Investigation on thin-layer drying kinetics of sprouted wheat in a tray dryer

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Abstract

The thin-layer drying behavior of sprouted wheat (cv. PBW 550) was experimented at different drying periods, such as 24 h, 36 h and 48 h. The samples were dried in a tray dryer at 50–80°C at an interval of 10°C. The moisture ratio was fitted to the six thin-layer drying models, and the performance of the models was assessed by statistical parameters. The Wang and Singh model has accurately predicted the drying behavior of sprouted wheat for all sprouting periods and drying temperatures. In addition, the effective moisture diffusivity of grain sprouts at three drying periods (24 h, 36 h and 48 h) of sprouted wheat was increased from 1.79×10^{-9} to 2.58×10^{-9} $m^2 s^{-1}$, 1.921 $\times 10^{-9}$ to 2.781×10^{-9} $m^2 s^{-1}$ and 1.858×10^{-9} to 2.561×10^{-9} $m^2 s^{-1}$ with increase in drying temperature from 50°C to 80°C. Moreover, at the above-stated drying periods, the activation energy for sprouted wheat was 11.357 kJ mol^{-1}, 11.428 kJ mol^{-1} and 9.427 kJ mol^{-1}, respectively. Therefore, thin-layer drying of sprouted wheat was successfully simulated between 50°C and 80°C for various drying periods. This study provided imperative information to understand the drying behavior and relationship between various drying parameters of sprouted grains that could produce nutritive functional flour.

Keywords: sprouted wheat; mathematical modeling; drying characteristics; effective moisture diffusivity; activation energy

Practical application

Consumers are liable for using health-promoting products obtained from various traditional food products. Wheat is an important food grain, popularly known for its flour being used in several food formulations over the decades. Nevertheless, the wheat flour has margins for shortage of amino acids, protein content, starch and excess of anti-nutritional and flatulence causing units that can be taken care of by one of the simplest methods called 'sprouting'. Before making flour, drying is a common procedure to preserve sprouted wheat grain for a longer duration without affecting its nutritional and sensory properties. Hence, drying with hot convective air in a controlled cabinet is faster and hygienic for industrial purposes. The present study deals with the thin-layer drying characteristics of sprouted wheat at different periods and air temperatures. Moreover, this study establishes the required level of moisture content of sprouted wheat flour to allow safe storage over a longer period and brings a substantial reduction in weight and volume, thereby minimizing packaging, storage and transportation costs.

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Introduction

Wheat is a very popular grain worldwide because of its agronomical adaptability, its flour utilization in different food formulations, and storage simplicity. However, the nutritional quality of wheat becomes inferior because of shortage in certain essential amino acids, gluten intolerance to a certain segment of the population, and lower protein and starch contents. Sprouting of grain enhances its nutritive value (Lemmens *et al.*, 2019; Liu *et al.*, 2022). Various nutritional elements, such as vitamins, minerals and some nutritional trace elements, are increased by sprouting (Akkad *et al.*, 2021; Ertaş, 2015; Marchini *et al.*, 2021). In addition, sprouting effectively reduces phytic acid and flatulence and generates oligosaccharides, such as stachyose and raffinose. Moreover, protein digestibility, as well as sensory properties, is enhanced (Faltermaier *et al.*, 2015; Seguchi *et al.*, 2010). The process of sprouting has been opted for cereal seeds since decades, as it softens the kernel structure and enhances their nutritional values by mitigating anti-nutritional factors. Furthermore, the flour produced from fermented and sprouted cereal seeds is available for *in vitro* protein and starch digestibility (Baranzelli *et al.*, 2018; Liu *et al.*, 2017). Improvement in nutritional properties is mainly affected by the type and quality of cereal seeds, sprouting, and drying conditions (Lemmens *et al.*, 2019). Hence, it affects quality and commercial application of grain. Sprouted grains can be kept for a few days to over a week under refrigeration. After drying, these can be used in various food products such as breakfast items, soups, pasta, cereal-based beverages and weaning foods. Therefore, information regarding distribution of moisture and temperature in food products should be known for designing of drying process and control of food quality.

The drying of food is one of the complex phenomena that tells its drying behavior. Optimization of drying behavior is a very tedious process and can be done by mathematical models (Delfiya *et al.*, 2022; Jeevarathinam *et al.*, 2021; Pravitha *et al.*, 2022). Among those models, the thin-layer drying empirical models are mainly considered based on the product characteristics. There are some relevant studies on the thin-layer drying of various foods, such as slices of red beetroot (Dasore *et al.*, 2020), lemon verbena leaves (Ghasemi *et al.*, 2021), red amaranth leaves (Sultana and Ghosh, 2021), taro roots (Nipa and Mondal, 2021), cassava starch (Aviara and Igbeka, 2016), and finger millet. Even though extensive studies have investigated the drying of wheat (Hosain *et al.*, 2016; Mykhailyk *et al.*, 2016), a very few works of literature have studied drying characteristics of sprouted grains (Dziki *et al.*, 2015; Shingare and Thorat, 2013). Since drying is crucial for producing weaning and other value-added products from sprouted wheat, the current study was conducted on the thin-layer drying characteristics of sprouted wheat. Hence, the present work was intended to: (a) investigate the thin-layer drying kinetics of sprouted wheat using a mechanical tray dryer, (b) establishing an appropriate mathematical drying model, and (c) evaluating effective moisture diffusivity and its respective activation energy of sprouted wheat at different drying periods and temperatures.

Materials and Methods

Preparation of sample

The study was conducted in the Food Grains and Oilseeds Processing Division of the Central Institute of Post-Harvest Engineering and Technology, Ludhiana, Punjab, India. The wheat samples (cv. PBW 550) were taken from the Punjab Agricultural University, Ludhiana, Punjab, India. Once the cleaning was completed, the samples were soaked in distilled water at a ratio of 1:2 in a glass container for recommended least time of soaking, that is, 8 h at room temperature. Then, the seeds were taken out from the container and gently rolled over a thick absorbent cloth to remove adherent moisture. Finally, in order to sprout, the grains were preserved in a humidity- and temperature-controlled cabinet having a constant relative humidity (RH) of 95% and temperature of 35°C in darkness. The time for sprouting was taken as 0 (s) while the soaked sample was kept in a germination chamber.

Experimental set-up

The experiment was performed in triplicate for each drying period of 24 h, 36 h and 48 h in the laboratory of Food Grains and Oilseeds Processing Division. Only distilled water was sprinkled on the grains during sprouting period at an interval of 8 h for washing the sample to avoid mould and fungus infection. The sample was kept for 3 days till the sprouts were observed. After sprouting, the sprouted wheat samples with initial moisture content (M; % wet basis [wb]) of 32–35% were subjected to drying at 50ºC, 60ºC, 70ºC and 80ºC at different time intervals. The drying was exercised in a mechanical convective tray dryer (Model-MSW 216; Macro Scientific Works, Delhi, India) till the moisture content (% wb) ranged between 7% and 10%. The moisture content of the wheat grain sample was determined by drying in a hot air oven at 105°C till it achieved a constant weight (Horwitz, 2010).

The following equation represented the moisture ratio (MR) of the grain sample while drying:

$$MR = \frac{(M - M_e)}{(M_0 - M_e)}, \quad (1)$$

where MR is the moisture ratio (dimensionless), and M, M_o and M_e are the instantaneous (at time t [s]), initial and equilibrium moisture contents, respectively.

The value of M_e was comparatively lower than that of M or M_o. Hence, MR was simplified as follows (Kertész *et al.*, 2015; Motevali *et al.*, 2013):

$$\mathrm{MR} = \frac{\mathrm{M}}{\mathrm{M_0}}. \tag{2}$$

The relationship between MR and drying periods was represented by drying curves/models fitted in six different thin-layer drying mathematical equations. The drying curves/models are described in Table 2, from which the best fit model was evaluated to define the drying process of sprouted sample.

Drying

Sprouted wheat was dried in a tray dryer at an air temperature of 50, 60, 70 and 80 ± 1°C for different drying periods of 24 h, 36 h and 48 h. In order to have uniform drying, 500-g of sprouted wheat was homogeneously spread as a layer on a perforated stainless steel tray. A constant temperature was maintained during drying by turning off heaters and blowers. In every run, the air was blown at a constant velocity of 3.7 m/min, suitable for drying as suggested by Soydan and Doymaz (2021). The constant velocity was maintained to achieve uniform drying of the sample. The moisture loss was noted using a digital balance with a least count of 0.01 mg at an interval of 1 h. Then, the drying was continued up to a steady magnitude of moisture loss. The drying air was not regulated by its relative humidity, which varied from 18% to 45%. Each experiment was conducted in triplicate.

Statistical analysis

The nonlinear regression equations were analyzed by the MATLAB (version 6.5) software. The model was chosen as the best fitting model according to its coefficient of determination (R^2) and coefficient of correlation (r) . In addition, the selection criteria of the models were evaluated using different statistical parameters, such as standard error (SE), root mean square error (RMSE), reduced Chi-square (χ^2), and mean bias error (MBE). According to Pandiselvam *et al.* (2017), the value of R^2 must be more significant, and the values of rest of ancillary parameters must be lower for the best fit model. Equations (3)–(5) represent ancillary parameters:

$$\chi^2 = \frac{\sum_{i=1}^{N} (\mathrm{MR_{exp}} - \mathrm{MR_{pre}})^2}{\mathrm{N} - \mathrm{z}}, \tag{3}$$

$$\mathrm{MBE} = \frac{1}{\mathrm{N}} \sum_{i=1}^{N} \left(\mathrm{MR_{exp}} - \mathrm{MR_{pre}}\right), \tag{4}$$

and

$$\mathrm{RMSE} = \left[\frac{1}{\mathrm{N}} \sum_{i=1}^{N} (\mathrm{MR_{exp}} - \mathrm{MR_{pre}})^2\right]^{\frac{1}{2}}, \tag{5}$$

where MR_{exp} and MR_{pre} are observed and predicted moisture ratios; z and N are drying constant and experiment numbers, respectively.

Calculation of effective moisture diffusivity (D_{eff})

Fick's diffusion law was applied to define drying, with diffusivity assumed to be constant (Suna and Özkan-Karabacak, 2019). The mean volume (V, in m^3) of sprouted wheat, calculated as 0.06 cm^3, was obtained by the toluene displacement procedure. Here, the mean equivalent radius (R_e) of sprouted grain sample was 2.43 × 10^{-3} m, which was calculated by using Equation (6):

$$\mathrm{V} = \frac{4}{3} \pi \mathrm{R_e^3}. \tag{6}$$

The universal series of Fick's equation representing MR with spherical coordinates is given by

$$\mathrm{MR} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \exp\left(\frac{-\mathrm{n}^2 \pi^2 \mathrm{D_{eff}}\, \mathrm{t}}{\mathrm{R_e}^2}\right), \tag{7}$$

where MR is the moisture ratio, R_e is the equivalent radius (m), D_{eff} is the effective diffusivity ($m^2 s^{-1}$), and t is the drying time (s). In Fick's equation, the first term is identified as Henderson and Pabis model. The moisture diffusivity relates to the slope and coefficient k, which is given by

$$\mathrm{k} = \left(\frac{\pi^2 \mathrm{D_{eff}}}{\mathrm{R_e}^2}\right). \tag{8}$$

Determination of activation energy

According to Bozkir (2020), the following relationship, known as the Arrhenius equation, represents the activation energy required for drying:

$$\mathrm{D_{eff}} = \mathrm{D_0} \exp\left(\frac{\mathrm{E_a}}{\mathrm{RT}}\right), \tag{9}$$

where $D_{eff,}$ is the effective moisture diffusivity (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 kJ/mol), and T is the absolute air temperature

Table 1. List of physiochemical, cooking, nutritional and sensory properties of unsprouted and sprouted wheat grains (Mridula *et al.*, 2015, 2013).

S. No.	Properties	Name of the properties	Units	Unsprouted wheat	Sprouted wheat
1.	Physical properties	Bulk density	g/mm^3	0.690	0.53
		True density	g/mm^3		1.33
		Porosity	%		48.07
		Peak viscosity	cP		83.67
		Color L	-	70.03	75.85
		a	-	6.94	4.55
		b	-	20.70	16.41
		Hue angle	-	71.47	74.53
		Chroma	-	21.83	17.03
2.	Cooking qualities	Cooking time	Min.	4.41	3.91
		Hydration ratio	-	3.20	3.450
		Solid loss in cooking water	%	12.66	14.29
3.	Nutritional qualities	Moisture	Wet basis (%)	7.31	6.28
		Protein	%	10.23	10.26
		Fat	%	1.31	1.32
		Crude fiber	%	3.19	3.23
		Minerals	%	1.47	1.29
		Carbohydrates	%	74.41	77.24
		Calories	kCal/100 g	350	359.31
		In vitro digestibility	%	47.46	62.75
		Iron	mg/100 g	1.11	1.18
		Calcium	mg/100 g	42.67	44.67
4.	Sensory qualities	Appearance and color	Hedonic scale	7.75	8.08
		Texture	Hedonic scale	7.71	7.71
		Flavor and taste	Hedonic scale	7.96	8.25
		Mouth feel	Hedonic scale	7.67	7.67
		Overall acceptability	Hedonic scale	7.69	7.98

Table 2. Thin-layer drying models given by various authors.

Model Names	Equations	References
Newton	$MR = e^{-kt}$	Motevali *et al.*, 2013
Wang and Singh	$MR = 1 + at + bt^2$	Manikantan *et al.*, 2014)
Henderson and Pabis	$MR = ae^{-kt}$	Abbaspour-Gilandeh *et al.*, 2020
Two-term	$MR = ae^{-k_0 t} + be^{-k_1 t}$	Onwude *et al.*, 2016
Logarithmic	$MR = ae^{-kt} + c$	Darvishi *et al.*, 2014
Page	$MR = e^{-kt^n}$	Doymaz and Smail, 2011

(K [Kelvin]). The intercept of y-axis represents the constant D_o derived from the graph.

Equation (9) can be written in a linear form by considering natural logarithm on two sides and is given by

$$\ln(D_{eff}) = \ln(D_0) - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right). \quad (10)$$

The value of E_a was evaluated from the slope of graph between logarithmic (ln) (D_{eff}) and $1/T$ from Equation (10).

Results and Discussion

Drying kinetics data are important to find out optimum drying conditions for a specific product and also for designing a suitable dryer. Besides, several research articles have studied the physical, chemical, nutritional, cooking and sensory qualities of sprouted wheat at different time periods (Mridula *et al.*, 2015, 2013). The stated properties significantly improved in sprouted wheat as compared to control unsprouted wheat. Considering the physical properties, the bulk density was lowered and the true density was ameliorated due to sprouting. Besides, yellow and red colors of sprouted wheat were lowered. Moreover, the cooking time was reduced in case of sprouted wheat, and solid loss was increased by the sprouting process. However, the sprouting process lowered the moisture content of wheat grains whereas other nutritional qualities were improved significantly. The sensory qualities of sprouted wheat, for instance appearance, texture, flavor and overall acceptability, were increased significantly in sprouted grains compared to control wheat grains. In most of the studies, the wheat grains are kept for 2–3 days for having improved qualities. All the properties of both sprouted wheat grains kept for 36 h and control unsprouted wheat grains are given in Table 1.

Apart from sprouting of wheat grains, studies have been conducted on sprouting of other grains to analyze physiochemical, nutritional, functional and microstructural properties. In a study of wheat noodles, Zhang *et al.* (2022) investigated the quality of noodles after adding sprouted quinoa flour into wheat flour. By addition of quinoa flour, the cooking and water absorption rate were significantly reduced without changing the texture of noodles. On the other hand, the sprouted Nitta bean flour had higher phenolic content and antioxidant activity along with more physiochemical properties compared to hydrothermal treatments. Moreover, germination caused structural and morphological changes in beans so that gel formation capacity and emulsion capacity were lowered compared to control samples (Medhe *et al.*, 2022).

Rani *et al.* (2022) investigated physiochemical and anti-nutritional properties of oat flour following the sprouting process. The protein and fiber contents in oat flour were significantly increased after sprouting whereas the color values, such as a* and b*, were reduced significantly. Moreover, the anti-nutritional properties, such as phytic acid and tannin contents, were reduced to a higher amount by the sprouting process. Also, in a study conducted on pigeon pea, sprouting enhanced the protein and fiber contents along with minerals, vitamins, phenolic compounds, resistant starch, protein digestibility, and antioxidant properties. However, sprouting of pea reduced some amino acids, phytic acid and trypsin inhibitor activity (Chinma *et al.*, 2022). It is clear from the above studies that sprouting of grains or pulses for certain period induces their qualities.

In case of winter jujube slices, nutritional factors, such as vitamins, total acidity and reducing sugar content, were reduced significantly with increase of drying time, air velocity and temperature (Niu *et al.*, 2021). Also, Doymaz and Karasu (2018) investigated the drying of sage leaves under low temperature (45°C), with restrained phenolic content and antioxidant activity. The drying kinetics revealed direct dependency between drying temperature and drying period. Changes in drying period were determined by MR. Therefore, application of thin-layer drying kinetics model could predict relation of moisture evaporation with drying time and temperature; the nutritional and physiochemical properties could be preserved for a longer period by drying for certain period and temperature.

Effect on moisture ratio

The impact of drying periods and air temperatures on the MR of sprouted wheat is presented in Figure 1. The figure shows the continuous reduction of MR pertaining to rise in drying period; this indicated that drying occurred with a decrease in rate period and an increase in drying time. This consideration indicated that moisture movement in the sample followed the liquid and vapor diffusion mechanism as described by Behera *et al.* (2021). As expected, rise in drying air temperature lessened the relative humidity, thus raising the moisture difference between surrounding air and grains. Heat transfer between the product to be dried and the drying air was gradually increased so that moisture migrated rapidly (Nag and Dash, 2016; Sayyad *et al.*, 2021). In the primary phase, drying started rapidly because of the presence of free moisture. Then, the drying rate decreased gradually at the final stage by lowering

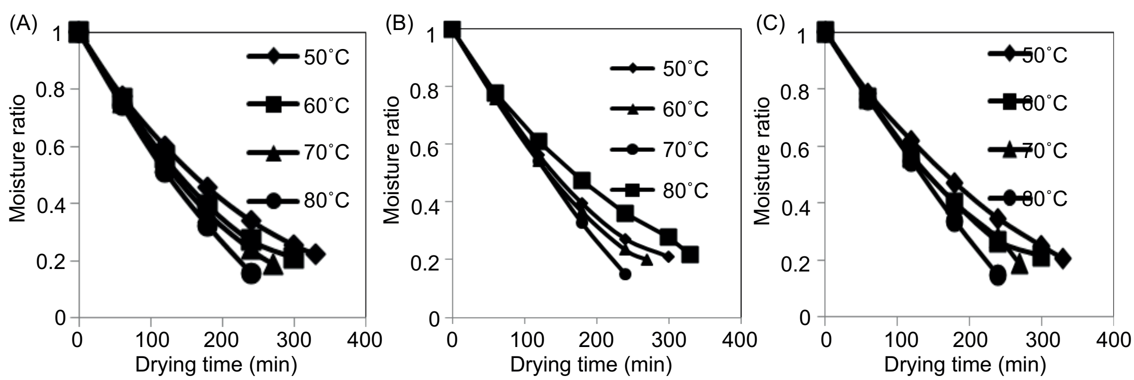

Figure 1. **Thin-layer drying curves of different period sprouted wheat at four different air temperatures. (A) 24 hours; (B) 36 hours; (C) 48 hours.**

the movement of moisture from inward to outward surface (Taheri-Garavand *et al.*, 2011). In addition, with rise in air temperature, the drying period was reduced. This demonstrated that a certain level of moisture ratio was reached first at a higher temperature. The present study revealed that drying air temperature was vital for deviations in drying time. Some identical results were observed by the following researchers: Aviara and Igbeka (2016) for cassava starch, Ee *et al.* (2021) for kedondong fruit, Gazor and Mohsenimanesh (2010) for canola, Ingle *et al.* (2019) for bottle gourd, Kertész *et al.* (2015) for carrot slices, Markowski *et al.* (2010) for barley, Moezzi *et al.* (2021) for grapefruit, Nipa and Mondal (2021) for taro roots, Rayaguru and Routray (2012) for apple slices, Shen *et al.* (2011) for sweet sorghum stalk, and Taheri-Garavand *et al.* (2011) for bell pepper.

Comparison between models

The drying procedure was examined with six different drying models for its fitness by determining the moisture ratio of sprouted wheat at three drying air temperatures and drying periods. Table 3 presents the detailed statistical results of analyses, such as r^2, SE, χ^2, MBE and RMSE. These results were attained from nonlinear regression analysis by using MATLAB for six drying models. According to the higher value of r^2 and the lower values of SE, χ^2, MBE and RMSE, the best fit model was designated to define the drying characteristics of sprouted wheat (Demiray *et al.*, 2017; Mbegbu *et al.*, 2021; Onwude *et al.*, 2016). It was observed that all models were good fit for drying processes having $r^2 > 0.99$. As shown in Table 3, Wang and Singh's empirical equation perfectly illustrated the drying characteristics of sprouted wheat with greater importance to the correlation coefficient of all drying temperatures and sprouting periods. In addition, this model was suitable for fit drying kinetics, as observed by Akpinar (2010) for mint leaves, Farhang *et al.* (2010) for alfalfa, Ghasemi *et al.* (2021) for lemon verbena leaves, Kumar *et al.* (2013) for bamboo shoots slices, and Manikantan *et al.* (2014) for paddy. Moreover, numerous studies (Agarry, 2016; Demiray and Tulek, 2012; Nag and Dash, 2016; Torres-Ossandón *et al.*, 2018) have demonstrated that the drying models give useful information to evaluate optimal drying conditions, such as temperature and time to attain an ultimate moisture value for sprouted wheat for further processing. Hence, information on drying kinetics and its modeling is necessary for designing, simulation and optimization of drying processes.

Effect on effective moisture diffusivity

The slope of equation established between ln (MR) and drying period for sprouted wheat dried at different air temperatures showed moisture diffusivity (Felizardo *et al.*, 2021; Taheri-Garavand *et al.*, 2011). Table 4 presents moisture diffusivity at different air temperatures and sprouting periods. Rise in drying air temperature amplified the moisture diffusivity of sprouted wheat. As a result, increase in the vapor pressure of sprouted wheat samples was caused by rapid heating by intense thermal energy as studied by Kadam *et al.* (2011) in basil leaves and Nipa and Mondal (2021) in taro roots. Moisture diffusivity for the drying period of 24-, 36- and 48-h sprouted wheat was found to increase from 1.790×10^{-9} to 2.580×10^{-9} m^2 s^{-1}, 1.921×10^{-9} to 2.781×10^{-9} m^2 s^{-1} and 1.858×10^{-9} to 2.561×10^{-9} m^2 s^{-1}, respectively, for the drying air temperatures of 50–80°C. In general, each food material has moisture diffusivity ranging from 10^{-9} m^2 s^{-1} to 10^{-11} m^2 s^{-1} with falling time periods, where drying occurs by internal moisture diffusion (Darvishi *et al.*, 2014; Khawas *et al.*, 2014). During the first 36 h of sprouting, the texture was continuously soft compared to the soaked seeds; however, the softness of sprouted seeds decreased thereafter. The effective moisture diffusivity also increased with sprouting period of up to 36 h, but decreased gradually thereafter. According to Joshi *et al.* (2011), structural components, such as cell walls, proteins and carbohydrates of the cotyledon are broken due to enzymatic action. Some examples of food materials where drying time influences mass transfer are Bambara beans (Awotona *et al.*, 2021), elephant apple (Nag and Dash, 2016) and red amaranths leaves (Sultana and Ghosh, 2021).

Effect on activation energy

It is observed that the lowest energy allows the movement of water particles inside the solid by breaking water–water and/or water–solid interactions. The lesser activation energy of the grain shows that water molecules can transfer rapidly. It relates to the lowest quantity of energy required for transmission of moisture inside sprouted wheat throughout the drying process. It was calculated from the slope of straight line between logarithmic moisture diffusivity (ln D_{eff}) and absolute temperature (1/T) of Arrhenius expression shown in Equation (10). The activation energy for 24-, 36- and 48-h wheat samples was 11.357 kJ mol^{-1}, 11.428 kJ mol^{-1} and 9.427 kJ mol^{-1}, respectively. It was observed that 36-h sprouted wheat sample required maximum activation energy to remove sample water. The moisture was firmly bounded to the material structure and its removal required more activation energy (E_a) (Perea-Flores *et al.*, 2012). An inversely proportional relationship was observed between activation energy and temperature, hence E_a decreased with increase in temperature. Apart from this, more activation energy was required with increasing drying period; less E_a was required at a significantly shorter period (<36 h), but more E_a was involved for longer period (>36 h) because

Table 3. Drying constants and statistical parameters attained from the six certain drying models for sprouted wheat at different drying timings and air temperatures.

Sample condition (sprouting period, drying temperature)	Model Names	Constants	R^2	SE	MBE	χ^2	RMSE
24 h, 50°C	Newton	k = 0.004390755	0.999136	0.008419	0.00052	8.01494E-05	0.008288513
	Wang and Singh	a = –0.0038704294 b = 4.6717404e^{-006}	0.999878	0.003466	0.000146	1.0915E-05	0.002675691
	Henderson and Pabis	a = 1.0080396 k = 0.0044346021	0.999318	0.008192	0.001962	7.70394E-05	0.007418097
	Two-term	a = 0.49487101 k_0 = 0.0044291665 b = 0.51316614 k_1 = 0.0044396937	0.999318	0.010576	0.001965	0.000128433	0.007419089
	Logarithmic	a = 1.0643075 k = 0.0039725023 c = -0.062088415	0.999766	0.005367	0.0014	2.06668E-05	0.003436509
	Page	k = 0.0033309755 n = 1.051801	0.999874	0.003517	0.001412	1.12448E-05	0.002834076
36 h, 50°C	Newton	k = 0.0042724165	0.998345	0.011516	0.000277	0.000162335	0.011795944
	Wang and Singh	a = -0.0037136246 b = 4.2266864e^{-006}	0.999323	0.007405	0.000203	0.000166973	0.00620926
	Henderson and Pabis	a = 1.0069057 k = 0.0043096496	0.998484	0.012074	0.000981	0.000183816	0.011458488
	Two-term	a = 0.49845292 k_0 = 0.004323715 b = 0.50845279 k_1 = 0.0042958557	0.998484	0.015588	0.000982	0.000306379	0.01145886
	Logarithmic	a = 1.1022023 k = 0.0036146467 c = -0.10411231	0.999175	0.007943	0.000209	7.97741E-05	0.00675168
	Page	k = 0.0032099774 n = 1.0534994	0.999133	0.009129	0.000732	0.000118046	0.009182496
48 h, 50°C	Newton	k = 0.0043789399	0.993968	0.02286	0.000524	0.000418533	0.01894049
	Wang and Singh	a = -0.0035891286 b = 3.5830869e^{-006}	0.999974	0.002187	0.001038	3.55291E-05	0.00303765
	Henderson and Pabis	a = 1.0190995 k = 0.004481155	0.994951	0.02291	0.002993	0.000425471	0.017432947
	Two-term	a = 0.50454831 k_0 = 0.0044753589 b = 0.51454857 k_1 = 0.0044867184	0.994951	0.029577	0.002995	0.000709133	0.017433135
	Logarithmic	a = 1.2836798 k = 0.0029396301 c = -0.28430143	0.999951	0.002536	0.00104	1.93595E-05	0.003326048
	Page	k = 0.0020269304 n = 1.1442255	0.999055	0.00991	0.002051	9.07097E-05	0.008049389
24 h, 60°C	Newton	k = 0.0050773771	0.996138	0.018926	0.002066	0.000358205	0.01727727
	Wang and Singh	a = -0.0043799635 b = 5.7764784e^{-006}	0.999512	0.007523	0.001059	5.65998E-05	0.006142733
	Henderson and Pabis	a = 1.0162183 k = 0.0051788475	0.996874	0.019036	0.001159	0.00036237	0.01554285
	Two-term	a = 0.527777224 k_0 = 0.0052368523 b = 0.4884494 k_1 = 0.0051167846	0.996872	0.026931	0.001165	0.000725262	0.015548444

(continues)

Table 3. Continued.

Sample condition (sprouting period, drying temperature)	Model Names	Constants	R^2	SE	MBE	χ^2	RMSE
	Logarithmic	a = 1.1152749 k = 0.0043163657 c = -0.10774605	0.998243	0.016479	2.54E-07	0.000271573	0.011652738
	Page	k = 0.0028122979 n = 1.1140214	0.999281	0.00913	0.000529	8.33597E-05	0.007454741
36 h, 60°C	Newton	k = 0.0050741664	0.995393	0.020749	0.002258	0.000430504	0.018940791
	Wang and Singh	a = -0.0043498021 b = 5.644663e^{-006}	0.999353	0.008691	0.001247	7.55292E-05	0.007095971
	Henderson and Pabis	a = 1.0179824 k = 0.0051863915	0.996292	0.020811	0.001328	0.000433078	0.016991719
	Two-term	a = 0.48932767 k_0 = 0.0051466276 b = 0.52865132 k_1 = 0.0052232648	0.996291	0.029435	0.001332	0.000866396	0.016994079
	Logarithmic	a = 1.1338387 k = 0.0042072924 c = -0.12573514	0.998065	0.017358	7.03E-06	0.000301296	0.012273881
	Page	k = 0.0026167743 n = 1.1278032	0.999284	0.009148	0.000555	8.36946E-05	0.007469701
48 h, 60°C	Newton	k = 0.0050840176	0.995628	0.020158	0.004021	0.000734008	0.024732036
	Wang and Singh	a = -0.0043747135 b = 5.7421359e^{-006}	0.999216	0.009542	0.004567	0.000127441	0.002313718
	Henderson and Pabis	a = 1.0160328 k = 0.0051843162	0.996346	0.020603	0.001236	0.000424466	0.016821937
	Two-term	a = 0.49820017 k_0 = 0.0051404027 b = 0.51782961 k_1 = 0.005226709	0.996345	0.029141	0.001239	0.000849217	0.016824749
	Logarithmic	a = 1.1226114 k = 0.0042674922 c = -0.1158139	0.997896	0.018055	2.31E-06	0.000325983	0.012766806
	Page	k = 0.0027822823 n = 1.1163467	0.998878	0.011418	0.000383	0.000130373	0.009322848
24 h, 70°C	Newton	k = 0.005573578	0.992092	0.028055	0.001977	0.000787065	0.025610297
	Wang and Singh	a = -0.004490333 b = 5.5003264e^{-006}	0.999904	0.003465	0.00045	1.2004E-05	0.002828899
	Henderson and Pabis	a = 1.0230558 k = 0.0057210484	0.993451	0.028543	0.002576	0.000814708	0.02330533
	Two-term	a = 0.54094272 k_0 = 0.0057406455 b = 0.48211976 k_1 = 0.0056992913	0.993451	0.040367	0.002576	0.001629516	0.023306052
	Logarithmic	a = 1.3073288 k = 0.0036498026 c = -0.30338258	0.999602	0.008128	3.01E-08	6.6062E-05	0.005747261
	Page	k = 0.0020764868 n = 1.1918991	0.999858	0.004198	0.000396	1.76238E-05	0.00342771
36 h, 70°C	Newton	k = 0.0055352988	0.992489	0.02721	0.002126	0.000740381	0.024839162
	Wang and Singh	a = -0.0045109033 b = 5.6562327e^{-006}	0.999621	0.004838	0.00076	2.67564E-05	0.00358308
	Henderson and Pabis	a = 1.0226635 k = 0.0056800696	0.993816	0.027603	0.002353	0.000761938	0.022537934

(continues)

Table 3. Continued.

Sample condition (sprouting period, drying temperature)	Model Names	Constants	R^2	SE	MBE	χ^2	RMSE
	Two-term	a = 0.54026756 k_0 = 0.0056581782 b = 0.48238859 k_1 = 0.0057043448	0.993816	0.039038	0.002357	0.001523995	0.022538816
	Logarithmic	a = 1.2764755 k = 0.0037706389 c = -0.27137054	0.999086	0.012256	6.89E-08	0.000150212	0.008666381
	Page	k = 0.0021366934 n = 1.1849638	0.999775	0.005262	0.000159	2.76878E-05	0.004296337
48 h, 70°C	Newton	k = 0.0052190283	0.987246	0.034969	0.00825	0.000656482	0.023389501
	Wang and Singh	a = -0.0040456527 b = 3.9933337e^{-006}	0.999146	0.010996	0.008532	0.000136412	0.008258699
	Henderson and Pabis	a = 1.0255301 k = 0.0053776643	0.989009	0.036295	0.002849	0.001317295	0.029634379
	Two-term	a = 0.53250586 k_0 = 0.0053645893 b = 0.49302156 k_1 = 0.0053916959	0.989008	0.051329	0.00285	0.002634644	0.029634687
	Logarithmic	a = 1.5542401 k = 0.0026925102 c = -0.55399498	0.998991	0.01168	2.36E-07	0.000503706	0.018324962
	Page	k = 0.0016353612 n = 1.2243713	0.997651	0.016777	0.134394	0.035727671	0.154332263
24 h, 80°C	Newton	k = 0.0061808162	0.979192	0.048352	0.002379	0.002337947	0.043247633
	Wang and Singh	a = -0.0045632708 b = 4.3613613e^{-006}	0.999957	0.002525	0.000174	6.37693E-06	0.001956057
	Henderson and Pabis	a = 1.0296019 k = 0.006394302	0.981571	0.052545	0.004562	0.002760974	0.040701162
	Two-term	a = 0.495468 k_0 = 0.0063947152 b = 0.53414989 k_1 = 0.0063948243	0.981571	0.091011	0.004551	0.008282921	0.040701158
	Logarithmic	a = 1.8806759 k = 0.0024920358 c = -0.87915999	0.999926	0.004073	5.51E-07	1.65896E-05	0.00257601
	Page	k = 0.0012014776 n = 1.3273881	0.997792	0.018186	0.001768	0.000330714	0.014086453
36 h, 80°C	Newton	k = 0.0059814928	0.9676	0.06079	0.003253	0.003695408	0.05437211
	Wang and Singh	a = -0.0041448575 b = 2.4726901e^{-006}	0.999853	0.004721	0.000225	2.22912E-05	0.003657144
	Henderson and Pabis	a = 1.036442 k = 0.0062384386	0.971185	0.066197	0.005472	0.004381996	0.051275703
	Two-term	a = 0.4983129 k_0 = 0.0062373337 b = 0.53811781 k_1 = 0.0062391482	0.971185	0.114656	0.005472	0.013145989	0.051275704
	Logarithmic	a = 2.9372788 k = 0.0014281681 c = -1.9358758	0.999822	0.00638	0.000741	4.07078E-05	0.004035237
	Page	k = 0.00072031607 n = 1.4216865	0.996123	0.02428	0.002718	0.00058953	0.018807397

(continues)

Table 3. Continued.

Sample condition (sprouting period, drying temperature)	Model Names	Constants	R^2	SE	MBE	χ^2	RMSE
48 h, 80°C	Newton	k = 0.0059142997	0.964116	0.063967	0.003415	0.004091825	0.057214157
	Wang and Singh	a = -0.0040104366 b = 1.884286e^{-006}	0.999966	0.002284	7.64E-05	5.21651E-06	0.001769154
	Henderson and Pabis	a = 1.037557 k = 0.0061769228					
	Two-term	a = 0.49998882 k_0 = 0.0061783583 b = 0.53756115 k_1 = 0.006175343	0.967938	0.12093	0.005656	0.014624105	0.054081614
	Logarithmic	a = 3.650306 k = 0.0011079726 c = -2.649812	0.999949	0.003398	0.000811	1.15457E-05	0.002149018
	Page	k = 0.0006516673 n = 1.4388616	0.994814	0.028081	0.003104	0.000788529	0.021751261

a, b, c and n: drying model constants; k: drying rate constant (h^{-1}).

Table 4. Effective moisture diffusivity (D_{eff}) at various timings and air temperature for drying of sprouted wheat.

Drying temperature (°C)	Sprouting period (h)	D_{eff} ($\times 10^{-9}$ m^2/s)
50	24	1.790
	36	1.921
	48	1.858
60	24	2.092
	36	2.310
	48	2.149
70	24	2.310
	36	2.530
	48	2.229
80	24	2.580
	36	2.781
	48	2.561

of decrease in moisture diffusivity. Some examples of food products which required higher activation energy than observed in the present study are cassava starch (Aviara and Igbeka, 2016), cardamom (Dash *et al.*, 2021), taro roots (Nipa and Mondal, 2021) and amaranth leaves (Sultana and Ghosh, 2021). Likewise, examples of food products requiring lower activation energy than sprouted wheat are chickpeas (Cavalcanti-Mata *et al.*, 2020) and canola (Gazor and Mohsenimanesh, 2010).

Conclusions

The impact of drying air temperature on sprouted wheat at different drying periods in a tray dryer was investigated. It was demonstrated that drying occurred with falling rate period, where the moisture was removed due to diffusion phenomenon. Hence, using the Fick's equation, it was possible to characterize the drying of sprouted wheat. According to statistical analysis, the Wang and Singh model was described as the most acceptable representation of drying characteristics of sprouted wheat with higher correlation coefficient values and lower ancillary parameters for each drying temperature. Hence, this could be a valuable tool for simulating the drying operations and development of dryers at industrial scale. Moreover, the diffusivity was increased from 1.790×10^{-9} m^2/s to 2.781×10^{-9} m^2/s when both drying air temperature and time were raised. Diffusivity was highest at an air temperature of 80°C used for drying wheat grains for 36 h. Sprouted wheat at a drying period of 36 h required more activation energy to remove its moisture. Based on the Arrhenius equation, activation energy was determined as 11.428 kJ/mol^{-1} at an air temperature of 80°C. Hence, the drying parameters of sprouted wheat were considerably affected by different drying temperatures and periods using a tray dryer.

Nomenclature

M	Moisture content (DB)
N	Experiment numbers
z	Drying constant numbers
V	Mean volume (m^3)
R_e	Equivalent radius (m)
T	Absolute air temperature (K)
E_a	Activation energy (kJ/mol)
t	Drying period (h)

D	Moisture diffusivity (m^2/s)
r^2	Coefficient of determination
a b, c, n	Drying model constants
k	Drying rate constant (h^{-1})

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Data availability Statement

The data that supported the findings of this study are available from the corresponding author upon reasonable request.

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