OPTIMIZATION OF FLUIDIZED BED DRYING PARAMETERS FOR CHANA DAL - EXPERIMENTAL KINETICS AND MODEL COMPARISONS

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ABSTRACT
Fluidized bed drying (FBD) is a widely adopted method in the food processing industry, particularly for grains such as chana dal (split chickpeas), due to its advantages in enhancing heat and mass transfer, ensuring uniform drying, and reducing drying time. This study aims to investigate the drying kinetics of chana dal in a fluidized bed dryer, focusing on the effects of critical parameters such as drying medium temperature, air velocity, and solid holdup. Experimental drying kinetics data were collected and analyzed to understand the drying behavior under various conditions. The study also evaluates the applicability of different drying models, including Newton's model and the Page model, in predicting the drying kinetics of chana dal. The Page model, with its additional exponent term, was found to provide a better fit compared to Newton's model. Furthermore, the research explores the optimization of FBD parameters to maximize drying efficiency and product quality. The findings contribute to a deeper understanding of the fluidized bed drying process, offering valuable insights for optimizing industrial drying operations for chana dal.
Key words: Food Grain Drying, Drying Kinetics, Solid Holdup, Newton's Model, Page Model

INTRODUCTION
Chana Dal, also known as Bengal Gram, has a crunchy and nutty flavor. When ground, it becomes Besan, a key ingredient in many delicacies. Cultivated in India for a long time, Chana Dal is believed to have originated in the Eastern Mediterranean region. While many are familiar with the benefits of consuming whole chana, chana dal itself offers numerous, lesser-known health benefits. Fluidized bed drying, a widely used technique in the food processing industry for drying grains like chana dal, provides advantages such as uniform drying, efficient heat transfer, and reduced drying time compared to conventional methods. The drying kinetics of chana dal in a fluidized bed dryer is influenced by parameters such as the drying medium's temperature, air velocity, and solid holdup. Modeling this drying kinetics is crucial for optimizing the drying process and improving energy efficiency.

LITERATURE REVIEW
2.1 Fluidized Bed Drying of Food Grains: Hydrodynamics and Drying Kinetics
Fluidized bed drying is a process where solid particles are suspended in an upward-flowing gas stream, creating a fluid-like state. This method is particularly effective for chana dal (split chickpeas) due to its advantages in providing uniform drying and reducing drying times (Mujumdar, 2014; Sabarez, 2012). Experimental studies on drying kinetics provide valuable insights into the behavior of chana dal during the drying process. Studies by Arun et al. (2013) and Arora et al. (2015) have shown that the drying rate is significantly influenced by the properties of the drying medium and the physical characteristics of the chana dal. The temperature of the drying medium is a critical factor in fluidized bed drying. Higher temperatures typically increase the drying rate by enhancing the moisture diffusion within the grains. Zhang et al. (2016) and Li et al. (2017) demonstrated that increasing the air temperature from 40°C to 80°C substantially reduces the drying time of chana dal, highlighting the importance of optimizing the drying temperature for efficient drying processes. Air velocity plays a crucial role in fluidized bed drying by affecting the fluidization quality and the drying rate. Studies by Chou and Chua (2001) and Parikh et al. (2009) indicated that there exists an optimal air velocity beyond which no significant increase in drying rate is observed. This optimal velocity ensures adequate fluidization without excessive energy consumption. Solid holdup, the amount of solid material in the dryer, influences the contact between the drying medium and the grains. Research by Kunii and Levenspiel (1991) and Azharul Karim and Hawlader (2005) revealed that higher solid holdup can lead

to reduced drying rates due to the decreased surface area available for heat and mass transfer. Balancing solid holdup is essential for efficient drying.

2.2 Drying Kinetic Modeling

Accurate modeling of drying kinetics is crucial for predicting the drying behavior and optimizing the drying process. Several models, including Newton's model and the Page model, have been employed to describe the drying kinetics of chana dal in a fluidized bed dryer. Newton's model is one of the simplest models for describing drying kinetics, assuming a constant drying rate period followed by a falling rate period. The model, however, often lacks accuracy for complex drying processes (Midilli et al., 2002).The Page model, an empirical modification of the Newton model, provides a better fit for the drying data of various agricultural products. The model accounts for the decreasing drying rate more accurately (Page, 1949; Akpinar, 2006). Studies by Doymaz (2007) and Pala et al. (1996) have shown the Page model to be effective in predicting the drying behavior of chana dal in fluidized bed dryers. Comparative studies by researchers such as Erbay and Icier (2010) and Lahsasni et al. (2004) indicate that the Page model generally offers a superior fit to experimental drying kinetics data compared to Newton's model. These comparisons highlight the importance of selecting appropriate models for different drying conditions and materials to achieve accurate predictions.

MATERIALS AND METHODS

The following materials and methods are used for the experimental work in fluidized bed drying of grains.

3.1 Materials:

Food grains which are used as the materials for fluidized bed drying are obtained from the local market in Hyderabad. Table 3.1 illustrates the characteristics of food grains that are considered for experiment.

Table 3.1. Characteristics of Food Grains Used

Name of Food Grain	Particle Size(mm)	Density(kg/m³)	Minimum fluidization velocity U_{mf}(m/s)	Bed Voidage at minimum fluidization velocity (ε_{mf})
Chana Dal	2.9	1203	0.99	0.45

3.2 Description of Fluidized Bed Drier:

The Fluidized Bed Dryer, shown in Figure 3.1, features a cylindrical column with an internal diameter of 16 cm and a height of 18 cm. It includes an air blower controlled by a thyristor circuit for smooth speed variation and a 2 kW finned heater element capable of heating air up to 200°C. A two-term temperature controller provides an accuracy of ±1°C. Air velocity is adjustable via blower speed control, and temperature is displayed on both analogue and optional digital screens. The glass column allows for visual observation, with the ability to feed solids from the top and measure outlet wet and dry bulb temperatures

Figure 3.1: Photograph of Fluidized Bed Dryer Set-up

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Vol-14, Issue-6, No.04, June: 2024

3.3 Methods used for Experimental Study:

3.3.1 Testing Methods

The following standard methods are adopted to determine the initial moisture content, total ash content, protein content, fat content and crude fiber content in food grains.

3.3.2 Determination of Initial Moisture content:

Petri plates, weighing balance, Electric Oven controlled at 105 ± 1ºC and Desiccators are used to estimate the moisture content of food grains. Moisture content of the samples was determined using the hot air oven method. Three samples of each five grams were taken and kept in the hot air oven at 105±10ºC for half an hour. After half an hour, the samples were taken out and placed in a desiccator and cooled. This process was repeated until the constant reading was attained. (Method No: FSSAI 03.006:2023). The moisture content was calculated using the following formula,

$$\text{Moisture content (\%)} = \textit{Moisture content} = \frac{w_3 - w_2}{w_1} \times 100 \rightarrow (3.1)$$

where

w_3 is weight of petriplate and sample before drying, g

w_2 is weight of petriplate and sample after drying, g

w_1 is weight of sample taken, g

3.3.3 Estimation of Total Ash:

Crucible, weighing balance, Muffle furnace operating at 550 ± 10ºC and Desiccators are used for the estimation of the total ash content in food samples. About five grams of the sample was weighed accurately into a porcelain crucible. This was transferred into a muffle furnace set at 600°C and left for about 4 hours. About this time, it had turned into white ash. The crucible and its content were cooled to about 100°C in air then to room temperature in desiccators and weighed. The percentage ash was calculated from the formula below. (AOAC 1995).

$$\%\, of Ash = \frac{weight\ of\ ash}{weight\ of\ sample} \times 100 \rightarrow (3.2)$$

1.3.4 Determination of protein:

Proteins are polymers of amino acids, the majority of which are of amino acids having general formula $NH_2CHRCOOH$ may be distinguished from fats & carbohydrates is being the only macro nutrient in food containing nitrogen. (AOAC 976.05(2005)). Reagents of concentrated H_2SO_4, Catalyst titrates, 40% NaOH solution, O.1 N NaOH, O.1 N H_2SO_4, Methyl red indicator are used. 0.55g of sample in digestion tube of instrument taken & 25 ml concentrated H_2SO_4 and 1-2 catalyst stabilizers are added. The temperature was adjusted to 370°C and keep for digestion for 4-6 hours till the solution becomes blue in colour. Then the tube was removed from 0.1N H_2SO_4 solution in a titration flask, placed on the distillation unit and attached a tube containing digested sample to distillation until the press start button to affect a metered addition of NaOH and to initiate steam distillation stops add 5 drops to yellow color. This is the end point. Now using 25ml of 0.1N HCl with 0.1N NaOH in burette.

$$\%Nitrogen = \frac{1.4 \times normality \times blank\ sample \times kjeldhal\ factor}{weight\ of\ sample} \rightarrow (3.3)$$

$$\%\, Protein = (Nitrogen\% \times conversion\ factor) \rightarrow (3.4)$$

3.3.5 Determination of fat content:

Raise the collection vessels and place them in an oven at 100°C along with the samples to remove moisture. Once dry, cool them in a desiccator and weigh the empty vessels (W1). Insert the thimble into the S.S. spring thimble holder and place it on the collection vessels. Weigh a 3-gram sample and transfer it to the thimble. Fill the collection vessels to 3/4 of their volume with solvent and load them into the system. Set the system to the solvent's boiling point, about 100°C higher than the solvent's maximum boiling point, and run for 45-60 minutes. Afterward, increase the temperature to the solvent recovery temperature and rinse twice to collect remaining fat. Remove the vessels and place them in a hot air oven for 15-20 minutes, then cool them in a desiccator for about 5 minutes. Weigh the vessels again to determine the final weight. Calculate the fat content using the appropriate formula. (AOAC Official Method 2003)

$$\% \, \boldsymbol{fat} = \frac{\boldsymbol{W_2 - W_1}}{\boldsymbol{W}} \times \mathbf{100} \rightarrow (\mathbf{3.5})$$

where
W = Weight of sample
W_1 = Weight of empty collection vessel
W_2 = Weight of collection vessel containing fat

3.3.6 Determination of Crude Fiber:

This method involves solubilizing non-cellulosic compounds with sulfuric acid and KOH solution. First, determine the sample moisture by heating 1g of ground sample in an oven at 105°C until constant weight, then cool in a desiccator. For fiber determination, mix 1g of the sample with 1.25% sulfuric acid up to 150ml in a crucible, preheat with a hotplate, and add 3-5 drops of n-octanol as an antifoam agent. Boil for 30 minutes, then drain using a vacuum. Wash three times with 30ml of hot deionized water, stirring with compressed air each time.

Next, add 150ml of preheated 1.25% KOH and 3-5 drops of n-octanol, boil for 30 minutes, filter, and wash three times with water and then three times with 25ml of acetone, stirring with compressed air each time. Dry the crucibles at 105°C for an hour or until constant weight. For ash content, place the crucibles in a muffle furnace at 550°C for 3 hours and reweigh after cooling in a desiccator. The weight difference represents the crude fiber content without ash. (AOAC, 2005)

$$\% \, \boldsymbol{Crude\ fibre} = \frac{\boldsymbol{F_1 - F_2}}{\boldsymbol{F_0}} \times \mathbf{100} \rightarrow (\mathbf{3.6})$$

where
F_1 is weight of the residue in the crucible after digestion
F_2 is weight of the ash in the crucible
F_0 is weight of the sample in the crucible

3.3.6 Drying Kinetics Study in Fluidized Bed:

A known weight of food grains with initial moisture content is fed into the fluidized bed dryer from the top. Air at a selected temperature and velocity, based on the minimum fluidization velocity, flows through the fluidization column. The dryer cabinet includes an electric heater, temperature controller, timer, and air blower fan, with the air velocity controlled by a thyristor circuit. The column temperature is maintained by the heater. During drying, inlet and outlet wet and dry bulb temperatures are recorded every 5 minutes until steady-state readings are achieved. Experiments are conducted at varying temperatures, velocities, and solid holdups.

Table 3.2: Range of Operating conditions in Fluidized Bed Dryer

Name of the grains	Solid holdups (kg)	Velocity (m/s)	Temperature (°C)
Chana dal	0.100, 0.150 and 0.200	1.75, 1.80 and 1.85	50, 60 and 70

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3.3.7 Estimation of moisture content

The operating conditions for effect of temperature, effect of velocity, effect of solid holdups for Chana dal is given in the table 3.3.

Table 3.3: Operating conditions for effect of solid holdups, velocity and temperature for food grains

Solid holdups (kg)	Velocity(m/s)	Temperature(°C)
0.100	1.80	60°C
0.150	1.80	60°C
0.200	1.80	60°C
0.100	1.75	60°C
0.100	1.80	60°C
0.100	1.85	60°C
0.100	1.80	50°C
0.100	1.80	60°C
0.100	1.80	70°C

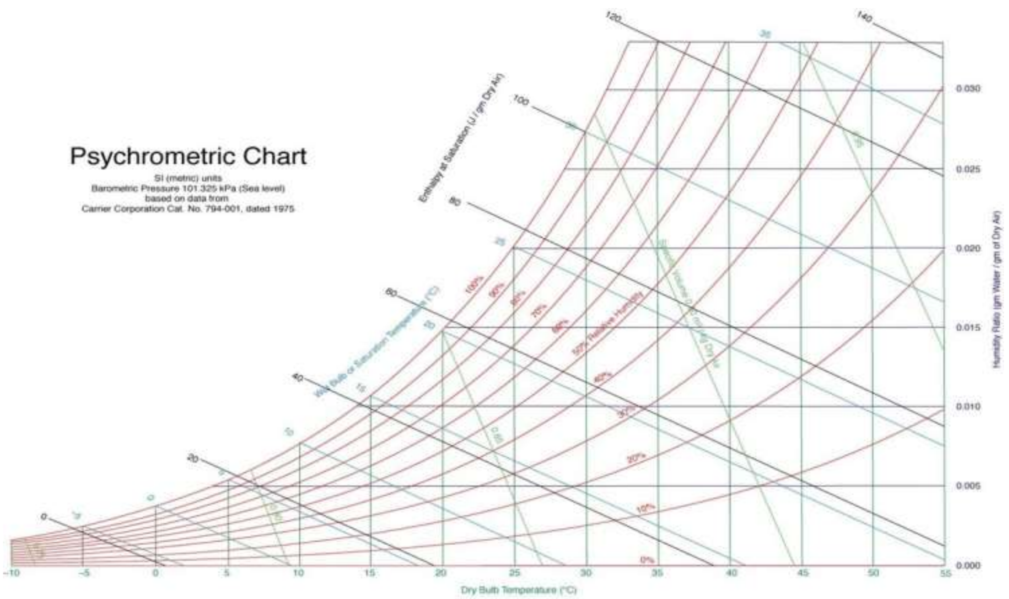

Figure 3.2: Estimation of humidity in air by using the humidity chart

Figure 3.2 illustrates the procedure for determining the humidity of air. The outlet air humidity is estimated from the humidity chart. Based on the difference between the humidity of inlet air and outlet air the humidity value is calculated. This value is equal to the loss of moisture from food grains. The difference between the initial moisture and the moisture loss at that time gives the moisture present in the sample at that time which is denoted as **X.** The drying kinetics data for all the food grains were found to moisture ratio (**MR**) versus drying time (t). The moisture ratio (**MR**) is determined by using equation 3.7.

$$\boldsymbol{MR = \frac{M_t - M_e}{M_0 - M_e}} \rightarrow (\mathbf{3.7})$$

where,
M_t is moisture content at time (t)
M_0 is moisture content at time t = 0
M_e is equilibrium moisture content

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Vol-14, Issue-6, No.04, June: 2024

Table 3.4: Experimental Drying Kinetics Data in Fluidized Bed

(A) Drying kinetics of Chana dal									
Time(min)	MR Air velocity = 1.80m/s Solid holdup = 0.100 kg			MR Temperature = 60ºC Solid holdups = 0.100 kg			MR Temperature = 60ºC Air velocity = 1.80m/s		
	50ºC	60ºC	70ºC	1.75m/s	1.80m/s	1.85m/s	100g	150g	200g
0	1	1	1	1	1	1	1	1	1
5	0.81	0.75	0.705	0.81	0.78	0.74	0.75	0.89	0.921
10	0.69	0.62	0.54	0.67	0.6	0.54	0.625	0.78	0.83
15	0.57	0.5	0.411	0.55	0.48	0.42	0.5	0.68	0.73
20	0.45	0.37	0.294	0.45	0.37	0.3	0.375	0.57	0.63
25	0.34	0.25	0.176	0.34	0.25	0.18	0.25	0.478	0.53
30	0.23	0.15	0.1	0.23	0.15	0.09	0.16	0.376	0.43
35	0.13	0.06	0.03	0.14	0.07	0.02	0.062	0.275	0.34
40	0.05	0	0	0.06	0	0		0.173	0.238

4.0 Results and Discussions

4.1 Drying Kinetics in Fluidized Bed Dryer

The drying of Chana dal is conducted in fluidized bed dryer at various drying conditions of drying medium (air) temperature, Air velocity, and solid holdup. During the drying, the kinetics data were analyzed and found the effect of temperature, velocity and solid holdup on drying kinetics in a fluidized bed dryer. For the discussion of obtained results, the drying temperature of 50, 60, 70ºC, the air velocities of 1.75, 1.80,1.85 m/s and solid holdups of 0.100, 0.150, 0.200 kg were considered.

4.1.1 The Effect of Drying Medium Air) Temperature on Drying Kinetics

The figure 4.1 shows the effect of temperature on drying kinetics for Chana dal. From these figures it can be known that the drying rates are low at lower temperatures than at higher temperatures. At higher drying temperatures in bed there exists a higher intra-particle moisture diffusion which leads to increase in drying rate. The falling rate period is more predominant during the drying of food grains. The constant rate period is insignificant. The experimental data obtained for all the food grains are similar in trend which is having relation with concepts of mass transfer.

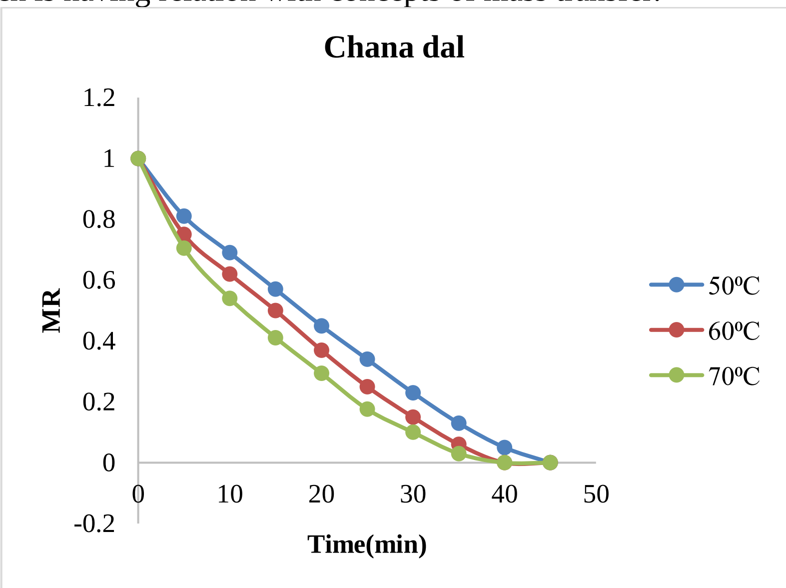

Figure-4.1: Effect of Drying Medium (Air) Temperature (0.100 kg of Chana dal and 1.80 m/s Air Velocity)

4.1.2 Effect of Air Velocity on Drying Kinetics in Fluidized Bed Dryer

The figure 4.2 shows the effect of drying medium (air) velocity on drying kinetics of food grains such as Chana dal. The increase in the velocity of the drying medium (air) reduced the external resistance for mass transfer which leading to a higher transfer rate. The intra-particle moisture diffusion controls drying during the falling rate period. However an increase in the velocity of the drying medium results in dispersion of diffused moisture from solids in a larger volume of inlet air, which results in higher bed temperature. The higher bed temperature leading to higher diffusion of moisture results in increase in drying rate.

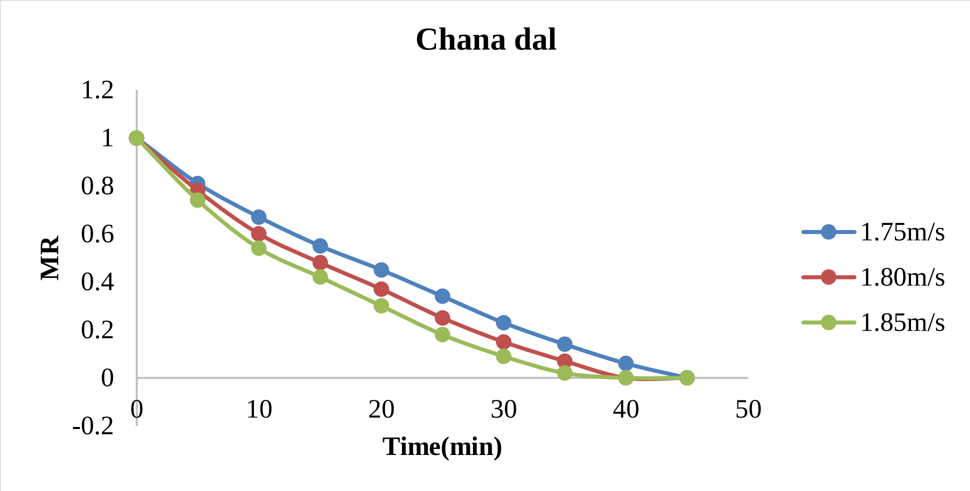

Figure-4.2: Effect of Drying Medium (Air) Velocity (at 0.100 kg of Chana dal and 60°C Temperature)

From the above figure it is observed that the increased air velocity increases rate of drying and also at given drying conditions, the moisture removal is more for 1.85m/s velocity for all the food grains.

4.1.3 Effect of Solid holdup on Drying Kinetics

Figure 4.3 show the effect of solid load in the fluidized bed on drying kinetics. An increase in solid load is observed to decrease drying rate. It is due to the lower effective bed temperature at higher solid load. Similar trend is observed in cases of drying of all the food grains.

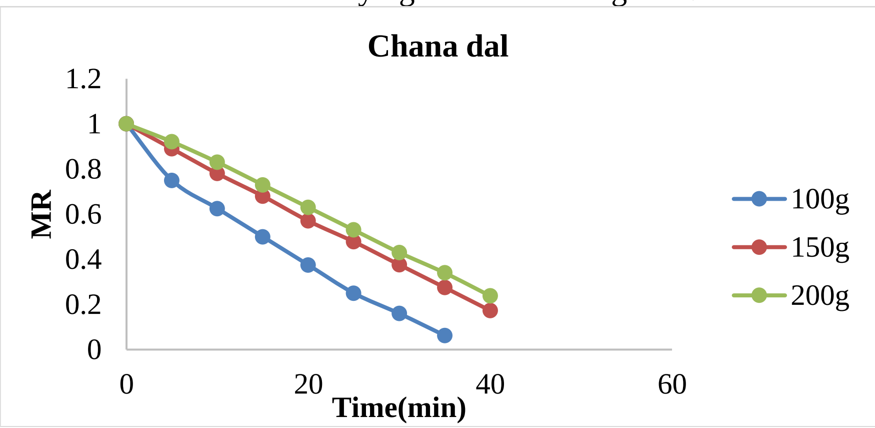

Figure-4.3: Effect of solid holdup (at 60°C temperature and 1.80m/s Air Velocity)

The higher the solid load leading to the lowering of the bed temperature, which decreases the drying rate. The larger quantity of moisture diffuses from the solids resulting in a lower bed temperature which leading to lower drying rates

4.2 Modeling of Drying Kinetics in Fluidized Bed Drying

4.2.1 Newton's Model

The drying rate is observed to increase significantly with increase in temperature and air velocity, while decrease with increase in solid holdup. The duration of constant rate period is insignificant, considering the total drying period and kinetics are expected to follow the Newton's exponential decay model. This model assumes no internal resistance to moisture movement from within the solids to surface of the food particles. As per this, drying rate is proportional to material being dried and equilibrium moisture content in drying air condition, the moisture ratio (MR) can be calculated using equation (4.1).

$$MR = \frac{M_t - M_e}{M_0 - M_e} = e^{(-kt)} \rightarrow (4.1)$$

To verify this model parameters **k,** the **ln (MR)** versus time**(t)** data calculated from the kinetics data obtained during the drying for all the food grains such as Chana dal. The **ln (MR)** versus **t** is plotted in figures 4.4 to 4.6 Newton Model parameters is predicted for various operating conditions maintained in fluidized bed dryer for all the food grains. The **k** values were estimated from these figures and are tabulated in 4.1.

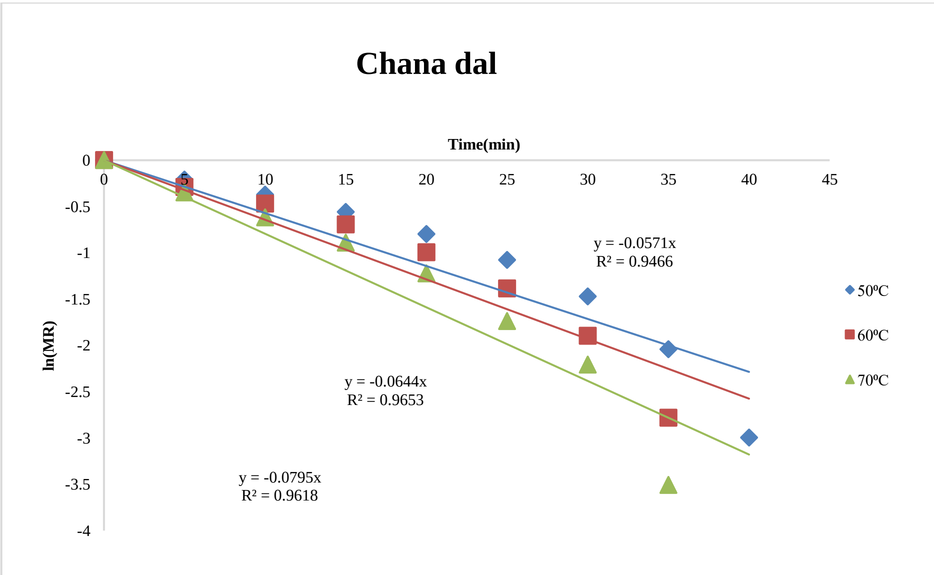

Figure- 4.4: Prediction of Newton model with experimental data (at 0.100 kg Chana dal and 1.80m/s Air Velocity, effect of temperature 50, 60 and 70ºC)

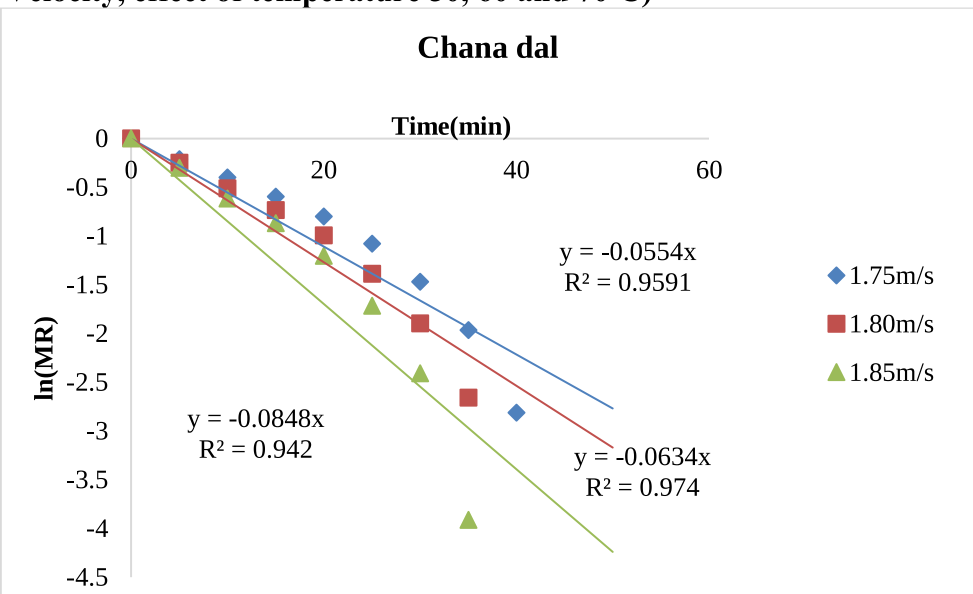

Figure-4.5: Prediction of Newton Model with experimental data (at 0.100 kg of Chana dal and 60ºC Temperature, 1.75, 1.80, 1.85m/s Effect of Air Velocity)

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Vol-14, Issue-6, No.04, June: 2024

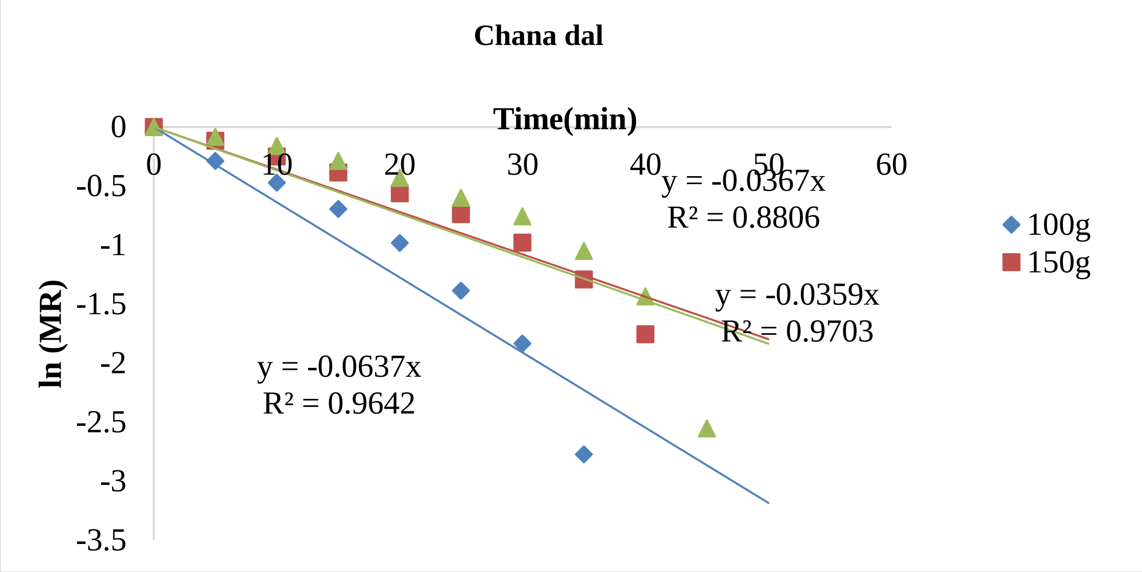

Figure-4.6: Prediction of Newton Model with Experimental data (at 1.80m/s Air velocity, 60°C Temperature and effect of solid holdups of Chana dal 0.100, 0.150, 0.200 kg)

Table 4.1: The evaluated *k* values for Newton Model in fluidized bed dryer
Newton Model parameters(k) Values obtained from ln (MR) versus time (t)

Drying conditions	Chana dal
0.100 kg, 1.80m/s, 50°C	0.0571
0.100 kg, 1.80m/s,60°C	0.09466
0.100 kg, 1.80m/s,70°C	0.0795
0.100 kg, 60°C, 1.75m/s	0.0554
0.100 kg, 60°C, 1.80m/s	0.0634
0.100 kg, 60°C, 1.85m/s	0.0848
1.80m/s, 60°C,0.100kg	0.0637
1.80m/s, 60°C,0.150kg	0.0359
1.80m/s, 60°C,0.200kg	0.0367

4.2.2 Page Model: Page Model is also recommended with a modification of two empirical-constants exponential model to correct its time decaying pattern of drying kinetics. In this model, the duration of constant rate period is negligible and falling rate period is predominant. This model can be represented by following equation (4.2).

$$MR = \frac{M_t - M_e}{M_0 - M_e} = e^{(-kt^n)} \rightarrow (4.2)$$

Where "n" is exponential constant
The equation (4.2) can be modified by applying logarithms on both sides as

$$\ln(MR) = -kt^n \rightarrow (4.3)$$

Then equation (4.3) is further modified as

$$\ln(\ln(MR)) = -\ln(k) - n\ln(t) \rightarrow (4.4)$$

The experimentally obtained drying kinetic data were used to estimate the Page Model parameters (***k*** and ***n***) by plotting ln $(\ln(MR))$ versus ln (t). Figure 4.7 to 4.9 explains the procedure how Page Model parameters are predicted for various drying conditions for all the food grains. The estimated parameters are tabulated in table (4.2).

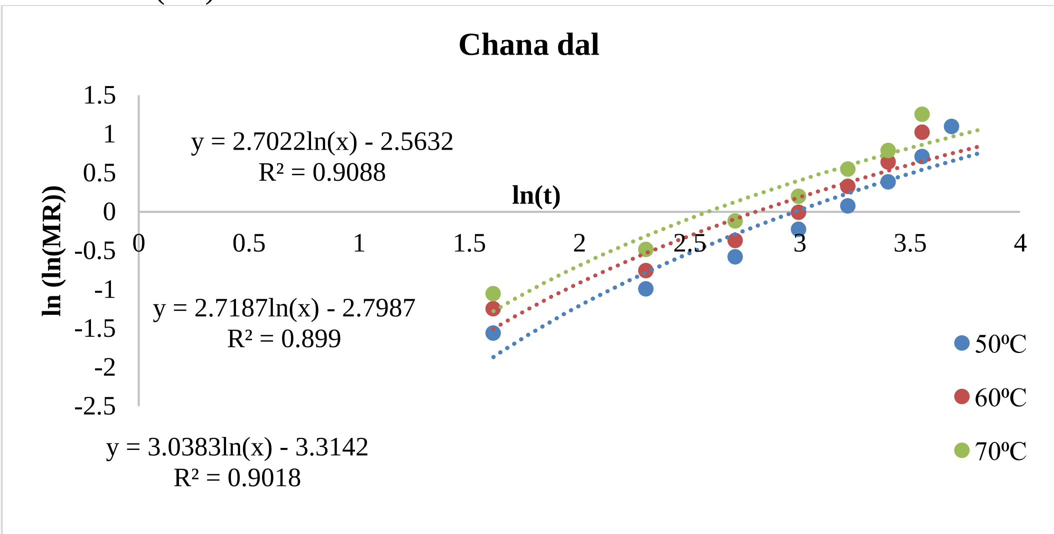

Figure-4.7: Prediction of Page model with experimental data (at 0.100 kg Chana dal and 1.80m/s Air Velocity, effect of temperature 50, 60 and 70ºC)

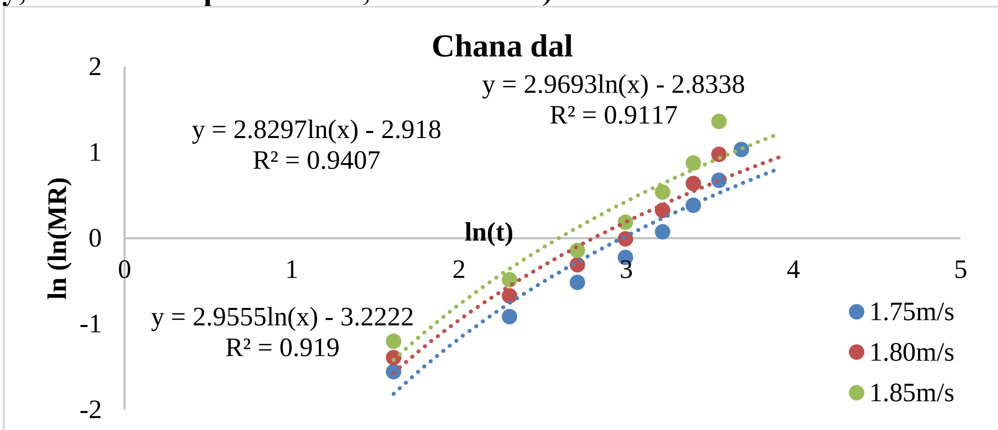

Figure-4.8: Prediction of Page Model with experimental data (at 0.100 kg of Chana dal and 60ºC Temperature, 1.75, 1.80, 1.85m/s Effect of Air Velocity)

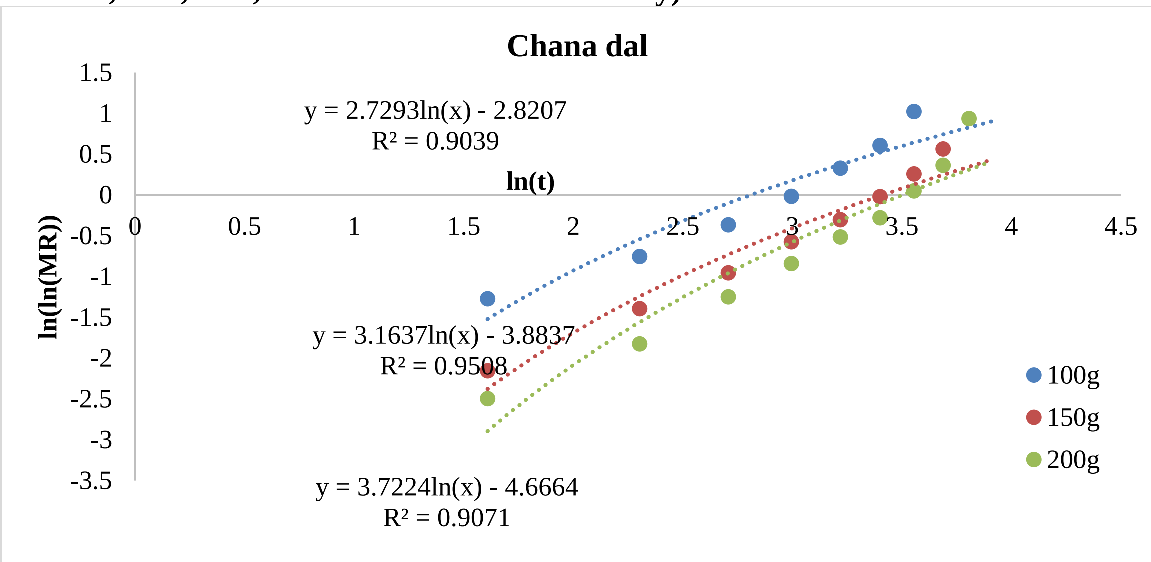

Figure-4.9: Prediction of Page Model with Experimental data (at 1.80m/s Air velocity, 60ºC Temperature and effect of solid holdups of Chana dal 0.100, 0.150, 0.200 kg)

Table-4.2: The evaluated k and n values for Page Model in fluidized bed dryer

Page Model parameters (k) Values obtained from ln (MR) versus time ln(t)

Drying conditions	Chana Dal	
	k	n
0.100 kg, 1.80m/s, 50ºC	0.0364	3.0383
0.100 kg, 1.80m/s,60ºC	0.0609	2.7187
0.100 kg, 1.80m/s,70ºC	0.0771	2.7022
0.100 kg, 60ºC, 1.75m/s	0.0399	2.9555
0.100 kg, 60ºC, 1.80m/s	0.054	2.8297
0.100 kg, 60ºC, 1.85m/s	0.0588	2.9693
1.80m/s, 60ºC,0.100kg	0.0596	2.7293
1.80m/s, 60ºC,0.150kg	0.0206	3.1637
1.80m/s, 60ºC,0.200kg	0.00941	3.7224

5.0 Comparison of Models with Experimental Drying Kinetics

All the model predictions for various operating conditions were compared with experimental drying data for all the food grains from Figures 5.1 to 5.2. It was found that Newton Model is fitted with the experimental kinetics in drying period. From the table 4.1 the k values increased with increase in temperature and increased with increase in velocity and decreased with increase in solid holdups. The model parameters can be utilized to estimate the drying time as well as for the design and scaleup of the drying process

Page model is not fitted with the experimental kinetics in drying period. Page model is deviating with experimental values for all the food grains. It can be seen from the Figures 4.1 that the Page model not matching the experimental data. However from the table 4.2, it can be seen that the coefficient **k** is increasing with increasing temperature for Chana dal but not for other grains and deviations in the **k** values of Mustard seeds, Ragi and Wheat.

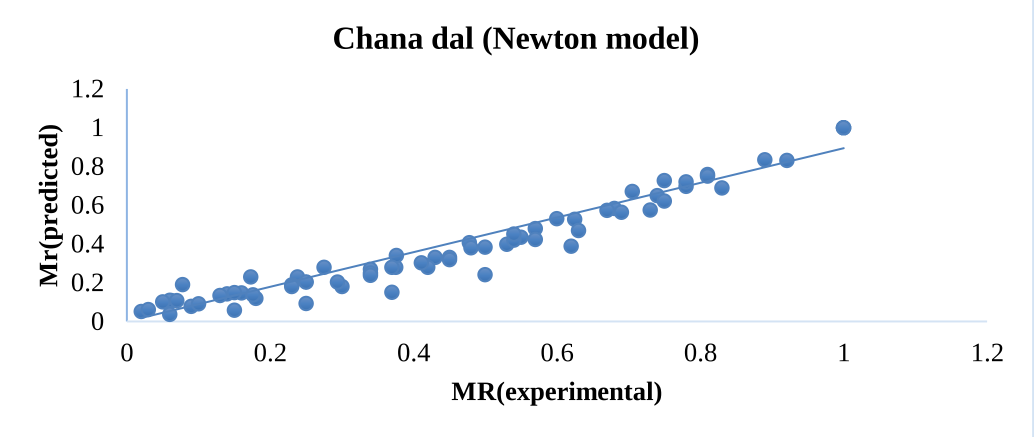

Figure – 5.1: Comparison of Newton Model with experimental drying of Chana dal

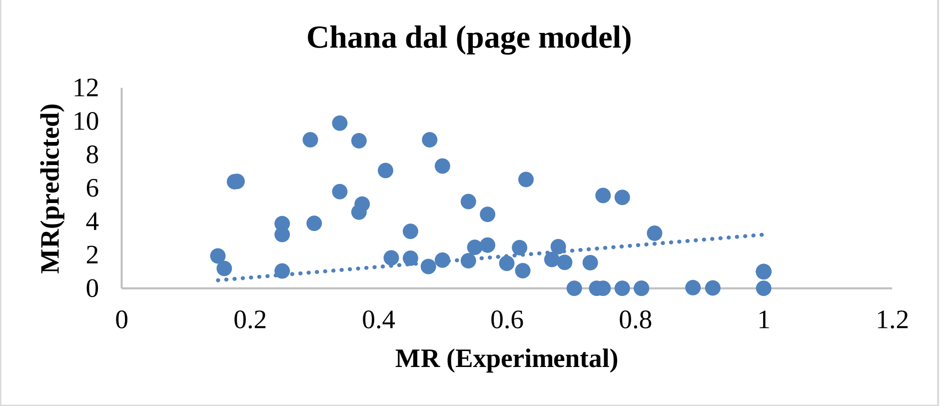

Figure-5.2: Comparison of Page model with experimental drying kinetics of Chana dal

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6.0 Conclusion:

The drying of Channa dal is conducted in a fluidized bed dryer under varying conditions, including drying medium (air) temperature, air velocity, and solid holdup. During the drying process, kinetics data were analyzed to determine the effects of temperature, velocity, and solid holdup on drying kinetics in a fluidized bed dryer. For the discussion of the results, drying temperatures of 50, 60, and 70°C, air velocities of 1.75, 1.80, and 1.85 m/s, and solid holdups of 0.100, 0.150, and 0.200 kg were considered.

The drying rates are lower at lower temperatures compared to higher temperatures. At higher drying temperatures, increased intra-particle moisture diffusion leads to a higher drying rate. The falling rate period is more predominant during the drying of food grains. The drying rate also increases with higher air velocity, as increased velocity improves convective heat transfer to the material. Faster air effectively carries away moisture, reducing the boundary layer thickness and causing quicker evaporation from the material. However, an increase in solid holdups decreases the drying rate. With more solid material, air flow and circulation through the material are reduced. A higher solid holdup increases the bed thickness, thereby increasing the resistance to heat and mass transfer.

7.0 References:

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