0.2252		
Newton	0.9897	0.005999	0.03464	0.009558					

Table 3. Model constants and statistical parameters for drying of paddy at inlet air flow rate 1 m^3/min and 60°C

Model name	R^2	SSE	RMSE	K (h^{-1})	K_1	K_2	a	B	n
Page	0.9706	0.02046	0.06397	0.00618					1.31
Wang & Singh	0.9889	0.00775	0.03939				-0.014	4.046e-05	
Approximation of diffusion	0.9855	0.01014	0.0581	0.00993			1.308	0.0516	
Verma et al.	0.9855	0.01014	0.05813		0.01684	0.02729	0.434		
Modified Page	0.9536	0.03237	0.08046	1.05					0.02
Two terms	0.9855	0.01014	0.0712		-0.01684	0.02729	0.592	0.5303	
Henderson and Pabis	0.9855	0.01014	0.05035	0.0104			0.351		
Newton	0.9855	0.01014	0.04503	0.0104					

The value of the coefficient of determination (R^2) and RMSE value was 0.9927 and 0.0292 respectively for the drying conditions of inlet air flow rate 1.26 m^3/min. and 55°C. (Table 2) in case of inlet drying airflow rate 1m^3/min and drying air temperature 60 C the corresponding values for the model was 0.9889 and.03939 respectively (Table 3). Figs. 4 and 5 show the fitting curves of experimental data and the selected thin layer drying models. Newton model and Henderson and Pabis models were other models which effectively described the drying kinetics behaviour of paddy in the static bed batch dryer [15]. Thus, this model can be used to predict the drying parameters of paddy in the dryer. Wang and Singh's model was also found to have the best fit in experiments conducted to explain the drying behaviour of banana [16] parsley leaves [17] and bamboo shoot slices [18].

4. CONCLUSION

A static flat-bed batch dryer was developed and its performance was evaluated by drying 20 kg of paddy. The drying time was 90 times in totality for moisture reduction up to 12% from harvesting M.C of 24%. The experimental data were fit against 8 thin layer models and Wang and Singh model were found the best fit for the experimental data. Thus this model can be apprehensively used for predicting the drying behaviour of paddy in the developed dryer. The usage of these models helps us in optimising the drying performance of the dryer. The developed dryer can be apprehensively used for small scale drying of paddy. The drying behaviour of paddy grain dried under thin layer drying process in the developed dryer can be predicted using the suitable evaluated Wang and Singh model.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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