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Research Article

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Investigation of drying kinetics of finger millet in fluidized bed dryer

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ABSTRACT

Finger millet (Ragi) is a highly nutritious cereal, rich in calcium, proteins, iron and other minerals. Drying technique is usually employed to preserve Ragi for a longer time. In this work, the drying process was carried out in laboratory scale fluidised bed dryer and the drying kinetics was studied. The experimental data were made to fit with fifteen thin layer models and the model with best fit was chosen based on the statistical analysis values of R^2, RMSE and SSE. The best fit models were Modified Henderson and pabis model, Midilli model and Modified Page model II with maximum R^2 values and minimum RMSE, SSE values. The experiments were also carried out to study the effect of temperature and velocity of air, initial moisture content and loading of ragi on drying time. By using fick's diffusion equation the effective diffusivity values were determined and they varied between 3.26×10^{-10} and 1.29×10^{-9} m^2/minute. The activation energy value varied between 19.318 and 59.78 kJ/mol. The heat and mass transfer co-efficient for a single particle of Ragi was also calculated.

Key words: Finger millet, fluidised bed dryer, statistical analysis, thin layer models

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INTRODUCTION

Finger millet (Ragi) is a hardy crop that grows in high altitudes and withstands harsh weather conditions. In India, Karnataka is the largest producer contributing 58% in annual production. Ragi is a highly nutritious cereal loaded with calcium, proteins, iron and other minerals. It helps in reducing weight and used to treat various diseases like Brittle bones, Osteoporosis, Anaemia, Diabetes etc., In order to preserve Ragi and store it for a longer time, it needs to be dried.

Drying is employed in agro based industries for moisture removal in the presence of heat thus preserves materials by avoiding microbial growth and undesirable chemical reactions. It results in reduction of packaging, storage and transportation costs [2, 16, 21]. Fluidized bed drying is an efficient drying method due to good mixing, high heat and mass transfer coefficients and also it exhibits shorter drying time [9].

Various agricultural products like canola [8,17], ragi [10,22], green peas [7], potatoes [13], shelled corn [15], pepper corn [16], coconut [18], sweet potatoes [19] etc., and with other products like ammonium chloride [21], lignite [4], bovine intestine [11], baker's yeast [12] , coated sodium per carbonate particles [1] etc., have been dried in Fluidised bed dryer and studied. Although work has been reported with ragi [10, 22], the modelling work is not yet done.

The main objective of this study is to determine the model which successfully describes the drying kinetics of ragi among fifteen thin layer models based on statistical analysis and to investigate the effect of temperature, velocity, load and initial moisture content on drying time. In addition to this, effective moisture diffusivity and activation energy is determined. Further heat and mass transfer co-efficient is also calculated.

EXPERIMENTAL SECTION

2.1. RAW MATERIAL
Finger millet (*Eleusine coracana*) was used as the material for testing and the characteristic values are listed in table 1.

2.2. EXPERIMENTAL SET UP AND PROCEDURE
The set up consist of a Glass column, the conical portion of which was filled with fluidizing material. The material was supported on the screen mesh held between two flanges. Air from the Blower was heated in the heater box and passed through the column. Orifice with differential manometer was provided to measure the air flow rate. The flow rate can be adjusted by needle valve provided for air supply to the column. Sensors were given at different positions to measure the temperature at different points. The experimental set up and schematic representation is shown in fig.1, 2.

Sample of about 150g of Ragi with the initial moisture content of 18% was loaded into the column. The set point was fixed as 40^0C for temperature and 3 m/s for velocity. At regular time interval of 10 minutes sample was collected. 2g of sample was weighed, packed and dried in the hot air oven at 105^0C for 24 hours to determine the moisture content. The experiments were repeated for various operating conditions as listed in table 2.

2.3. FLUIDISATION BEHAVIOUR
Prediction of minimum fluidisation velocity is important because the velocity should be maintained above this. Ergun equation was widely used for the determination of minimum fluidisation velocity for spherical particles [12] and it is given by

$$\frac{1.75\rho u_{mf}^2(1-\varepsilon)}{\phi d_p \varepsilon^3}+\frac{150\mu u_{mf}(1-\varepsilon)^2}{\phi^2 d_p^2 \varepsilon^3}-\square\rho g(1-\varepsilon)=0 \qquad (1)$$

The terminal settling velocity is calculated using Haider and Levespiel correlation

$$u_t^* = u_t\left[\frac{\rho^2}{\mu(\rho_p - u_t^* g}\right]^{1/3} \qquad (2)$$

$$u_t^* = \left[\frac{18}{(d_p^*)^2}+\frac{2.335-1.744\phi}{(d_p^*)^{0.5}}\right]^{-1} \qquad (3)$$

The experimental minimum fluidisation velocity lies between the theoretical minimum fluidisation velocity and terminal settling velocity so that the particle will be under fluidisation. Prediction of fluidisation behaviour is important and it was done by using Walli's model. The expression is given by

$$\frac{1.79}{n}\left(\frac{gd_p}{u_t^2}\right)^{0.5}\left(\frac{\rho_p-\rho_f}{\rho_p}\right)^{0.5}\left(\frac{\varepsilon_{st}^{1-n}}{(1-\varepsilon_{st})^{0.5}}\right)-1=V_e \qquad (4)$$

The fluidisation regime for corresponding values of Walli's factor (V_e) is
$V_e > 0$ Homogenous regime
$V_e < 0$ Bubbling regime

2.4. EFFECT OF DRYING CONDITIONS
To optimise the operating conditions for drying, experiments were conducted to study the effect of temperature and velocity of inlet air, load and initial moisture content of ragi on drying time.

2.5. MATHEMATICAL MODELLING OF FINGER MILLET
The experimental data obtained were fitted with fifteen models [1] to determine the model which successfully explain and predict the drying behaviour of ragi. These models uses moisture ratio and it is represented as

$$MR = \frac{X_t - X_e}{X_i - X_e} \qquad (5)$$

The models and their equations are listed in table 3. The modelling work was done by non-linear regression analysis using least square algorithm in MATLAB software. The co-efficient of determination (R^2) was one of the main criteria in choosing the best fit model. In addition to this, the goodness of fit was evaluated by Root mean square error (RMSE) and Sum of squares error (SSE). For best fit model the value of R^2 should be higher and value of RMSE,SSE should be lower.

2.6. EFFECTIVE MOISTURE DIFFUSIVITY

Fick's diffusion equation was widely used for the determination of effective moisture diffusivity and is given by

$$MR = \frac{6}{\pi^2}\exp\left(\frac{-\pi^2 D_{eff}\, t}{r^2}\right) \quad (6)$$

The effective moisture diffusivity was obtained by plotting graph between ln(MR) and time.

The Activation energy can be computed using Arrhenius type equation and is given by

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad (7)$$

2.7. HEAT AND MASS TRANSFER CO-EFFICIENT

The heat and mass transfer co-efficients are required for ideal dryer design. The heat and mass transfer co-efficient in a bed for a single particle is given by the correlations [24].

$$Nu = 2 + 1.8\,Re_p^{1/2}\,Pr^{1/3} \quad (8)$$

$$Sh = 2 + 1.8\,Re_p^{1/2}\,Sc^{1/3} \quad (9)$$

RESULTS AND DISCUSSION

3.1. EFFECT OF OPERATING CONDITIONS ON DRYING TIME

Fig.3 show that the drying time decreases as the inlet air temperature increases. It's due to high thermal input to the system. The rate of drying increases as inlet air temperature increases because of the intensity of heat. Fig.4 show that with the increase in velocity of air the drying time decreases and the rate of drying increases. The effect of load on drying time is unpredictable and in this case increase in load results in decrease in drying time due to variations in contacting pattern between the sample and air as shown in Fig.5. Fig.6 shows that increase in initial moisture content of ragi, the total moisture available for removal will be more so the drying time increases.

The falling rate period alone was alone observed in the rate of drying curve as shown in Fig.7. It was the typical characteristic of agricultural products as reported earlier and it symbolise that internal mass diffusion governs the process.

3.2 MODELLING OF DRYING KINETICS

Modelling work for ragi was done by non-linear regression analysis using least square algorithm in MATLAB for various temperatures and velocities. Statistical results are summarised in table 4 for fifteen thin layer drying models for various conditions. Based on statistical results, Modified Henderson and Pabis model, Midilli model and Modified Page model II contains maximum values of R^2 and minimum values of RMSE, SSE. So these models fit with the experimental data and successfully describe drying kinetics of ragi. The model constants for the best fit models are listed in table 5.The comparison of statistical results for the best fit models is shown in Fig.8.

3.3. EFFECTIVE MOISTURE DIFFUSIVITY

Temperature and velocity have significant effect on effective diffusivity i.e Effective moisture diffusivity increases with increase in temperature and velocity of air. The values obtained were within the range as previously reported for food materials and are tabulated in table 6.1.The values of activation energy (E_a) and the pre-exponential factor (D_0) values for various velocities are tabulated in table 6.2.

3.4. TRANSFER CO-EFFICIENT

The heat and mass transfer co-efficient for a single spherical particle in air at various temperatures and velocities were calculated and are listed in table 7.1 and 7.2. The heat transfer co-efficient increases with increase in inlet air velocity and the mass transfer co-efficient increases with increase in inlet air temperature and velocity.

Table 1: Characteristics of Finger millet

Parameters	Characteristic value
Shape of seed	Spherical
Mean particle diameter in mm	1.071
Density in kg/m^3	1474.926
Gas hold up	0.348
Minimum fluidisation velocity in m/s	0.283
Terminal settling velocity in m/s	5.6
Fluidisation regime	Bubbling regime

Table 2: Experimental conditions

Parameters	Characteristic value
Temperature in ^{0}C	40, 50, 60
Velocity in m/s	2.1, 3, 3.4
Initial Moisture content (kg of moisture/kg of dry solid)	18%, 23%, 25%
Load in g	150, 200, 250

Table 3: Thin layer drying models used for the modelling of Ragi

No.	Model	Equation
1	Lewis or Exponential model	$MR = \exp(-kt)$
2	Page model	$MR = \exp(-kt^n)$
3	Henderson and Pabis model	$MR = a\exp(-kt)$
4	Modified Page model I	$MR = \exp(-(kt)^n)$
5	Wang and Singh model	$MR = 1 + at + bt^2$
6	Logarithmic model	$MR = a.\exp(-kt + c)$
7	Two term model	$MR = a.\exp(-k_0 t) + b.\exp(-k_1 t)$
8	Two term exponential model	$MR = a.\exp(-kt) + (1-a)\exp(-kat)$
9	Diffusion approach model	$MR = a.\exp(-kt) + (1-a)\exp(-kbt)$
10	Verma et al model	$MR = a.\exp(-kt) + (1-a)\exp(-gt)$
11	Modified Henderson and Pabis model	$MR = a.\exp(-kt) + b.\exp(-gt) + c.\exp(-ht)$
12	Midilli model	$MR = a.\exp(-kt^n) + bt$
13	Modified Page model II	$MR = \exp\left(-k\left(\frac{t}{L^2}\right)^n\right)$
14	Thomson model	$t = a.\ln(MR) + b.\ln(MR)^2$
15	Simplified Fick's diffusion equation	$MR = a.\exp\left[-c\left(\frac{t}{L^2}\right)\right]$

Table 4: Statistical analysis results for fifteen models for various operating conditions

M. no	T in ^{0}C	v in m/s 2.1 R^2	2.1 RMSE	2.1 SSE	3 R^2	3 RMSE	3 SSE	3.4 R^2	3.4 RMSE	3.4 SSE
1	40	0.9264	0.0307	0.0094	0.8342	0.0420	0.0176	0.2609	0.0790	0.0625
	50	0.7749	0.0642	0.0413	0.5890	0.0829	0.0688	0.6835	0.0884	0.0782
	60	0.8340	0.0719	0.0517	0.6235	0.0979	0.0959	0.8682	0.0776	0.0602
2	40	0.9583	0.0243	0.0053	0.9726	0.0180	0.0029	0.9902	0.0096	0.0008
	50	0.9941	0.0110	0.0011	0.9726	0.0226	0.0046	0.9971	0.0090	0.0007
	60	0.9829	0.0243	0.0053	0.9957	0.0104	0.0010	0.9963	0.0138	0.0017
3	40	0.9394	0.0293	0.0077	0.9048	0.0335	0.0101	0.6973	0.0533	0.0256
	50	0.8910	0.0471	0.0200	0.7944	0.0618	0.0344	0.8503	0.0641	0.0370
	60	0.9074	0.0566	0.0289	0.8174	0.0719	0.0465	0.9231	0.0624	0.0351
4	40	0.9602	0.0228	0.0057	0.9693	0.0169	0.0032	0.9606	0.0032	0.0001
	50	0.9880	0.3307	1.2030	0.9242	0.0216	0.0051	0.9933	0.0082	0.0007
	60	0.9719	0.0327	0.0118	0.9889	0.0096	0.0010	0.9915	0.0126	0.0017
5	40	0.9765	0.0183	0.0030	0.9891	0.0114	0.0012	0.8238	0.0107	0.0149
	50	0.9565	0.0298	0.0080	0.8879	0.0456	0.0188	0.8880	0.0553	0.0275
	60	0.9489	0.0421	0.0159	0.8707	0.0605	0.0329	0.9299	0.0566	0.0288
6	40	0.9691	0.0222	0.0039	0.9870	0.0131	0.0014	0.9804	0.0129	0.0013
	50	0.9931	0.0126	0.0013	0.9842	0.0182	0.0026	0.9774	0.0264	0.0056
	60	0.9784	0.0290	0.0067	0.9822	0.0238	0.0045	0.9886	0.0255	0.0052
7	40	0.9866	0.0156	0.0017	0.9909	0.0118	0.0010	0.9932	0.0090	0.0006
	50	0.9966	0.0094	0.0006	0.9895	0.0159	0.0018	0.9946	0.0138	0.0013
	60	0.9816	0.0286	0.0057	0.9960	0.0120	0.0010	0.9964	0.0154	0.0017
8	40	0.8841	0.0406	0.0148	0.9236	0.0300	0.0081	0.5285	0.0665	0.0399
	50	0.8937	0.0465	0.0195	0.7636	0.0663	0.0395	0.8287	0.8097	0.0686
	60	0.9213	0.0522	0.0245	0.7865	0.0777	0.0544	0.9442	0.0532	0.0255
9	40	0.9729	0.0208	0.0035	0.9901	0.0115	0.0010	0.9932	0.0085	0.0006
	50	0.9966	0.0088	0.0006	0.9894	0.0149	0.0018	0.9946	0.0130	0.0013
	60	0.9815	0.0268	0.0058	0.9960	0.0113	0.0010	0.9964	0.0144	0.0017
10	40	0.9864	0.0147	0.0017	0.9901	0.0115	0.0010	0.9932	0.0085	0.0006
	50	0.9966	0.0088	0.0006	0.9894	0.0149	0.0018	0.9946	0.0129	0.0013
	60	0.9815	0.0268	0.0058	0.9960	0.0113	0.0010	0.9964	0.0144	0.0017
11	40	0.9788	0.0233	0.0027	0.9935	0.0117	0.0006	0.9974	0.0066	0.0002
	50	0.9983	0.0078	0.0003	0.9906	0.0177	0.0016	0.9977	0.0107	0.0006
	60	0.9876	0.0278	0.0039	0.9981	0.0098	0.0005	0.9975	0.0152	0.0012
12	40	0.9785	0.0198	0.0027	0.9903	0.0121	0.0010	0.9970	0.0060	0.0003
	50	0.9982	0.0068	0.0003	0.9826	0.0204	0.0029	0.9973	0.0097	0.0007
	60	0.9849	0.0259	0.0047	0.9980	0.0086	0.0005	0.9971	0.0137	0.0013
13	40	0.9583	0.0258	0.0053	0.9726	0.0191	0.0029	0.9902	0.0102	0.0008
	50	0.9941	0.1164	0.0011	0.9726	0.0240	0.0046	0.9971	0.0095	0.0007
	60	0.9829	0.0258	0.0053	0.9962	0.0110	0.0010	0.9963	0.0146	0.0017
14	40	0.9206	9.8520	873.6	0.8694	12.6400	1437	0.6516	20.6400	3832
	50	0.8495	13.5600	1655.0	0.7527	17.3900	2721	0.8111	15.2000	2078
	60	0.8663	12.7800	1471.0	0.7759	16.5500	2465	0.8904	11.5700	1205
15	40	0.9394	0.0311	0.0077	0.9048	0.0356	0.0101	0.6973	0.0566	0.0256
	50	0.8910	0.0500	0.0200	0.7944	0.0656	0.0344	0.8503	0.0680	0.0370
	60	0.9074	0.0601	0.0289	0.8174	0.0762	0.0465	0.9231	0.0662	0.0351

Table 5: Best fit model constants for various conditions

T in ^{0}C	v in m/s	Modified Henderson and Pabis model constants a	b	c	g	h	k
40	2.1	0.0425	0.9689	-0.0116	0.0074	0.9896	-0.0166
	3	0.0184	0.9492	0.0323	0.0063	1.5590	-0.0236
	3.4	0.1005	0.2000	0.6995	0.0409	0.0002	1.8120
50	2.1	0.1990	0.6622	0.2188	0.0119	-0.0051	0.1496
	3	-0.8482	1.1490	0.6986	0.1145	0.0019	0.1384
	3.4	0.1629	0.3491	0.4879	0.0258	0.0010	0.4828
60	2.1	0.8579	0.1272	0.0143	0.7461	-0.0239	0.0109
	3	0.2973	0.1412	0.5615	1.6400	0.0021	0.0441
	3.4	0.2467	0.7313	0.0219	0.0130	-0.0153	0.1366

T in ^{0}C	v in m/s	Midilli model constants			
		a	b	k	N
40	2.1	0.9894	0.0044	0.0049	1.2260
	3	0.9952	0.0037	0.0116	0.9951
	3.4	1.0000	0.0015	0.0674	0.0476
50	2.1	0.9998	0.0017	0.0378	0.6979
	3	1.0030	0.0022	0.0517	0.6439
	3.4	0.9997	0.0004	0.0926	0.4835
60	2.1	0.9982	0.0012	0.0473	0.6980
	3	1.0000	0.0010	0.0960	0.5125
	3.4	1.0000	0.0007	0.0720	0.6554

T in ^{0}C	v in m/s	Modified Page model II constants		
		k	l	n
40	2.1	0.7282	14.3200	0.7625
	3	0.0301	1.0870	0.5832
	3.4	0.0598	0.3773	0.2846
50	2.1	0.0680	1.1700	0.5074
	3	0.6187	11.0200	0.4078
	3.4	0.7915	10.3100	0.4355
60	2.1	0.9406	10.6900	0.5605
	3	0.1119	0.8763	0.4030
	3.4	0.1457	1.5540	0.5757

Table 6.1: Effective diffusivity at various temperatures and velocities

Temperature\Velocity	2.1	3	3.4
40	5.71E-10	4.19E-10	3.26E-10
50	6.06E-10	5.36E-10	7.46E-10
60	8.95E-10	7.56E-10	1.29E-09

Effective diffusivity in m^2/minute, Temperature in ^{0}C and velocity in m/s

Table 6.2: Activation energy at different velocities

velocity in m/s	E_a in kJ/mol	D_0 in m^2/s
2.1	19318.4104	9.053E-07
3	25437.51	7.246E-06
3.4	59780.9856	3.2152336

Table 7.1: Heat transfer co-efficient H at various temperatures and velocity

Temperature/Velocity	2.1	3	3.4
40	524.9837039	617.4279224	653.9784814
50	524.4913457	616.0452243	652.995894
60	523.8416593	615.5525164	651.8131193

Heat transfer co-efficient in W/m^2K; Temperature in ^{0}C and velocity in m/s

Table 7.2: Mass transfer co-efficient k_d at various temperature and velocity

Temperature/Velocity	2.1	3	3.4
40	0.462674844	0.544140909	0.57635093
50	0.477287597	0.561090255	0.594224118
60	0.492171048	0.578342731	0.612413257

Mass transfer co-efficient in m/s; Temperature in ^{0}C and velocity in m/s

Fig. 1 Experimental set up of fluidised bed dryer
1-Blower, 2- Preheater, 3- Drying chamber, 4- Cyclone separator, 5- Water manometer, 6- Temperature indicator

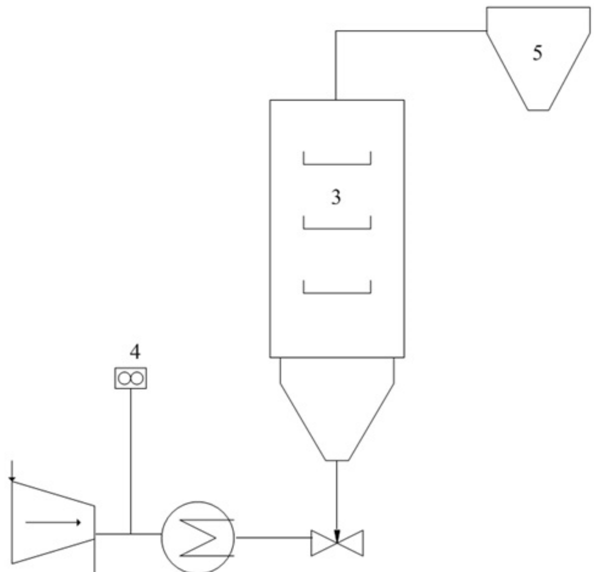

Fig. 2 Schematic representation of Fluidised bed dryer
1-Blower, 2-Preheater, 3-Drying chamber, 4-Water manometer, 5-Cyclone separator

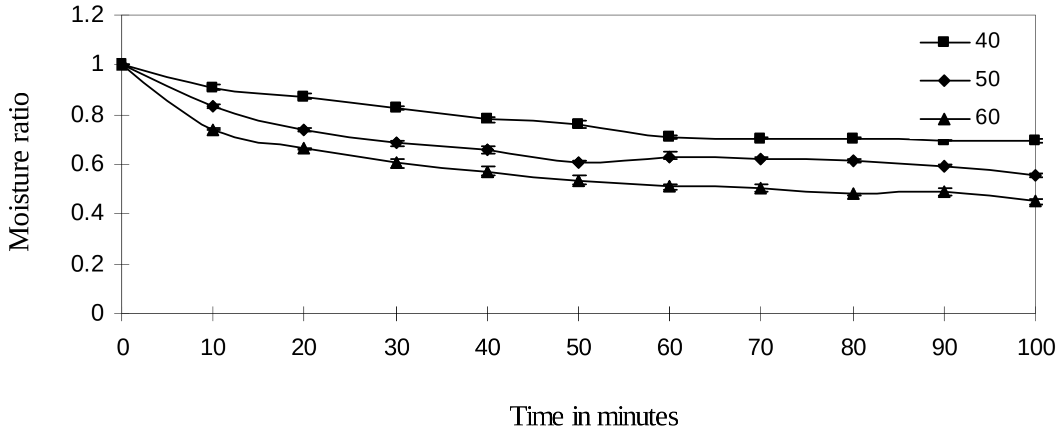

Fig.3 Effect of Inlet air temperature on drying time

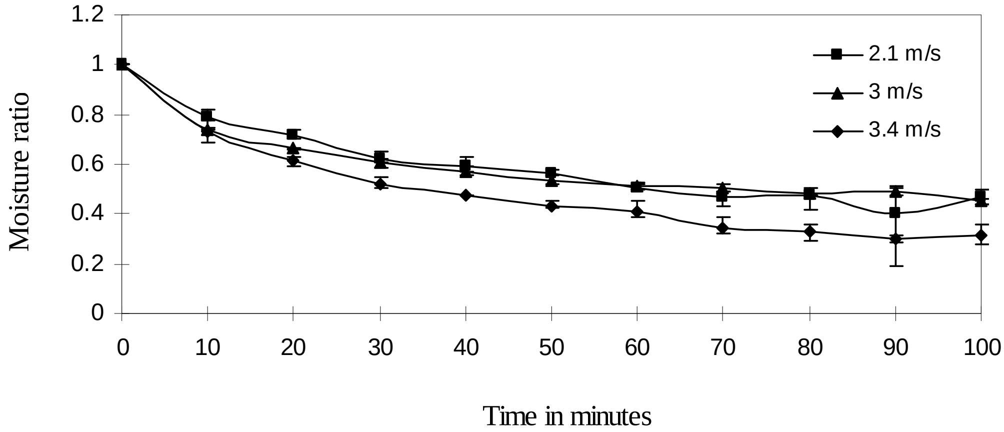

Fig.4 Effect of inlet air velocity on drying time

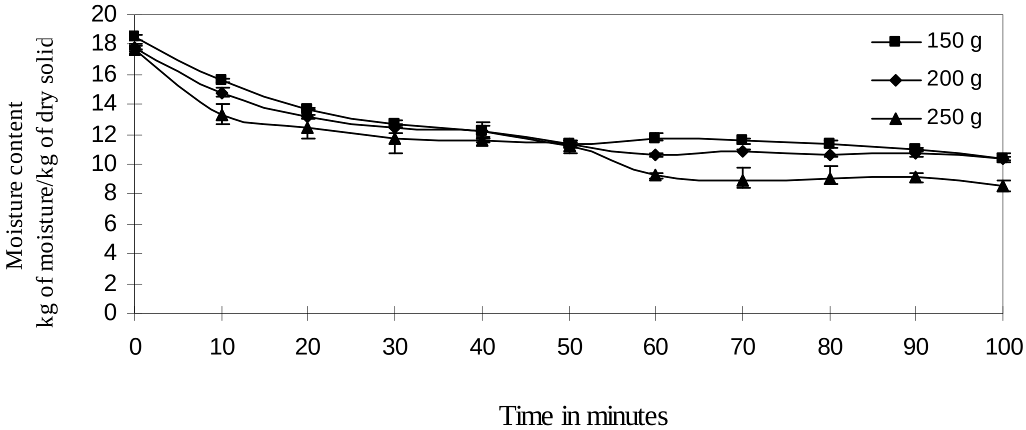

Fig.5 Effect of load on drying time

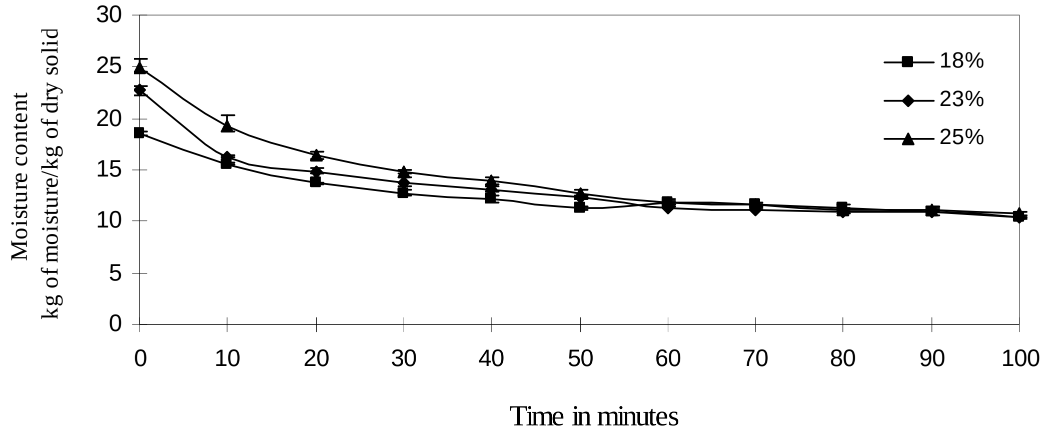

Fig. 6 Effect of Initial moisture content on drying time

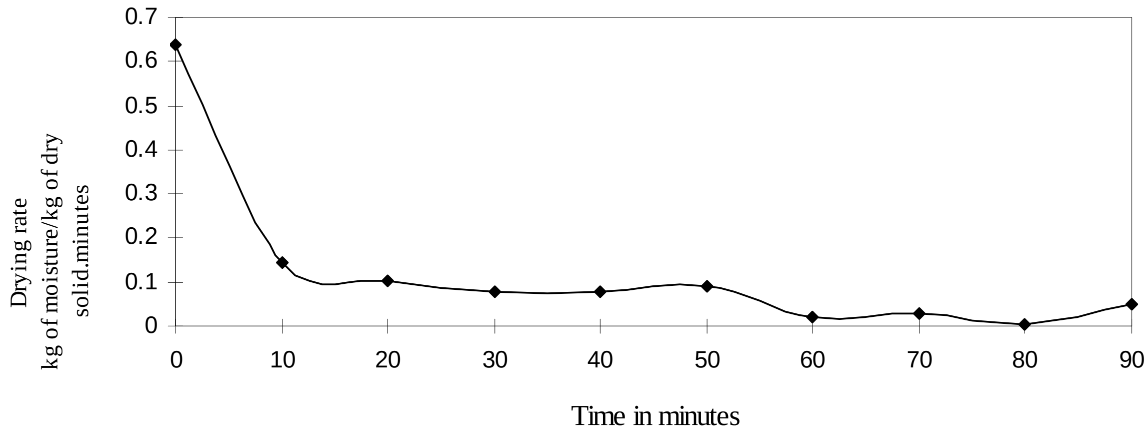

Fig.7 Rate of drying curve

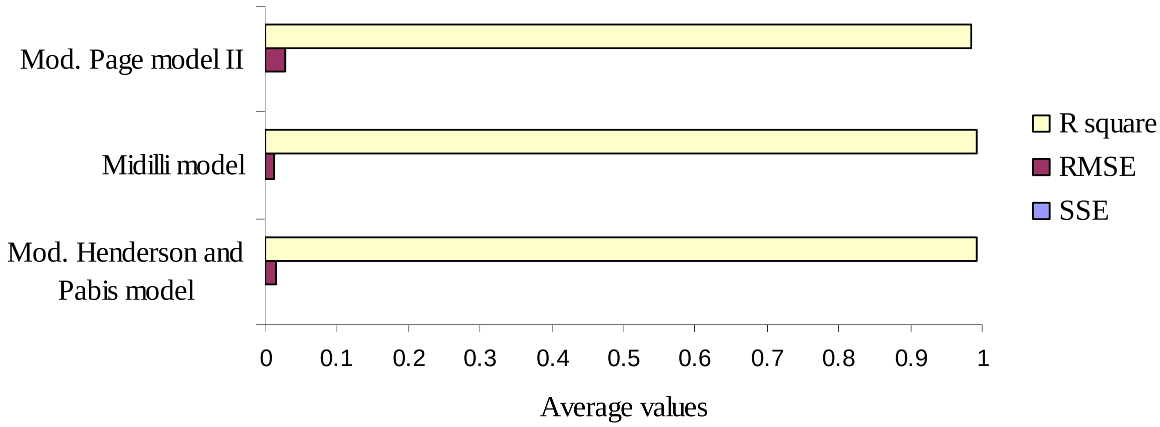

Fig. 8 Comparison of Statistical results for best fit models

CONCLUSION

The drying time of finger millet decreases with increase in inlet air temperature, velocity and load of sample, decrease in initial moisture content of sample. The falling rate period alone was present in the rate of drying curve which indicates internal mass diffusion governs the process. Among fifteen widely used thin layer models, Modified Henderson and Pabis model, Midilli model and Modified Page model II were found to be best fit models with maximum R^2 and minimum RMSE,SSE values and they successfully describes the drying kinetics.

The effective moisture diffusivity varies between 3.26 x 10^{-10} and 1.29 x 10^{-9} m^2/minutre. The activation energy ranges between 19.318 and 59.78 kJ/mol. The value of heat transfer co-efficient is in the range of 523.84 and 653.97W/m^2K. The mass transfer co-efficient is in the range of 0.462 and 0.612m/s.

NOMENCLATURE

a,b,c,k_0,k_1,k,n,g,h,L	Constants of the drying models
D_{eff}	Effective moisture diffusivity (m^2/minute)
d_p	Particle diameter (m)
D_o	Pre-exponential factor (m^2/minute)
E_a	Activation energy (kJ/mol)
g	Acceleration due to gravity(m/s^2)
H	Heat transfer co-efficient of a single sphere in gas (W/m^2K)
K_d	Mass transfer co-efficient of a single sphere in gas (m/s)
MR	Moisture Ratio
n	Richard zaki co-efficient
Nu	Nusselt number
Pr	Prandtl number
r	Radius of particle (m)
R	Universal gas constant (8.314kJ/kmol.K)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	Temperature (K)
t	Time (minutes)
U_{mf}	Minimum fluidisation velocity (m/s)
U_t	Terminal settling velocity (m/s)
X_t	Moisture content at time t (kg of moisture/kg of dry solid)
X_i	Initial moisture content (kg of moisture/kg of dry solid)
X_e	Equilibrium moisture content (kg of moisture/kg of dry solid)
Symbols	
ρ	Density of gas (kg/m^3)
ε	Gas phase hold up
ϕ	Sphericity
μ	Viscosity of gas (kg/m.s)
$\Delta\rho$	Density difference between particle and gas
ΔX	Difference in moisture content
Δt	Difference in time

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