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Research Paper

Modification and performance evaluation of pneumatic fluidized bed dryer

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ABSTRACT

The study focused on the modification of a pneumatic dryer for easing the process of sample intake and removal. A lever type arrangement was developed with hot air blown from the bottom to assess the working of the dryer. The performance evaluation of the dryer was conducted on potato (*Solanum tuberosum*) at different temperatures (60, 50 and 80^{o} C), cube sizes (1 and 1.5 cm^3) and treated with Sodium Meta Bisulphite (NaMS). The results were assessed through drying models for the appropriateness in characterizing the drying behaviour of potato. The results indicated the maximum dehydration ratio of 0.36, rehydration ratio of 1.90 at 80^{o} C for 1 cm^3 size. Moreover, the shrinkage percentage of 78.4 was recorded for 1 cm^3 at 60^{o} C, which was comparatively lower than 48.8 at 80^{o} C temperature. The colour change, that defined the visible change was 20.0 for 1.5 cm^3 at 80^{o} C and 1.71 for 1 cm^3 at 60^{o} C temperature. The optimization of the data through design expert 13.0 revealed the response value of 4.58, 24.97 and 5.0 for 80^{o} C temperature, 1 cm^3 cube size and 0% NaMS, respectively. The study can be beneficial for utilizing the pneumatic fluidized bed dryer for different crops for improvement in shelf life and nutrient quality.

Key words: Modification, optimization pneumatic dryer, potato, rehydration ratio

The removal of the moisture is perceived as critical to enhance the shelf life and preserve the nutritional quality of agricultural produce. It is the basic step in extracting the water before packaging and distribution process. Drying is fundamentally a mass transfer process where internal moisture migrates to the external surface of the material and evaporates into the surrounding atmosphere (Dasore *et al.,* 2020). The non-availability of sufficient moisture in the product reduces the microbial growth and hinders the biochemical reactions, thereby, improving the shelf life (Goncalves et al., 2023). Drying improves the availability of food products in off-seasons and preserves nutritional quality, color, and aroma (Rashid *et al.* 2022*).* The quality of the dried product depends on the method of drying and type of equipment employed (Gasa *et al*., 2022). In agricultural processing, drying not only reduces the bulk and weight of produce but also enhances handling, packaging, and transportation efficiency. However, the drying process is energy intensive owing to high amount of latent heat requirement and low efficiency of industrial dryers.

Sweet potato (*Ipomoea batatas* L.) with low glycemic index and high nutritional value is valued as essential to ensure the nutritional security of the people across the globe (Gasa *et al*., 2022). According to Gonclaves *et al*., 2023, the potato is cultivated in 8 million hectares with production of 92 million tonnes. However, the high percentage of moisture of 48.0 – 53.3% reduces the shelf life and induces challenges in transportation from production to consumption site (Nwakuba et al., 2016). It is widely believed that modern drying technologies can help in increasing the shelf life of sweet potato and improve its value (Vivek *et al*., 2021). However, applying high temperature can cause severe damage and structural collapse (Mujumdar, 2014). The drying process with manual and conventional methods are used for centuries, leveraging natural heat and air circulation for moisture removal. However, they are dependent on climatic conditions and often result in uneven drying and microbial contamination. On the other hand, advancements in drying technology have led to improved methods that reduce energy consumption and processing time while maintaining product quality. The modern drying methods like freeze drying, infrared, vacuum, microwave, pneumatic, fluidized bed drying and wind drying are adopted for different crops. Moreover, modern techniques provide controlled environments that significantly reduce drying time and improve consistency of the products Considering the global demand for extended shelf life and high-quality food products, optimizing drying processes has become increasingly important. Fluidized bed dryer, in particular, is prioritized due to its high thermal efficiency and low initial cost per square meter (Barathiraja *et al*., 2021). Due to intense gas-solid interaction and uniform heat transfer, fluidized-bed dryers offer significantly faster drying and up to 35% energy savings over conventional methods (Majumder *et al.*, 2022; Tupe & Kunde, 2024). This study focusses on the improvement of pneumatic fluidized bed dryer for sweet potato shred into small cubes and blanched in Sodium Meta Bisulphite (NaMS) solution. It also assessed the appropriateness of drying models to describe the drying potential of sweet potato.

MATERIALS AND METHODS

Modification of pneumatic dryer: The study initiated with the modification of lifting mechanism of pneumatic dryer. The fluidized bed dryer was modified to reduce the efforts in inserting the samples and removing after the completion of the experiment. The modification was also supposed to increase heat transfer and reduce the drying period. In the experimental process, the pneumatic dryer has a column in which samples need to be placed and hot air blown at the bottom. The removal of the sample was tedious as it requires the removal of column and then fitting it again at its respective place, Fig. 1. This process consumes time, labour and energy.

The modification involves the installation of a metallic strip between two round supports to permit up and down motion of the glass tube. A perforated mesh type bowl was placed below the drying chamber to distribute the moisture evenly and ensure uniform drying of the samples. The diameter and the height of sample holder were selected in such a way that it provides easy loading and unloading of samples. The height and diameter of the sample holder was made about 5 and 4.5 cm respectively. This modification allowed different sizes of granular materials to be tested in pneumatic dryer.

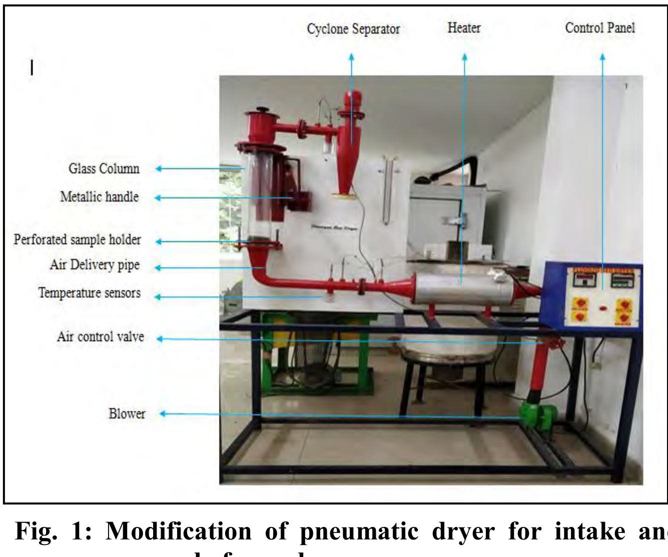


Fig. 1: Modification of pneumatic dryer for intake and removal of samples

Experimental setup: The evaluation of the pneumatic dryer was carried out according to the plan of the experiment, Table 1

Table 1: Experimental methodology for evaluation of modified pneumatic fluidized dryer

Parameters	Range	Responses
Temperature	60, 70 and 80° C	• Rehydration ratio
Size of cubes	1 and 1.5 cm^3	• Moisture ratio
		• Colour change
Chemical Treatment	Sodium Meta Bisulphite (NaMS)	• Shrinkage percentage

The preparation of the samples follows the trend of sorting, washing, cubing, blanching and drying, Fig. 2.

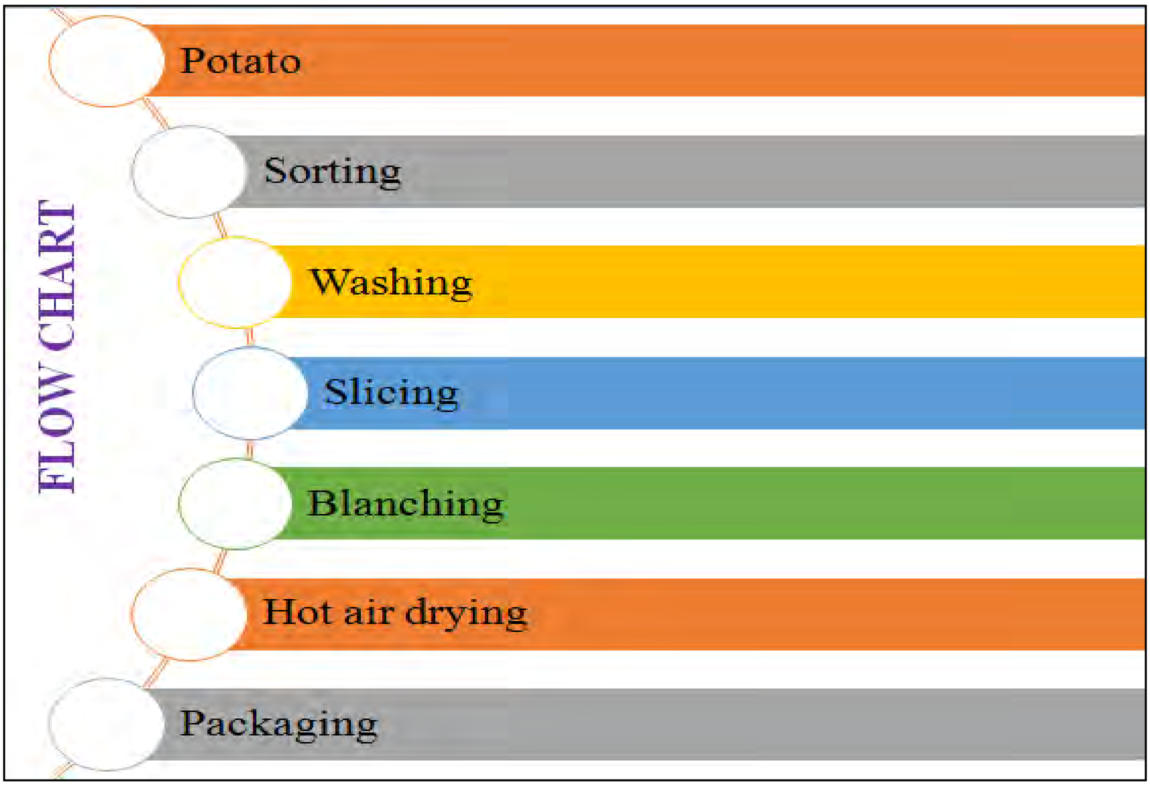


Fig. 2: Flow chart of the study

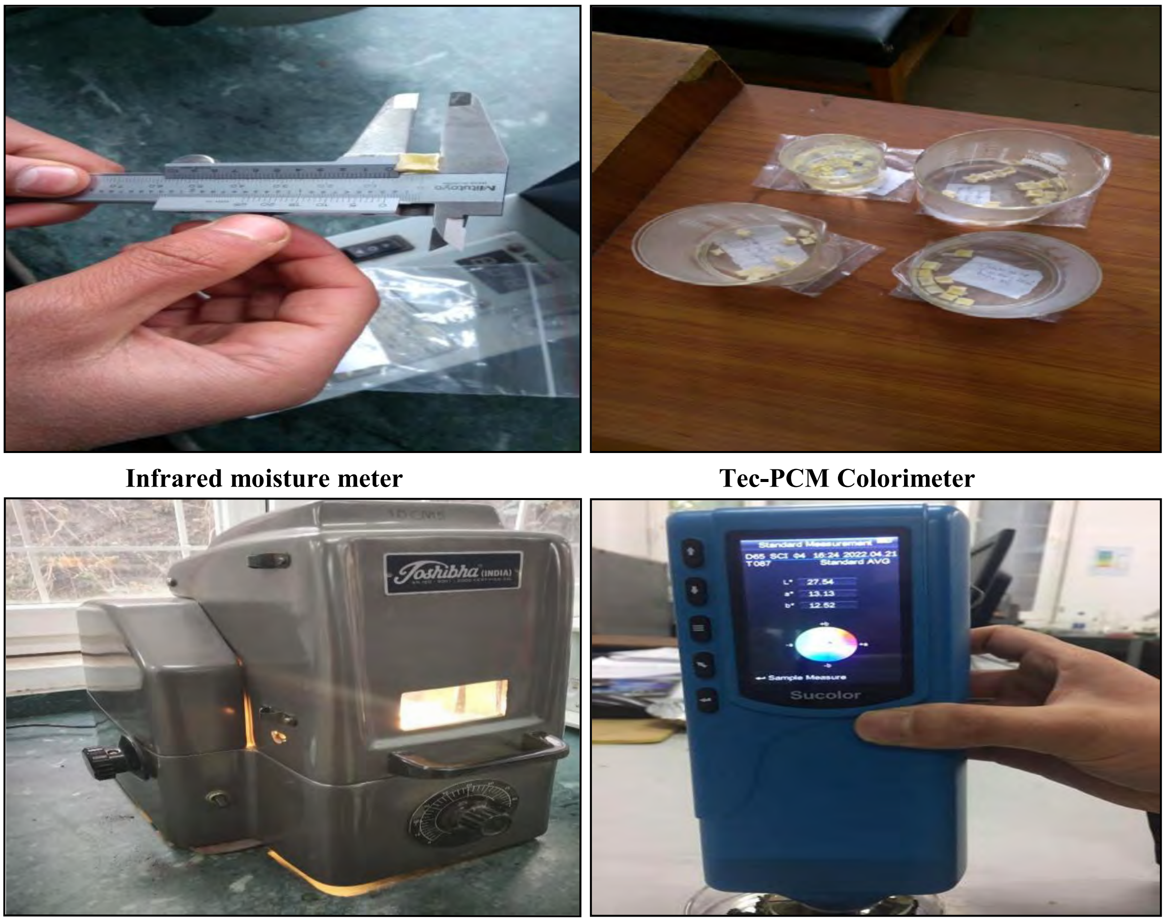
The sweet potatoes of Kufri Jyoti variety having uniform oval shape and large tuber size, preferably free from any defect were sorted out by hand picking and potatoes showing the sign of infection and infestation were separated. The sorted potatoes were splashed in cold water to eliminate soil and dust particles. Washed potatoes were cut in 1 cm^3, and 1.5 cm^3 cubes with a manual slicer fabricated in the department. The samples were then pretreated before drying them in the hot air oven. For blanching, 4.5 grams of NaMS was mixed in 450 ml of water to form 1% NaMS solution (Billah *et al.* 2025). About 50 grams of washed potato cubes were weighed & tied in a muslin cloth. The cubes were then dipped in 150 ml of the prepared solution for 5 minutes as per the reviews & the result obtained in the preliminary experiments to maintain a solid to solute ratio of 1:3. After 5 minutes the cube were removed and weighed again. The variety was chosen for its compatibility with product characteristics like heat sensitivity and moisture content, as well as its local availability. This ensures both efficient drying performance and cost-effective, sustainable sourcing for industrial use.

Drying models: The moisture content of the potato cubes were predicted with the help of drying models. These models describe the characteristics of potato cubes as the representative of the agricultural crops (Gasa *et al.,* 2022; Rashid *et al.* 2020). The appropriateness of three models - Power law, two term exponential and Midilli model were tested with the help of non-linear regression technique. The comparative analysis was performed on the three models in terms of coefficient of determination (R^2) and standard error of estimation (SEE).

$MR = At^b$	Power law (PL) model
$MR = ae^{-kt} + (1-a)e^{-kat}$	Two term exponential (TTE) model
$MR = ae^{-kt^n} + bt$	Midilli model

Measurement of response parameters:

Moisture content and moisture ratio: The moisture content defines the availability of the moisture in the sample. It was measured with the help of Gravimetric method, The samples were weighted and placed in hot air oven maintained at temperature of 105 °C for 24 hours and the difference in the initial weight (W_w) and final weight (W_d) (Malik *et al.* 2023), Fig. 3.



Infrared moisture meter **Tec-PCM Colorimeter**

Vernier caliper for potato cubes **Potato cubes in petri dish**

Fig. 3: Instruments used for the determination of response parameters

Moisture ratio, on the other hand, is the ratio of moisture content during drying and drying at zero time (Pezo *et al*. 2024). The standard formula involving M (moisture content at drying phase); M_o (moisture content at initiation; M_e (equilibrium moisture content) was employed for the measurement of moisture ratio.

$$Moisture\ Content\ (\%wb) = \frac{W_w - W_d}{W_w} ------(1)$$

$$Moisture\ Ratio = \frac{M - M_e}{M_o - M_e} --------------(2)$$

Rehydration ratio: The rehydration ratio was conducted on a 20-minute experimental trials. Two-gram sample was dipped in 100 ml boiling water maintained at 98°C for 20 minutes. The mixture was allowed to settle and cool to reach to room temperature. The final weight of the samples was recorded (Salehi *et al*. 2022). The ratio of rehydrated weight (R_w) and dehydrated weight (D_w) was used for the measurement of rehydration ratio.

$$Rehydration\ ratio = \frac{R_w\ (\text{rehydrated weight})}{D_w\ (\text{dehydrated weight})} ---------------(3)$$

Shrinkage percentage: The shrinkage percentage defines the drying quality of the product. It is perceived as critical as it directly influences the rehydration process of the product. The shrinkage percentage was measured from the difference of the size of potato cubes, before and after drying process (Mayor *et al*.2004). The electronic vernier calliper was used for the measurement.

$$Shrinkage\ Percentage = \frac{\text{Final size}(S_f) - \text{Initial size}(S_i)}{\text{Initial size}(S_i)} ----- (4)$$

Colour change: The Colour of the dried sample was evaluated in three replications with the use of a hand-held Colour Tec-PCM reflective colorimeter, Fig. 3. Colour values were recorded as L= lightness (0=black, 100=white), a (-a=greenness, +a = redness), and b (–b=blueness, +b = yellowness). Total colour change was calculated using Eq. (5) (Faisal *et al.* 2018) as:

$$\Delta E = \sqrt{(L - L*)^2 + (a - a*)^2 + (b - b*)^2} ------------(5)$$

Where,

ΔE is the Colour change.

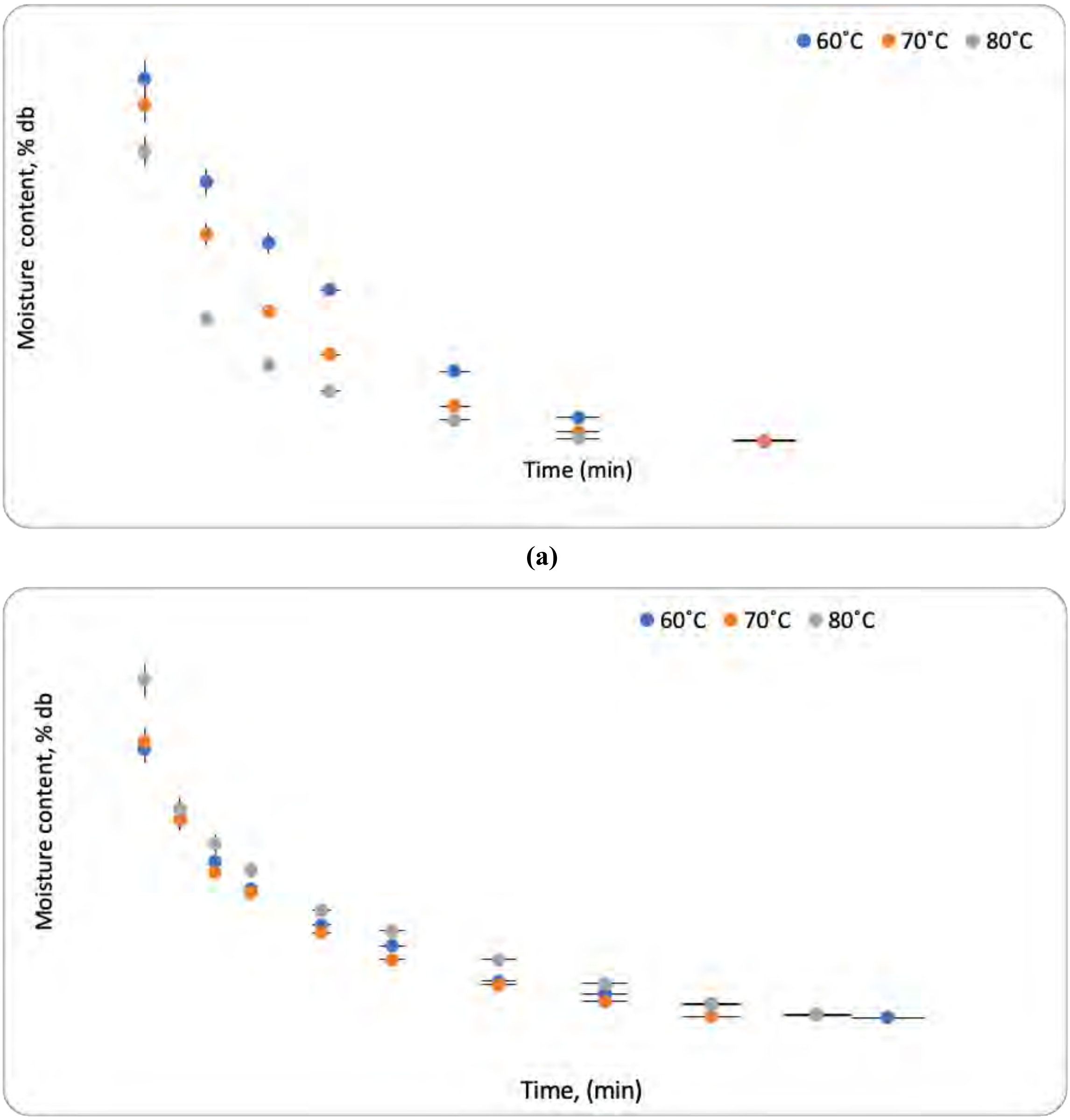
L, a and b represents Lightness, Redness and Yellowness.

L*, a* and b* represents final Lightness, Redness and Yellowness.

Statistical analysis and optimization: The analysis of the data was carried using Design Expert 13.0 and Analysis of variance (ANOVA). The qualitative parameter evaluation of dried products was carried out on the basis of response variables viz. Dehydration and Rehydration ratio, Shrinkage percentage and the colour change (Laskar *et al.* 2023) at 5% level of significance. The values of dehydration and rehydration ratio were set to maximize while percent shrinkage and colour change values were set to minimized in order to have a compromised optimum value of independent variables as well as responses.

RESULTS AND DISCUSSIONS

Effect of temperature on moisture content: The data revealed that the initial moisture content ranged from 80.0 % to 81.0 % (wet basis) at zero time of drying. It was observed that an increase in temperature from 60° C to 80° C, resulted in the reduction in time duration for 1 cc potato cubes, Fig. 4(a). At 60° C, the decrease in the moisture was rapid at the initial phase and gradually reduces after 30 minutes time interval. The experimental trials highlighted that the 90 minutes time interval created a phase of less moisture removal and arrival of asymptotic stage. This behavior aligns with typical fluidized bed drying patterns, where drying rate decreased after the constant-rate period (Majumder & Deb, 2022; Borkar *et al.*, 2023). Similar asymptotic behavior has been documented in drying studies of rice and pharmaceutical granules (Kale *et al.*, 2021). Consequently, the time required to bring down the moisture content to a safe level for the samples blanched in NaMS solution at 60°C was 100 minutes for the sample blanched in NaMS solution. A similar observation was witnessed at 70° C and 80° C and drying time was recorded as 100 minutes and 70 minutes, respectively. For 1.5 cc potato cubes, the impact of air temperature and blanching with NaMS solution was similar to that of 1 cc potato cubes, Fig. 4(b).



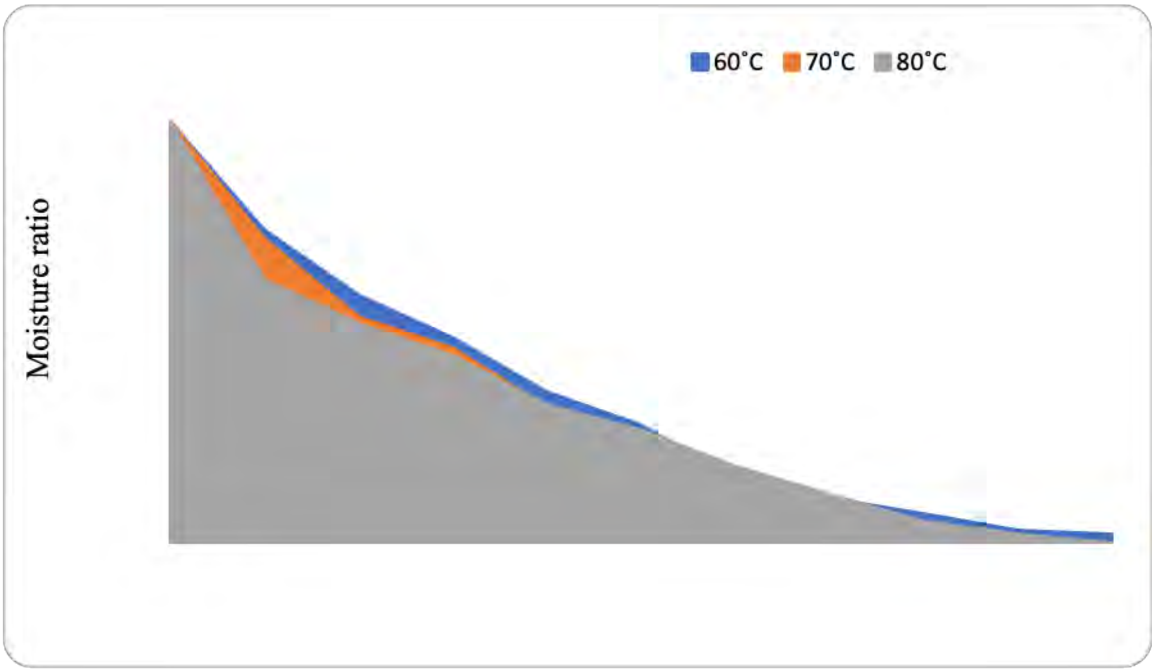
(a)

(b)

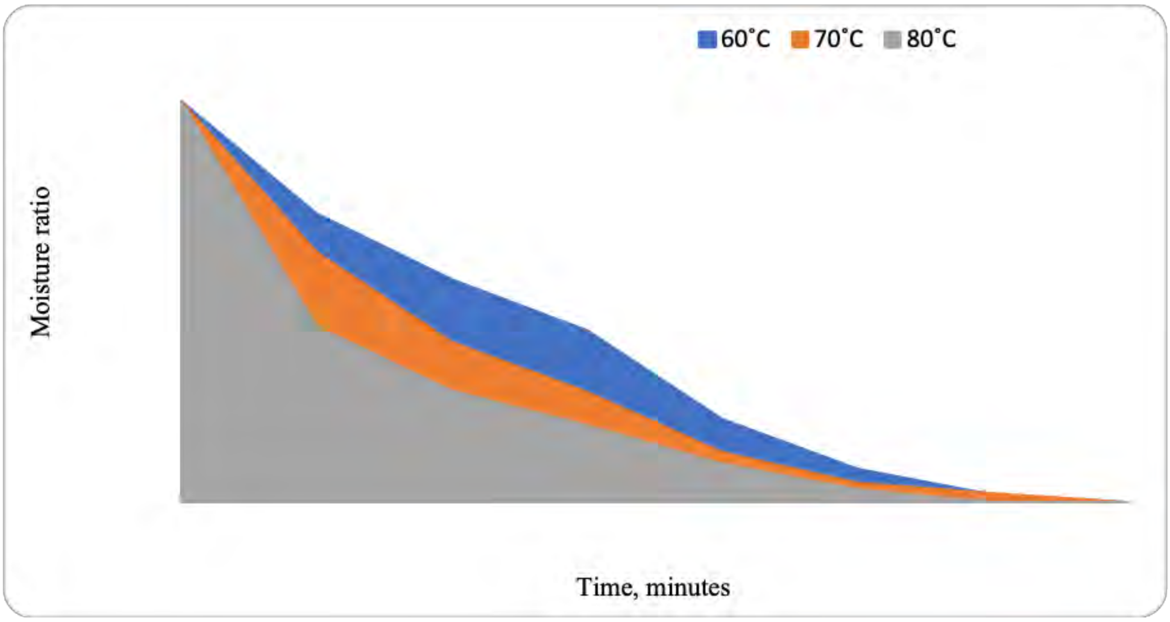
Fig. 4: Effect of air temperature on drying a) 1 cc b) 1.5 cc potato cubes

However, the gap was much smaller in comparison to 1 cc potato cubes blanched with NaMS and treated at different temperatures. The time required to reach the desired level of moisture content for the samples blanched with NaMS and treated at 60 °C was 210 minutes. Moreover, the time at 70°C and 80°C was 160 minutes and 190 minutes, respectively. The time for drying was higher in case of 1.5 cc cubes in comparison to the time required for 1 cc cubes treated at different temperatures.

Variation in moisture ratio with temperature: The moisture ratio of the samples was calculated and plotted at different air-drying temperatures and different cube sizes to evaluate a comparative analysis of the same on drying characteristics of potato cubes, Fig. 5 a and b



(a)



(b)

Fig. 5: Effect of temperature on moisture ratio

The curves revealed that drying rate increased with higher temperatures and lower cube sizes for all experimental runs. It takes less time to achieve safe moisture content (approximately 10% on dry basis) at higher temperatures. Furthermore, for lower sample size drying rate was found higher and requires less time to achieve final moisture at the same temperature.

Effect of drying rate with time: The drying curves showed a constant drying rate for approximately 20 minutes, then transitioned into a falling rate period until the final moisture content was reached, Fig. 6 a and b.

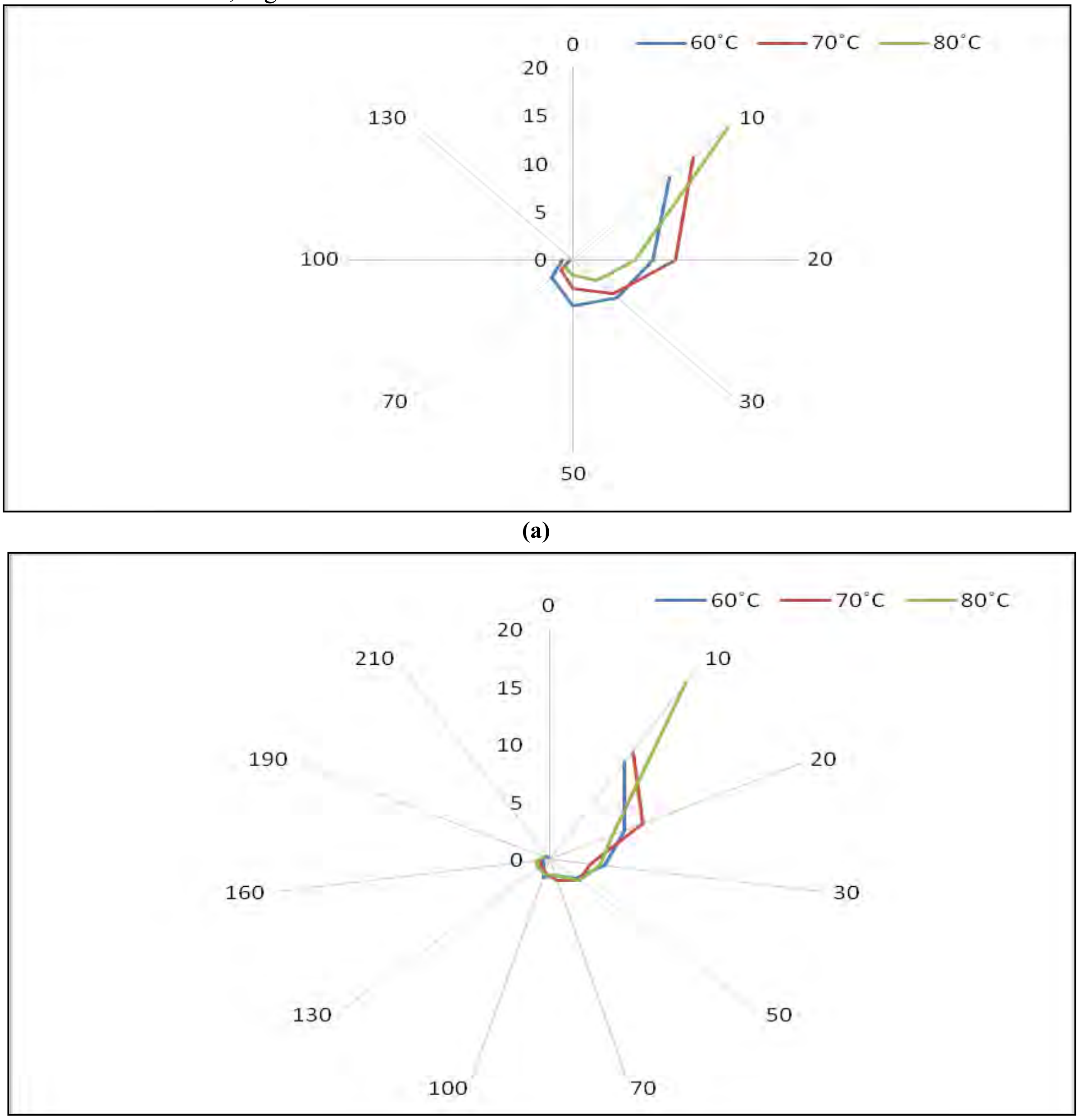


Fig. 6: Variation in drying rate with time

Since, potato is a high moisture food and provides a constant thin film of moisture enveloping its surface during constant rate drying through supply of moisture from interior to surface of the food to keep its surface wet.

It was observed that at higher drying air temperatures; the rate of drying was high and with larger cube size of 1.5 cc, the drying rate was comparatively lesser and require longer time to achieve final moisture content.

Change in shrinkage ratio and colour change: The results highlighted that shrinking ratio varied according to cube size and temperature, Table 2. The smaller cube size of 1 cc witnessed higher changes in comparison to 1.5 cc size cubes. The shrinkage percentage of 78.4 was observed with 1 cc at 60^{o} C, which was comparatively higher than 65.0 and 48.8 at 70^{o} C and 80^{o}

C, respectively. The reason can be attributed to the fact that lower temperature allowed changes at a slower rate. For higher cube size of 1.5 cc, the maximum shrinkage percentage of 76.3 was recorded at 60° C. This implies that cube size was not significantly influenced with the change in temperature. The colour change was influenced with size of the cubes and drying temperature. The colour change of 20.01 was significant with 1.5 cc at 80° C. At 60° C, the colour changes of 1 cc and 1.5 cc was 1.71 and 14.32 respectively. Since the lower temperature was inducing the

Parameters	Importance	Formula	Reference	Experimental trials					
Cube Size, cc	The size of the cube determines the efficiency of the drying process		-	1			1.5		
Temperature, degree Celsius	It is the most critical factor in drying process		-	60	70	80	60	70	80
Rehydration ratio		$\frac{R_w\ (\text{rehydrated weight})}{D_w\ (\text{dehydrated weight})}$	Salehi *et al.* 2022	1.30	1.41	1.90	1.10	1.28	1.60
Shrinkage percentage		$\frac{\text{Final size}(S_f)-\text{Initial size}(S_i)}{\text{Initial size}(S_i)}$	-	78.4	65	48.8	76.3	70	66
Colour change		$\sqrt{(L-L*)^2+(a-a*)^2+(b-b*)^2}$	Faisal *et al.* 2018	1.71	13.92	16.32	14.32	15.65	20.01

changes at slower rate, the change in colour was not significant at lower temperatures. However, the colour change was comparable at 70° C for 1 cc and 1.5 cc potato cube sizes, Table 2.

Table 2: Variation in response variables with independent parameters
Where, L, a and b represents Lightness, Redness and Yellowness; L*, a* and b* represents final Lightness, Redness and Yellowness

Model fitting: The analysis of the three models revealed that Midilli model has highest coefficient of determination (R^2) is lowest standard error of estimation (SEE), Table 3. This condition is perfect to serve as the representative of drying process of potato cubes in modified fluidized bed dryer. This signifies the relevance of Midilli model for the experimental study.

Table 3: Best fit model to characterise the drying behaviour of potato cubes

S No.	MODEL	R^2	S E E
1	Power law model	99.73	0.01
2	Two term exponential model	99.19	0.04
3	Midilli's model	99.92	0.01

The regression equation is essential for modelling the drying kinetics because it enables experimental data-based prediction of moisture content over time. The regression equation obtained from Midilli model is as follows:

$$MR = 0.999\, e^{-1.666\, t^{0.783}} + 0.023\, t$$

Where, t = drying time, minutes

Optimization: The numerical optimization of variables was carried out by using design expert 13.0 (Ali *et al.* 2024). It was observed that optimum value occurred with 1 cc potato cube size at

80° C with drying rate 0.35, rehydration ratio 1.867, shrinkage percentage 49.26 and colour change of 16.54, Table 4.

Table 4: Numerical optimization of the process variables

Name	Goal	Lower limit	Upper limit	Optimum value
Cube size, cm^3	Is in range	1.0	1.5	1.0
Temperature, °C	Is in range	60.0	80.0	80.0
Drying rate, % db/min	Maximize	0.13	0.36	0.35
Rehydration ratio	Maximize	1.1	1.9	1.86
Colour change, %	Minimize	11.714	20.012	16.54
Shrinkage percentage, %	Minimize	48.8	78.4	49.26

CONCLUSION

The study was initiated with the fabrication of a lifting mechanism to reduce the efforts in inserting and removing the samples in the drying chamber of pneumatic bed dryer. A metallic strip was placed in between two round supports to permit up and down motion of the glass tube covering the drying chamber of the sample. A perforated mesh type bowl was placed below the drying chamber to distribute the moisture evenly and ensure uniform drying of the samples. The whole intention was to convert the pneumatic bed dryer into fluidized bed dryer to incorporate different sizes of granular particles. The study concluded with the assertion that smaller cube of 1 cc results in higher reduction in moisture content, rehydration ratio, shrinking percentage and colour change. The overall acceptability of the optimized results was 1 cc cube size at 80°C temperature. The Midilli model with R^2 of 99.92 and SEE 0.0101 provided best fit model for the study. The study can be beneficial for drying food products in modified pneumatic dryer with higher efficiency.

CONFLIT OF INTEREST

All the authors affirm that there is no conflict of interest among them. All research activities comply with relevant legal, institutional and ethical standards.

AUTHOR CONTRIBUTION

All the authors contributed equally in the present study.

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