



Models of fluidized bed drying for thin-layer chopped coconut

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ABSTRACT

Methods for efficiently drying agricultural products are in ever-increasing demand. Due to its thorough mixing ability, a fluidized bed technique was employed to evaluate the drying kinetics of thin-layer chopped coconut. The experiments were conducted at drying temperatures of 60–120 °C and a constant velocity of 2.5 m/s. Chopped coconut was dried from about 105% d.b. to approximately 3% d.b. The moisture transport phenomenon in fluidized bed thin-layer drying is described by immense acceleration in MR diminution in the early stage of drying, followed by considerable deceleration. Falling-rate drying, an outgrowth of restraining moisture transfer via internal mass-diffusion mechanism, thoroughly characterized chopped coconut drying. Among the 10 selected models, statistic analysis inferred that the Modified Henderson and Pabis model could predict changes in moisture content most accurately. Compared with the values of D_{eff} derived from Fick's law for other food and biological materials usually dried in conventional tray dryers, the current values (5.9902×10^{-8} – 2.6616×10^{-7} m²/s) were substantially high, principally attributable to the unique characteristic of fluidized bed drying, remarkably encouraging heat and mass transfer. Activation energy was also described.

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1. Introduction

Coconuts are a widely cultivated economic crop in many parts of the world. Thailand, one of the world's 10 largest producers, generates about 1.5 million tons of coconut annually [1]. This product is consumed in various types of coconut-derived products – coconut milk, coconut flour, coconut juice, and desiccated coconut (DCN). The fine desiccated coconut, with moisture content of around 3% d.b. [2], is typically applicable to decoration ice cream, cake and donuts, and as the principal flavoring ingredient in chocolate bars.

Many studies have emphasized drying kinetics and thin-layer drying models for fruits, vegetables, and the by-products of some industrial processes – mint leaves [3], olive cake [4], strawberries [5], organic apple slices [6], apple pomace [7], green beans [8], par-boiled wheat [9], corn [10], carrots [11], rosehip [12], spirulina [13], black tea [14], raw mango slices [15], young coconut [16] and olive oil extraction [17]. As a crucial factor influencing drying kinetics, drying temperature participated intimately in the drying-rate constants (k) of the drying models. In consequence, several studies ascertained a variety drying-rate constants, each for a specific temperature [3–5,8,10,11], while others attempted to relate drying-rate constants to drying temperature [6,7,9,12,16,17].

Although satisfactory for a variety of biological materials, the preceding thin-layer models provided no data for chopped coconut, and most originated from tray dryers, traditionally employed to dehydrate assorted materials. Consequently, some drawbacks are inherent in their use with an extended drying period and inconsistent properties of the products to be dried. Renowned as the most efficient drying technology because of its characteristic thorough mixing, which fosters vigorous heat and mass transfer, the potential of the fluidized bed has become increasingly recognized for drying food products [2,18]. The thin-layer characteristic, derived from fluidized bed drying is distinguished from conventional convective drying by the mixing motion, which enhances heat/mass transfer.

In this study, therefore, the attention is attracted to the thin-layer drying kinetics of finely chopped coconut in a fluidized bed dryer, and to fit various thin-layer models in which the drying-rate constants and model coefficients rely on drying temperature. In addition, effective diffusivity and activation energy are described.

2. Material and methods

2.1. Materials

Mature coconut with husk peeled off was cracked and washed thoroughly to remove dust and other foreign materials, and then soaked in 50-ppm chlorine solution for 5 min to inactive microorganisms [2]. It was chopped finely using a mechanical chopper to

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Nomenclature

a, b, c	essential coefficients of the models	p	number of constants
D_0	pre-exponential factor of the Arrhenius equation (m^2/s)	P	mean relative percent error
D_{eff}	effective diffusivity (m^2/s)	r	radius of the sphere (m)
E_a	activation energy (kJ/mol)	R	universal gas constant (kJ/mol K)
g, h, k, k_0, k_1	drying-rate constants of the models (min^{-1})	R^2	coefficient of determination
M	moisture content (kg water/kg dry matter)	Residuals	sum of residual
$M(t)$	moisture content at any time of drying (kg water/kg dry matter)	RMSE	root mean square error
M_0	initial moisture content (kg water/kg dry matter)	t	drying time (min)
M_{eq}	equilibrium moisture content (kg water/kg dry matter)	T	drying-air temperature ($^{\circ}\text{C}$)
MR	moisture ratio	T_{abs}	absolute temperature (K)
$\text{MR}_{\text{exp},i}$	experimental moisture ratios	<i>Greek letter</i>	
$\text{MR}_{\text{pre},i}$	predicted moisture ratios	χ^2	reduced chi-square
n	positive integer, essential coefficients of the model		
N	number of observations		

produce uniform coconut pieces. The mean diameter (d_m) obtained from sieving process was found to be 2.28 mm. Initial moisture content was about $105 \pm 15\%$ dry basis (d.b).

2.2. Experimental apparatus

Fig. 1 shows a schematic diagram of the overall experiment setup. The fluidized bed dryer consists of an acrylic cylindrical drying chamber with 210 mm i.d., 1200 mm in height. Supply air ducts and a cyclone are made of stainless steel. The fluidizing air was supplied by a 2-hp blower, and a 5 kW electrical heater was employed to heat up the air to desired drying temperatures. The temperatures were monitored using a data logger with an accuracy of $\pm 1^{\circ}\text{C}$ and type-K thermocouples, and controlled to $\pm 1^{\circ}\text{C}$ by a controller. Air velocity was adjusted manually and measured by a Venturi meter cooperated with a differential pressure sensor (accuracy $\pm 2\%$). In the earlier experiments, it was apparent that when fluidizing air penetrated through an air-distributor, portions of the chopped coconut pieces originally distributed thinly were swept aside, resulting in many bare spots on the distributor surface. Then, the upwardly projecting airstream will take shortcuts through these bare spots and the coconut will keep still. To over-

come this problem, continuously-rotating blades (stirring blades) operating at 40 rpm were disposed centrally within the drying chamber and just above the air-distributor plate, to stir the chopped coconut; this prevented the aggregation of chopped coconut particles being dehydrated, and reliably spread them uniformly over the distributor surface during the drying process. Observations after the installation of the stirring blades found fluidization had been achieved. Samples were removed at each nominated interval in the drying process and weighed with an electronic balance (accuracy ± 0.0001 g).

2.3. Experimental procedure

The experiments were performed at drying temperatures varying from 60 to 120 $^{\circ}\text{C}$, with 10 $^{\circ}\text{C}$ increment, and a fixed fluidizing velocity of 2.5 m/s for all circumstances. Use of a velocity less than 2.5 m/s was unable to encourage fluidization of the chopped coconut, even with concurrent use of stirring blades, while a velocity much greater than 2.5 m/s caused particle elutriation. The dryer operated without product inside for 30 min to stabilize the drying conditions. To determine how the effective diffusion coefficient (D_{eff}) was contingent on drying temperature, 10 ± 0.1 g of minced coconut was layered as thinly as possible on the air-distributor plate, to minimize temperature drop across the layer. Although the layer might not be exactly a single layer, it permitted only about 1 $^{\circ}\text{C}$ drop in drying-air temperature. The product was dried to about 3% d.b. Simultaneously, to trace changes in moisture content during the drying process and to prevent any disturbance of the moisture content evolution during the process due to sampling, the experiment was stopped at the end of each sampling interval, and most of the coconut was collected for determination of moisture content. Thereafter, a subsequent experiment for a succeeding sampling interval started with the same conditions: the same initial amount of product (10 ± 0.1 g), initial moisture content, and temperature. Coconut was gathered periodically: at 10-s intervals for the first 0–2 min, at 20-s intervals for 2–5 min, and then at 1-min intervals for 5–10 min. Most of the coconut withdrawn at each interval was cooled down and packed in low density polyethylene bags sealed by heat, before analyzed for moisture content. To minimize measurement uncertainties, all experiments were replicated at least 2 times, except some (at 60, 80, 110, and 120 $^{\circ}\text{C}$) which demonstrated noticeable differences between the duplicate and the original, which were further replicated once; the averages of the results were used in analysis. The whole sample (≈ 10 g) collected at each interval was divided into three smaller amount samples, and these triplicate samples were dried in a convective oven

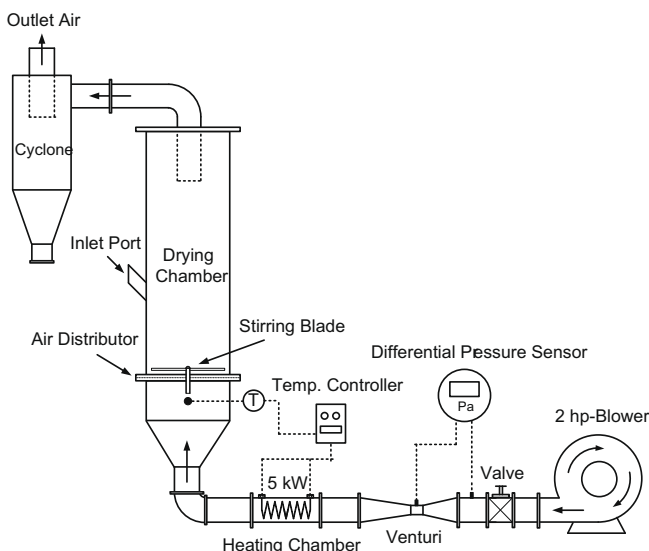


Fig. 1. A schematic diagram of fluidized bed apparatus.

at 103 °C for 72 h in order to determine the moisture content. Relative to the means of each set of the triplicate samples, the error in moisture content measurement due only to weighing was found 3.3% in average. The means of the triplicate samples of the original experiment and that of the replicated experiment were averaged together, and used to express as the data of moisture content. Error bars incorporated into the moisture content results indicate the standard deviation derived from the results of the original and replicated experiments. On the other hand, the error bars shown in the relevant figure represent the variation results of the original and replicated experiments, and therefore are representative of the error experiment (not the error measurement).

2.4. Theoretical considerations

2.4.1. Mathematical modeling of drying curves

Moisture ratio (MR), a dimensionless of moisture content, can be calculated as follows:

$$MR = \frac{M(t) - M_{eq}}{M_0 - M_{eq}} \tag{1}$$

where M_0 , $M(t)$ and M_{eq} are initial, at any moment (t), and equilibrium moisture content, respectively. Extremely small compared with M_0 and $M(t)$, M_{eq} included in the MR definition may be omitted [4,6,7,10], especially for drying at high temperature, where M_{eq} values normally approach zero. A huge number of mathematical models characterize the drying kinetics of food products; some are listed

Table 1
Thin-layer drying models adapted to chopped coconut drying.

No.	Model names	Model	References
1	Newton or Lawis	$MR = \exp(-kt)$	[3,4,8,9,12,14,15]
2	Page	$MR = \exp(-kt^n)$	[3,5,8,10,14,16]
3	Henderson and Pabis	$MR = a \exp(-kt)$	[4,5,11,12,14,15]
4	Logarithmic	$MR = a \exp(-kt) + b$	[3–5,7,12,15]
5	Two term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	[7,9,12,14,16]
6	Midilli	$MR = a \exp(-kt^n) + bt$	[6,17]
7	Verma et al.	$MR = a \exp(-kt) + (1 - a) \exp(-gt)$	[17]
8	Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	[6,17]

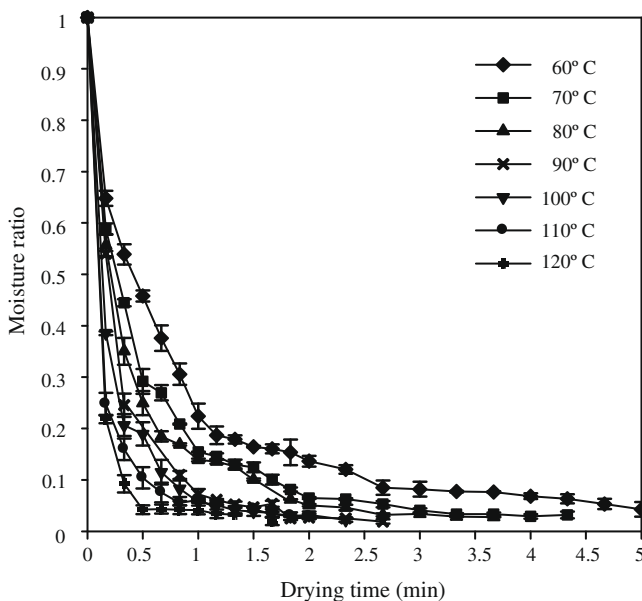


Fig. 2. Thin-layer drying curves of chopped coconut at different temperatures.

in Table 1, and adapted to experimental drying data for chopped coconut at different temperatures.

Non-linear regression was utilized to determine each constant for the tested model. The effectiveness of model fit was evaluated via the statistical criteria such as coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE), mean relative percent error (P), and residuals. The higher the R^2 and the lower the χ^2 , RMSE, P and residuals values, the better the model fit [3,6,7,19]. These parameters may be expressed as:

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

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{1/2} \tag{3}$$

$$P = \frac{100}{N} \sum_{i=1}^N \frac{|MR_{exp,i} - MR_{pre,i}|}{MR_{exp,i}} \tag{4}$$

$$Residuals = \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i}) \tag{5}$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are the i th experimental and predicted moisture ratios, respectively. N is the number of observations, and p is the number of constants.

2.4.2. Estimations of effective diffusivity

Fick’s model, symbolized as a mass-diffusion equation for drying biological products in a falling-rate period, is shown in the following equation:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \tag{6}$$

Primitively developed by Crank (1975), an analytical solution to the above equation is shown in Eq. (7), relevant to a spherical geometry and the assumptions of independence of diffusivities and temperature from interior moisture content, negligible volume shrinkage, and discounting the resistance of external convective mass transfer [20].

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

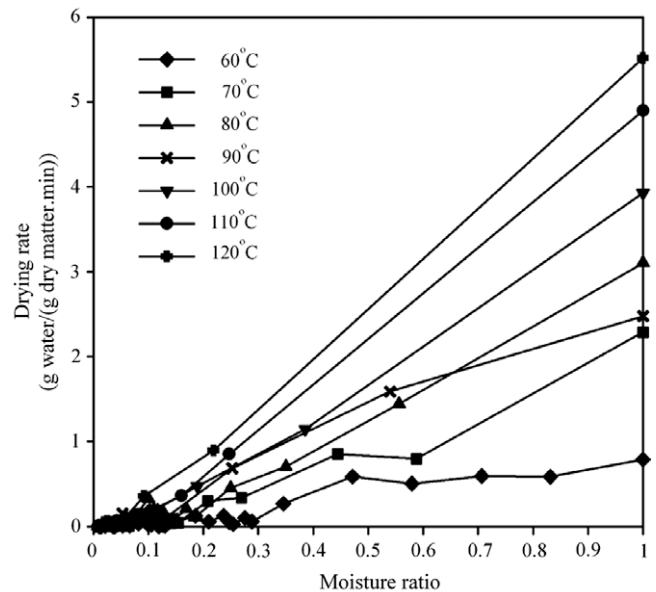


Fig. 3. Variation of drying rate with moisture ratio of chopped coconut at different temperatures.

where D_{eff} is the effective diffusivity (m^2/s), r is the radius of the sphere (m), and n is the positive integer. Concentrating solely on the first term in the series equation, and taking the natural logarithm of both sides [4,9,11,21], Eq.(7) may be simplified to a linear logarithmic form, as follows:

$$\ln \text{MR} = \ln \left(\frac{6}{\pi^2} \right) - \left(\frac{\pi^2 D_{\text{eff}} t}{r^2} \right) \quad (8)$$

To determine the effective diffusivity coefficient (D_{eff}), first the slope of the relationships between $\ln \text{MR}$ and time (Eq. (8)) is computed, and D_{eff} is then calculated by the following equation:

$$\text{Slope} = \frac{\pi^2 D_{\text{eff}}}{r^2} \quad (9)$$

2.4.3. Computation of activation energy

Activation energy can be obtained from the Arrhenius correlation [4,7,9–11,14,16], which demonstrates the effective diffusivity reliance on temperature, as shown in the following equation:

$$D_{\text{eff}} = D_0 \exp \left(-\frac{E_a}{RT_{\text{abs}}} \right) \quad (10)$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (kJ/mol K), and T_{abs} is the absolute temperature (K). By taking the natural logarithm of both sides, the above exponential form of Arrhenius can be transfigured into a linear logarithmic form, Eq. (11). Consequently, E_a can be calculated from the slope of

$$\ln D_{\text{eff}} = \ln D_0 - \frac{E_a}{RT_{\text{abs}}} \quad (11)$$

3. Results and discussion

3.1. Analysis of drying kinetics

With an initial moisture content of $105 \pm 15\%$ d.b., minced coconut was dried as a single layer to a final moisture content of around

3% d.b. at drying temperature 60–120 °C. Fig. 2 shows the dependence of moisture ratio (MR) on drying time. As expected for fluidized bed drying, moisture content dropped dramatically in the early drying stage, encompassing about one fourth of the overall time, and eventually changed little when close to a MR equivalent to moisture content of about 3% d.b. Initially, the abundance of free water on the product surface contributed to effortless moisture liberation. However, much more difficult it might be to expel water afterwards, when the product surface becomes harder due to shrinkage. The rate of moisture reduction was greater at a higher temperature, in response to influence of drying temperature on the ability to diffuse moisture. The encouragement of drying temperature on moisture migration has been reported for other foods—mint leaves [3], strawberries [5], green beans [8], parboiled wheat [9], corn [10], and carrots [11].

Fig. 3 depicts drying-rate changes with moisture ratio; no constant-rate drying period was observed; instead, the entire drying process was restricted to falling-rate drying, a typical of drying agricultural products. Some increments in drying rates appeared, while moisture ratios decreased. This contradiction occurred at 60 °C and 70 °C during the early drying stage (around the first 0.5 min), where moisture content drastically altered with time. The explanation may be as follows: each drying-rate value ($\Delta M/\Delta t$) within the first 2 min was computed by dividing change in moisture content (ΔM) by a corresponding fixed short-time interval of 10 s ($\Delta t = 10$ s). However, it is rarely possible to achieve precise 10-s intervals between successive experiments; there may also be slight errors in moisture content measurements. These factors may result in some unexpected drying-rate values. MR, derived from experimental moisture content, was fitted as a time function into the mathematical models (Table 1). The statistical results in terms of R^2 , P , χ^2 , RMSE, and residuals employed to evaluate the ability of the models to clarify drying behavior, are shown in Table 2. The models of Page, Two-terms, Midilli, Verma et al., and the modified Henderson and Pabis, possessed R^2 mostly >0.99, with small values for other criteria, implying excellent consistency of these five models with the experiments. Engaging intensively in drying kinetics, drying temperatures were correlated to the model constant of k (min^{-1}) and

Table 2
Statistical results derived from different thin-layer drying models.

No.	Model name	R^2	P (%)	χ^2	RMSE	Residuals
1	Newton or Lawis	0.95616	62.45	2.888×10^{-3}	0.052212	3.069161
2	Page	0.99236	19.63	0.502×10^{-3}	0.021792	0.327930
3	Henderson and Pabis	0.95634	60.53	2.868×10^{-3}	0.052102	3.055978
4	Logarithmic	0.98582	33.36	0.931×10^{-3}	0.029688	0.062136
5	Two term	0.99398	16.46	0.395×10^{-3}	0.019337	0.113451
6	Midilli	0.99399	14.61	0.394×10^{-3}	0.019330	0.021289
7	Verma et al.	0.99394	16.48	0.397×10^{-3}	0.019399	0.089966
8	Modified Henderson and Pabis	0.99524	12.43	0.312×10^{-3}	0.017199	0.025213

Table 3
Model and essential coefficients as functions of drying temperatures (°C) for various thin-layer drying models.

No.	Model name	Model coefficients
1	Newton	$k = 1.310072 - 0.051836T + 0.000884T^2$
2	Page	$k = -0.794814 - 0.035162T, n = 0.852593 - 0.00321T$
3	Henderson and Pabis	$a = 0.833139 + 0.001297T, k = -3.78802 + 0.082807T$
4	Logarithmic	$a = 0.763614 + 0.001775T, k = 0.7214 - 0.042844T + 0.000963T^2, b = 0.100558 - 0.0005T$
5	Two term	$a = 0.372032 + 0.004383T, k_0 = -4.30512 + 0.1205T, b = 0.602428 - 0.004139T, k_1 = -0.286181 + 0.012988T$
6	Midilli	$a = 0.985034 + 0.000171T, k = -0.910532 + 0.038027T, n = 0.946392 - 0.003725T, b = 0.006683 + 0.000005T$
7	Verma et al.	$a = 0.608060 - 0.004178T, k = -0.293238 + 0.013146T, g = -4.17195 - 0.119519T$
8	Modified Henderson and Pabis	$a = -0.419388 + 0.011311T, k = -0.103578 + 0.09027T, b = 1.207344 - 0.010573T, g = -0.022362 + 0.025925T, c = 0.193587 - 0.000553T, h = -0.725314 + 0.016026T$

the essential coefficients of the models. Desirable predictive correlations are shown in Table 3 and were incorporated into the corresponding models.

Fig. 4a and b shows comparisons of five outstanding models, simulated at 70 and 110 °C drying temperatures. Similar results were also apparent for other temperatures. While slightly underestimating moisture loss in the final stage of high-temperature drying, all showed a promise of predictability. In summary, the Modified Henderson and Pabis model is superior to others and yields maximum R^2 of 0.99524, P , χ^2 , RMSE, and residuals of 12.43%, 0.312×10^{-3} , 0.017199, and 0.025213, respectively. Fig. 5 depicts the predicted MR of the Modified Henderson and Pabis model compared with the experimental results. The data mainly scattered adjacent to the 45°-straight line, thus strengthening the view that this model could represent the drying characteristic of chopped coconut accurately.

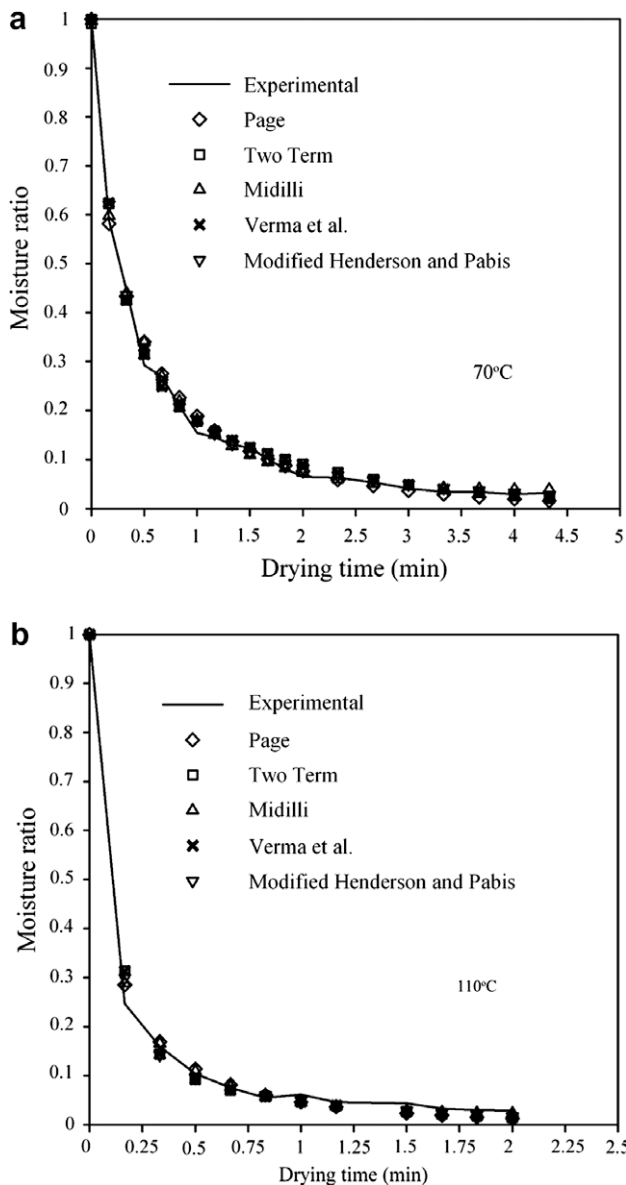


Fig. 4. Comparisons of the selected models fitted for chopped coconut dried at 70 °C and 110 °C.

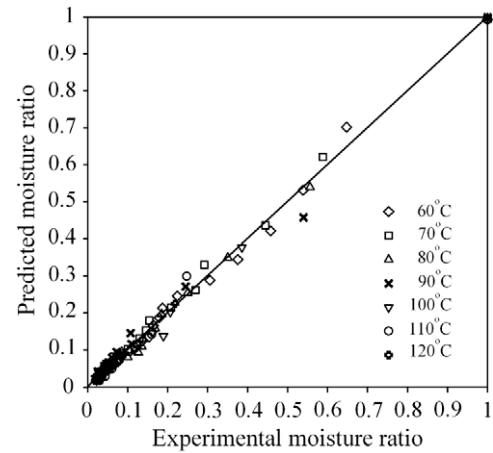


Fig. 5. Comparison of the experimental and predicted moisture ratios by Modified Henderson and Pabis model.

3.2. Effective diffusivity

The drying curves attest to the fact that the drying process is predominated by falling-rate drying, a consequence of internal mass-diffusion governing the whole process. Fick's law therefore can be adopted into the simulation. The values of D_{eff} associated with temperatures of 60–120 °C (Table 4) are 5.9902×10^{-8} – $2.6616 \times 10^{-7} \text{ m}^2/\text{s}$. As expected, drying temperature had an appreciable effect on D_{eff} , which increased vigorously with increases in temperature. It is important to underline that the typical values of D_{eff} for food and biological materials (Table 5), usually dried in hot-air tray dryers at temperature of 35–120 °C, ranged between 10^{-11} and $10^{-9} \text{ m}^2/\text{s}$, while those in the current study were far greater. Due to its effective mixing mechanism, fluidization can expedite heat and mass transfer between air and product: the more rapidly heat is conveyed to the product, the greater mass transfer rate is achievable; as a result, D_{eff} was enhanced. In addi-

Table 4

Values of effective diffusivity obtained from chopped coconut dried at different temperatures.

Temperature (°C)	Effective diffusivities (D_{eff}) (m^2/s)
60	5.9902×10^{-8}
70	9.6701×10^{-8}
80	1.1932×10^{-7}
90	1.7042×10^{-7}
100	1.9514×10^{-7}
110	2.2001×10^{-7}
120	2.6616×10^{-7}

Table 5

Effective diffusivities of chopped coconut and other products.

Product	Temperature (°C)	$D_{eff} \times 10^{-9}$	References
Chopped coconut	60–120	59.90–266.16	Present work
Mint leaves	35–60	3.06–19.41	[3]
Olive cake	50–110	3.38–11.34	[4]
Strawberry	50–65	0.49–1.42	[5]
Apple pomace	75–105	2.02–3.93	[7]
Green beans	50–70	2.64–5.71	[8]
Parboiled wheat	40–60	0.12–0.28	[9]
Corn	55–75	0.09–0.17	[10]
Carrots	50–70	0.77–9.33	[11]
Black tea	80–120	0.01–0.03	[14]
Young coconut strips	50–70	0.17–0.55	[16]

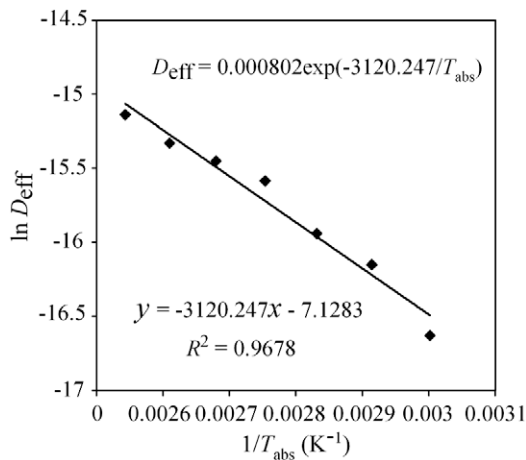


Fig. 6. Arrhenius-type relationship between effective diffusivity and reciprocal of absolute temperature.

Table 6

Activation energy of chopped coconut and other products.

Product	E_a (kJ/mol)	References
Chopped coconut	25.94	Present work
Mint leaves	62.96	[3]
Olive cake	17.97	[4]
Apple pomace	24.51	[7]
Green beans	35.43	[8]
Parboiled wheat	37.01	[9]
Corn	29.56	[10]
Carrots	28.36	[11]
Black tea	406.02	[14]
Young coconut strips	65.16	[16]

tion, the relatively small size of the chopped coconut ($d_m = 2.28$ mm) may aid dehydration, because the D_{eff} dominate mass transfer and the characteristic length (the diameter in case of spherical materials) played crucial roles. Characteristic length is inversely related to internal mass transfer resistance, so that the shorter the diameter of the product to be dried, the greater the moisture immigration to the product surface.

3.3. Activation energy

The \ln -values for activation energy, calculated by Arrhenius expression and plotted versus the reciprocal of absolute temperature (see Fig. 6), displayed a linear relationship. The activation energy (E_a) gained from the line slope yielded a value of 25.94 kJ/mol, and the pre-exponential (D_0) derived from the axis intercept point was $8.02 \times 10^{-4} \text{ m}^2/\text{s}$. As summarized in Table 6, a comparison of E_a with literature values for a diversity of agricultural products suggested that the present value was comparable to those in the table, other than the values for black tea, which were rather high.

4. Conclusions

Thin-layered chopped coconut was dried in a fluidized bed dryer at drying temperatures of 60–120 °C with a constant velocity of 2.5 m/s, to study drying kinetics and to fit various thin-layer

models. The model constants k (min^{-1}) were fitted so that they related to drying temperature. Unsurprisingly, changes in moisture content and drying-rate were contingent on drying temperature. Five of the 10 selected models impressively matched experimental data with R^2 , mostly >0.99 . Among these models, the Modified Henderson and Pabis model is considered the most precisely predictive model, reflected by $R^2 = 0.99524$ and small values for reduced chi-square, root mean square error, mean relative percent error and residuals. The drying-rate curves provided evidence that internal mass-diffusion predominated in the drying mechanism, where falling-rate drying encompassed throughout the drying period. Effective diffusivity D_{eff} , derived from Arrhenius type relation, varied between 5.9902×10^{-8} and $2.6616 \times 10^{-7} \text{ m}^2/\text{s}$ and increased substantially with increases in temperature. Comparisons relevant to values of D_{eff} , based on similar drying temperatures, revealed that the present values were much greater than for other food and agricultural products, conventionally dried in tray dryers. This was mainly due to the distinctive thorough mixing characteristics of fluidization, and may also be partly due to the small chopped coconut ($d_m = 2.28$ mm). Activation energy was found to be 25.92 kJ/mol.

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