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Kinetic Modelling of the Drying Behaviour of Palm Kernel (Dura Species)

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Abstract

Palm Kernel (PK) obtained from the oil palm fruit during palm oil milling, requires reduced moisture for efficient processing and storage. This study aimed to develop a drying kinetic model for predicting the drying behaviour of KP (Dura Species). The drying patterns of the PK at four temperatures: 40, 50, 60, and 70 °C, were studied using a conventional laboratory oven. The samples' weight loss and the corresponding moisture ratio were determined under the different temperatures. Five different mathematical models- Lewis, Page, Avhad and Marchetti, Logarithmic, and Henderson and Pabis were fitted to the experimental data and statistical indicators like Coefficient of determination (R^2), Root Mean Square Errors (RMSE), and Mean Sum of Squares of Errors (MSSE) were used to determine the most suitable model for the experimental data. The results showed that the rate of moisture evaporation increased at higher temperatures, but this rate slowed down progressively as the moisture content decreased over time. While all models adequately fit the experimental data, the Avhad and Marchetti model emerged as the most suitable for predicting PK drying kinetics. This model consistently matched the experimental data across all temperatures (40, 50, 60, and 70 °C), with R^2 values ranging from 0.9787 to 0.9944, RMSE values from 0.0406 to 0.0383, and MSSE from 0.0016 to 0.0014 across the different temperatures. Additionally, the palm kernel drying process was found to exhibit a low activation energy value (32.59 kJ/mol), indicating an energy-efficient drying process.

1. Introduction

Palm kernels are a significant by-product of palm oil extraction. The oil extracted from these kernels, known as palm kernel oil (PKO), is a versatile raw material used in producing soaps, detergents, cosmetics, and personal care products [1]. PKO is also suitable for the food industry as cooking oil, in margarine production, and as an ingredient in confectionery items [2].

Drying palm kernels before PKO extraction is crucial for several reasons. Primarily, it prevents spoilage by reducing moisture content, which inhibits mold and fungi growth, ensuring the product's quality and safety [3]. Proper drying also facilitates efficient storage and transportation. Drying is essential in various industries, including food processing, agriculture, and pharmaceuticals. This is to enhance product stability, shelf life, and quality by reducing moisture content. Drying involves the removal of water through evaporation, leading to the preservation and prevention of microbial

growth. Drying methods vary from traditional sun drying to modern techniques like freeze-drying and spray drying, each offering specific advantages based on the product and desired outcome [4].
The moisture content of palm kernels significantly impacts oil yield and quality during extraction. Studies have shown that the optimal moisture content for maximum oil yield lies between 6-12% (wet basis) [5]. Below this range, kernels become brittle and prone to breakage during processing, thereby reducing oil yield and quality [6]. Above this range, swelling of the mucilage creates a cushioning effect that hinders oil flow and rupturing of the kernel particles during expression [7]. Higher moisture content can also increase free fatty acid content and peroxide values, reducing oil quality and shelf life [6]. Therefore, maintaining optimal moisture content during processing is crucial for maximizing both oil yield and quality.
The efficiency and effectiveness of drying processes can be enhanced through mathematical models to predict and optimize drying behavior. These models help understand the complex interactions of heat and mass transfer during drying, leading to improved process control, reduced energy consumption, and enhanced product quality [8]. Integrating mathematical modeling into drying processes continues to advance efficiency and innovation. Thin-layer drying models have proven valuable in examining the drying processes of various marine and agricultural products [9, 10, 11]. Over the years, extensive research has been conducted using thin-layer drying models to investigate the drying behavior of various agricultural products, including Jatropha seeds [12], Macaúba almonds [13], pumpkin seeds [14], coconut [15], monkey cola [16], and Moringa oleifera seeds [17].
Based on the existing literature, there is a lack of research focused on the drying kinetics of palm kernels and available information on their drying characteristics is limited. This study aimed to fill this gap by investigating the drying behaviour of palm kernels at different temperatures (40, 50, 60, and 70 °C). The variation in moisture loss with time was monitored, the data fitted to five drying kinetic models, and the most suitable model for predicting the drying behavior of palm kernels was selected. Drying of agricultural products is often conducted at temperatures below 100 ^{o}C. A lower temperature reduces the risk of heat damage to the materials being dried. This is particularly important for maintaining the quality of the kernels, including their nutritional content, flavour, and appearance. The choice of the temperature range selected in this study was influenced by previously reported optimum drying temperatures for some agricultural products [12, 23].

2. Materials and Methods

2.1. Materials collection and preparation

The Palm kernels used for this study were obtained by cracking palm kernel shells discarded by local restaurants (Food court/Buka) at the University of Benin, Edo State, Nigeria. These palm kernel shells were wastes from the preparation of a local dish known as banga soup. The palm kernel shells were cracked manually and then placed in a local basket. The whole seeds of the kernels were selected and inspected properly to remove broken kernels or kernels that appear to have deep cuts which could lead to faster deterioration by microorganisms. The selected whole seeds were immediately mopped with a wet clean cloth and thereafter put in a water-proof polythene bag.

2.2. Drying experimental procedure

The drying experimental runs were carried out in a convective oven (Zenith DHG-9053A) following a similar procedure to those outlined by Subroto [18]. The initial moisture content of the palm kernels on a dry weight basis was determined by drying 20 g of the palm kernel sample at a temperature of 105 ^{o}C for 24 hours. The experiments were conducted at four distinct temperatures (40, 50, 60, and 70 °C). Two samples of the palm kernels, each weighing 20 g, were placed in the preheated oven, and the variances in weight were recorded at a specific time. The drying process was monitored by taking measurements at regular intervals. For the first 60 minutes, measurements were recorded every 10 minutes. After that, measurements were taken every 30 minutes for the next 4.5 hours of drying for each sample. The weight loss data collected at different time points was converted into two key parameters: Moisture content - using Equation (1) and the dimensionless moisture ratio - using Equation (2).

$$MC_{\text{dry basis}} = \frac{m_i - m_f}{m_i} \tag{1}$$

$$MR = \frac{X}{X_o} \tag{2}$$

Where, $MC_{\text{dry basis}}$ = moisture content on a dry basis, m_i = initial mass of palm kernels before drying, m_f = final mass of palm kernels after drying, X = moisture content at any time (t), and X_O = initial moisture content.

2.3. Drying kinetic modelling

The moisture ratio information was analyzed by fitting it to five distinct empirical thin-layer drying kinetic models outlined in Table 1. This fitting process involved utilizing non-linear regression analysis to minimize the sum of squared errors. The Solver tool in Microsoft Excel was employed for this analysis, enabling the determination of the specific constants associated with each model.

Table 1: Mathematical models and model formulas used in this study

S/N	Model Name	Formula
1	Lewis	MR = exp (-kt)
2	Page	MR = exp (-kt^n)
3	Henderson and Pabis.	MR = a exp (-kt)
4	Logarithmic	MR = a exp (-kt) + c
5	Avhad and Marchetti	MR = a exp (-kt^n)

Where, k = drying rate constant, t = drying time, and (a, c, and n) are the model constants.

In the evaluation of model fitness, a range of statistical indicators was utilized to evaluate and compare the suitability of the drying models. The statistical indicators used were R^2, RMSE, and MSSE and were respectively determined using Equations (3) – (5) [19 – 22].

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(MR_{exp.i} - MR_{cal,i})^2}{\sum_{i=1}^{n}(MR_{av,exp} - MR_{av,cal})^2} \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,\ i} - MR_{cal,\ i}\right)^2}{N}} \tag{4}$$

$$MSSE = \frac{\sum_{i=1}^{N}\left(MR_{exp,\ i} - MR_{cal,\ i}\right)^2}{N - n_p} \tag{5}$$

where, $MR_{exp,i}$ is the experimental moisture ratio for the ith run, $MR_{cal,i}$ is the calculated moisture ratio for the ith run, MR_{av} is the average moisture ratio, N is the number of runs conducted, and n_p is the number of variables to be determined

2.4 Determination of activation energy

The activation energy (E_A) of the palm kernel drying process was determined using the Arrhenius equation (Equation 6).

Equation 6 was transformed into a linearized form, resulting in Equation (7). This new equation establishes a linear relationship between the natural logarithm of the drying rate constant (ln(k)) and the reciprocal of the drying temperature (T^{-1}). Using Microsoft Excel 2019, a plot was created by graphing ln(k) against T^{-1}. This plot was generated using the data from the best-performing drying model, as determined by the statistical analysis [23].

$$k = k_o e^{\left(-\frac{E_A}{RT}\right)} \quad (6)$$

$$\ln k = \ln k_o - \frac{E_A}{R}\left(\frac{1}{T}\right) \quad (7)$$

Where, k_o' is the pre-exponential factor or Arrhenius constant (min^{-1}), E_A is the activation energy of the reaction (KJ/mol), R is the gas constant = 8.314×10^{-3} kJ/K.mol, and T is the reaction temperature (K).

3. Results and discussion

The outcomes of the palm kernel drying experiment, illustrating how the moisture ratio changes over time at different temperatures (40, 50, 60, and 70 °C), are depicted in Figure 1. The graph demonstrates that higher drying temperatures resulted in a faster evaporation rate of moisture from the palm kernel. Observing Figure 1, it is evident that at 40 °C, it took approximately three times longer for the moisture ratio of palm kernels to decrease below 0.5 compared to the time required at 70 °C. This trend mirrors observations made in various food products such as grape seeds [24], pumpkin seeds [25], castor beans [26], fresh jatropha seeds [27], sorghum grains [28], orange seeds [29], and Hass avocado seeds [23]. Increasing the temperature widens the disparity between the vapor pressure of the drying air and that of the seed samples, thereby resulting in more rapid and extensive water removal at higher temperatures [27, 29].

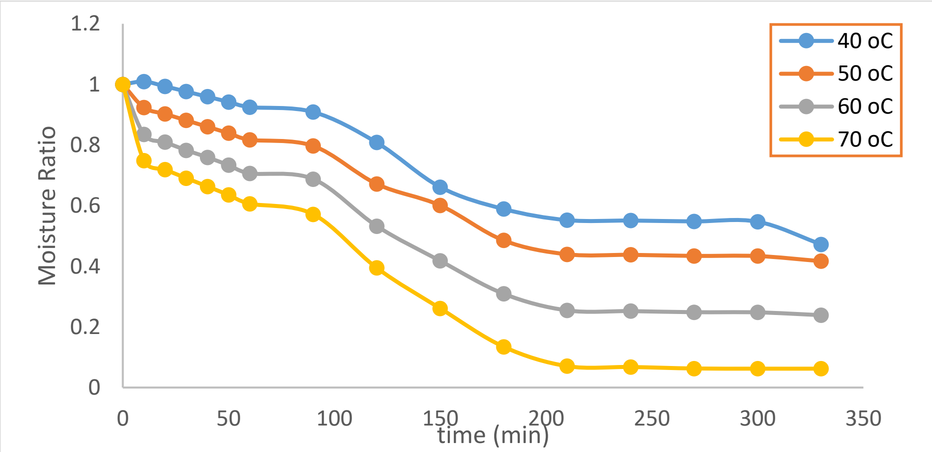


Figure 1: Variation of moisture ratio with time at 40, 50, 60, and 70 °C

In the drying process of whole palm kernel seeds, as depicted in Figure 1, the rate of moisture evaporation was initially high due to the substantial amount of water needing removal, but gradually decreased as it approached equilibrium moisture content. Initially, the rate of moisture evaporation is faster due to the higher moisture content of the seeds, but it slows down as the moisture content decreases during the drying process. The drying rate of seeds decreases over time, suggesting that there is no significant constant rate period or that such a period is very short compared to the overall drying process [30].

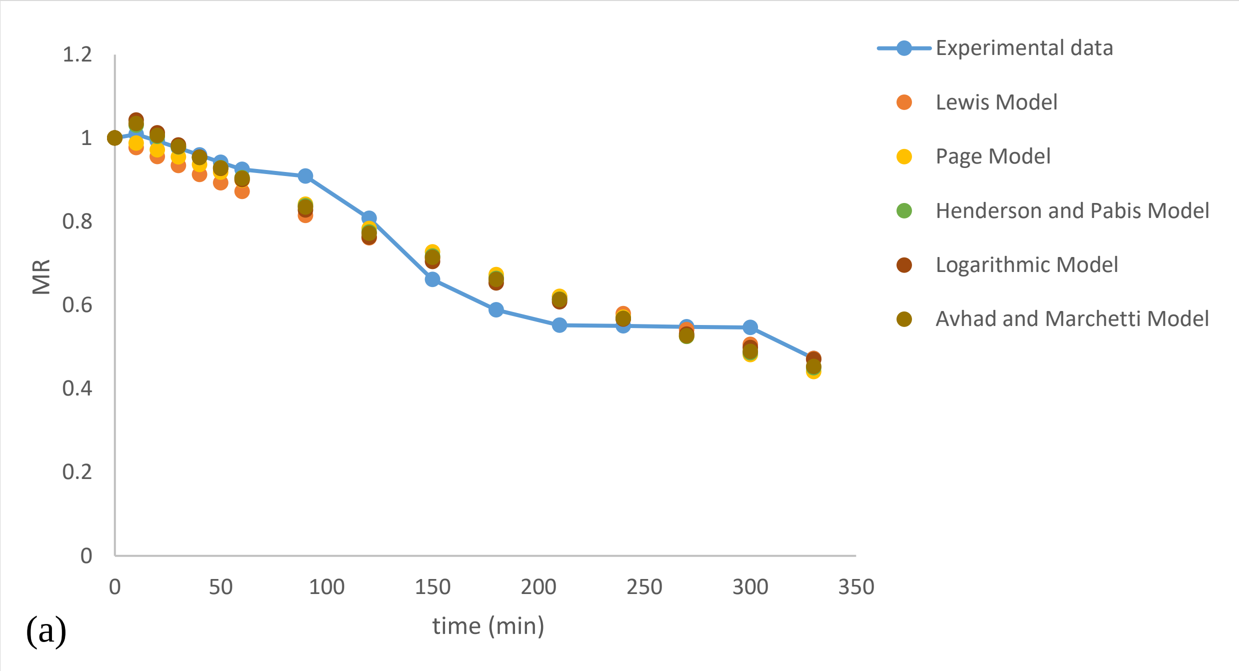
3.1. Kinetic modelling of the palm kernel drying process

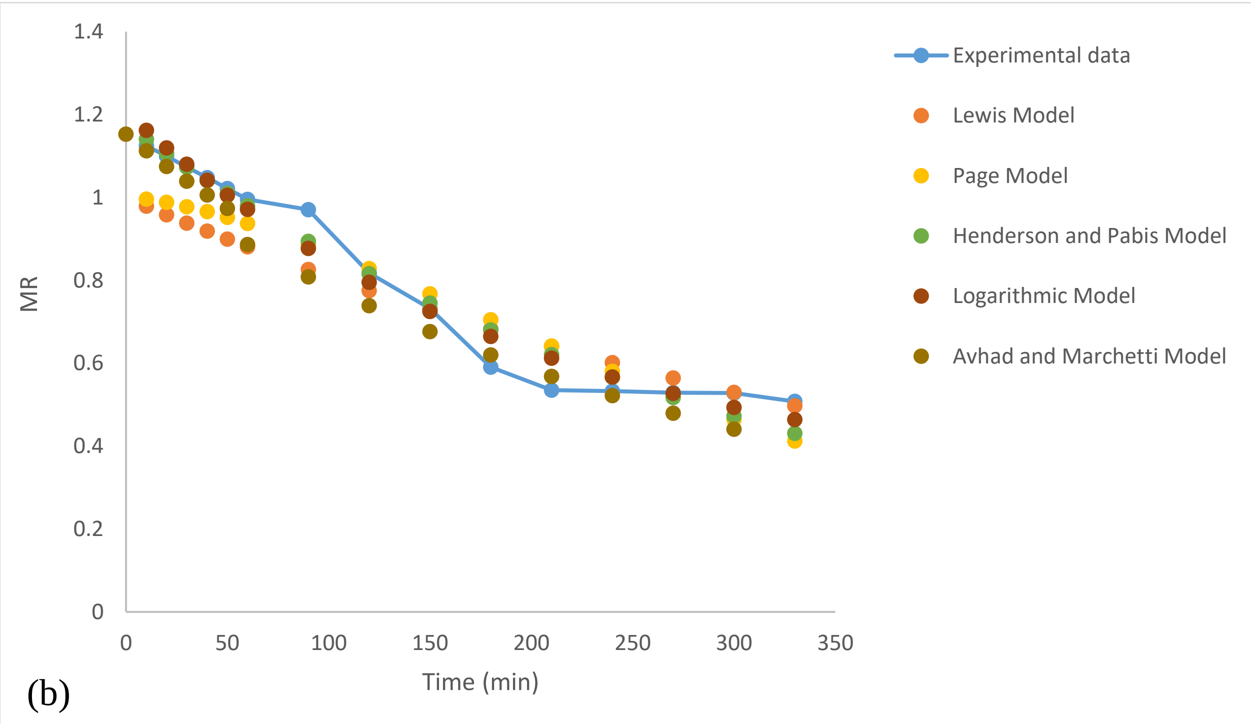
The results of the regression analysis performed on the drying kinetic experimental data obtained at temperatures of 40, 50, 60, and 70 °C are shown in Table 2. The Table also shows the values of the statistical indicators as well as the constants (a, n, and k) obtained for all the mathematical models utilized at the different temperatures. Interestingly, the values of the drying rate constant k, which represents the moisture removal rate, were observed to increase with the rise in drying temperature for the oil seed, as expected, affirming the temperature-dependent nature of rate constants. Nevertheless, the determined values for the parameters a and n exhibited variability rather than remaining constant, showing a trend of decline as the drying air temperature rose, alongside the increase in the drying rate constant, k. A similar observation was also reported by Keneni et al. [12] for the drying of *Jatropha curcas* L. seeds. However, a positive trend, where a and n increased with an increase in the drying temperature was reported for the drying of castor oil seeds [26]. In contrast to these findings, Simal et al. [31] reported a constant, temperature-independent n value of 0.796 using a Page model. The difference in the trends and values of the parameters observed in the various studies may be attributable to the nature and constituents of the materials being dried.

Table 2: Results of the regression analysis performed on the various model

Model	Temp (^{O}C)	Model Constants				Statistical Parameters		
		k	A	n	c	R^2	RMSE	MSSE
Lewis	40	0.002272				0.977946	0.050345	0.002535
	50	0.00326				0.97771	0.111703	0.010138
	60	0.004119				0.9747	0.074593	0.005564
	70	0.007257				0.9305	0.080903	0.006545
Page	40	0.00786		1.198467		0.976848	0.045225	0.002045
	50	0.00612		0.88016		0.9919	0.082165	0.006751
	60	0.0075		1.326922		0.9886	0.057357	0.00329
	70	0.0087		1.433072		0.94	0.0523	0.0027
Henderson and Pabis	40	0.0025	1.0576			0.980415	0.0406	0.0017
	50	0.0030	0.9655			0.9857	0.0463	0.0022
	60	0.0048	0.9323			0.9655	0.0537	0.0029
	70	0.0080	0.9160			0.915	0.0736	0.0054
Logarithmic	40	0.0039	0.8351		0.2403	0.9817	0.0392	0.0015
	50	0.0048	0.7627		0.2275	0.9657	0.0429	0.0018
	60	0.0072	0.7306		0.0363	0.9840	0.0537	0.0029
	70	0.0084	0.7160		0.0112	0.9770	0.0736	0.0054
Avhad and Marchetti	40	0.0032	1.0659	0.9636		0.9787	0.0406	0.0016
	50	0.0047	0.9860	0.9177		0.9817	0.0459	0.0021
	60	0.0049	0.9666	0.8812		0.9834	0.0525	0.0027
	70	0.0053	0.8880	0.8563		0.9944	0.0383	0.0014

Based on the results in Table 2, the various mathematical models were used to generate projected data that were juxtaposed with the actual drying data of the palm kernels as shown in Figures 2(a-d). This was done to identify the most appropriate model for characterizing the palm kernel drying process. From Figures 2(a–d), it is evident that all the models fit the drying kinetics data effectively. However, the selection of the most appropriate mathematical model was based on criteria such as R^2, MSSE, and RMSE values, with a primary emphasis on R^2 values [32].





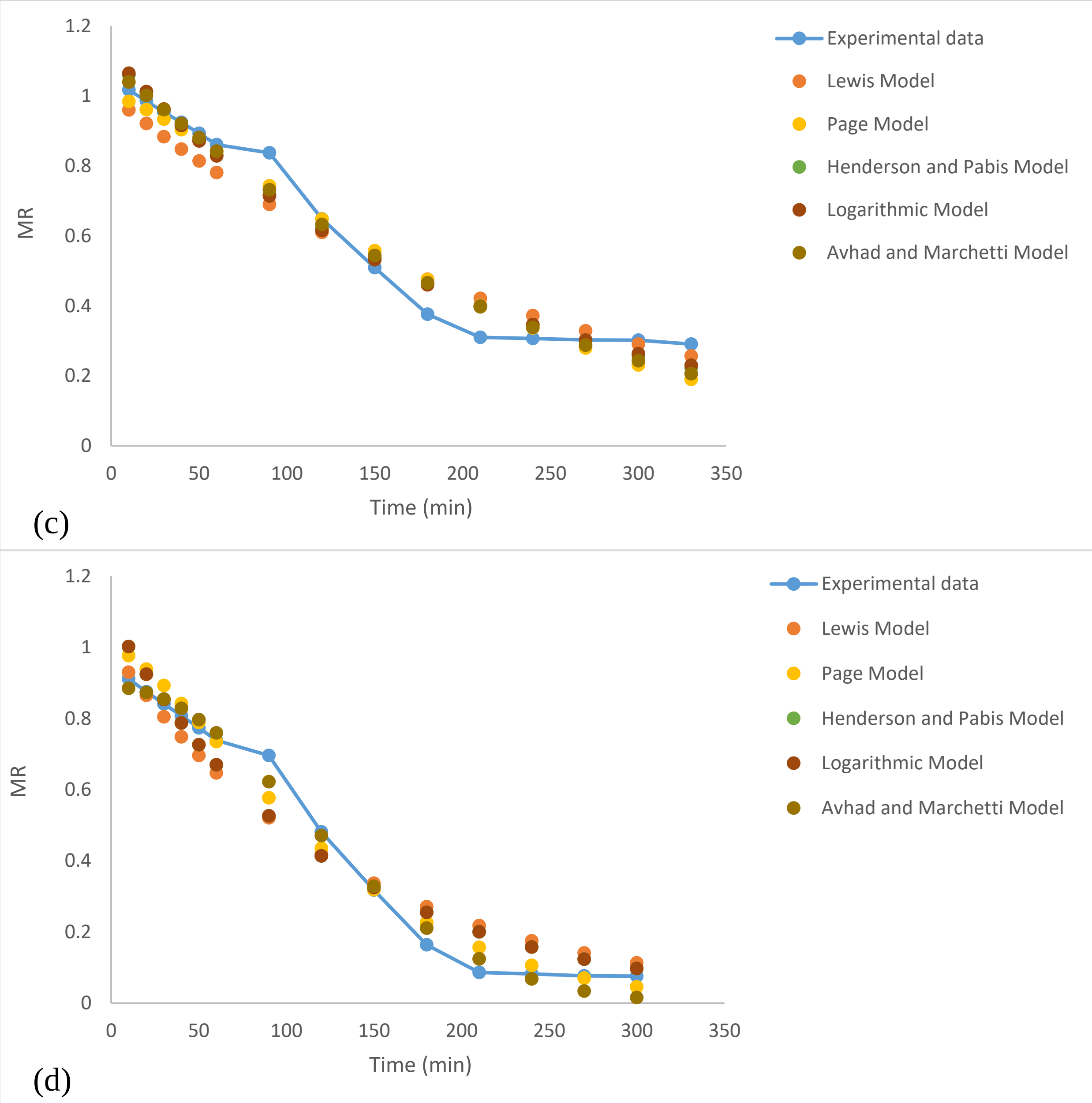
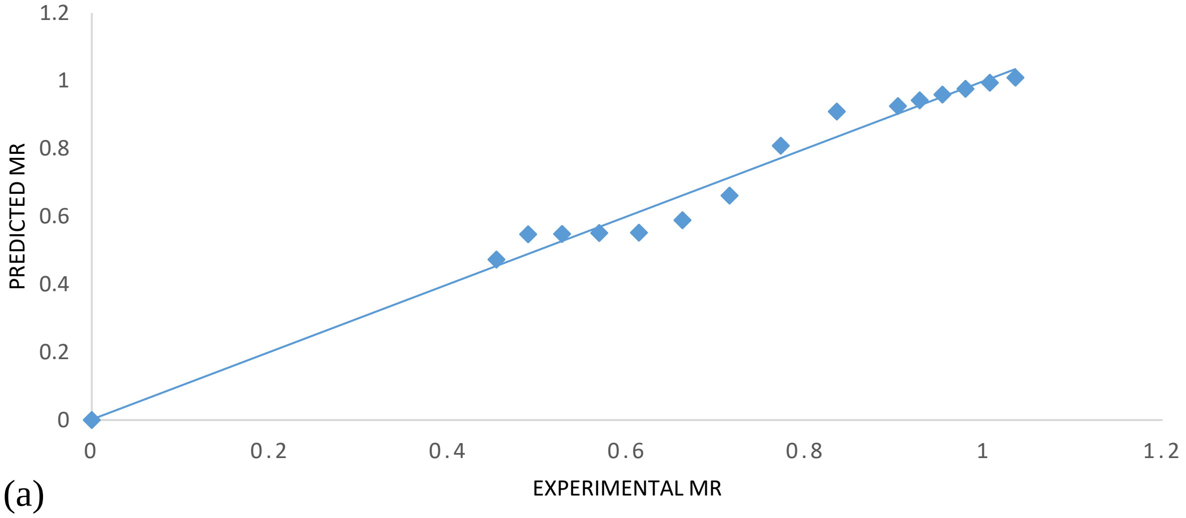
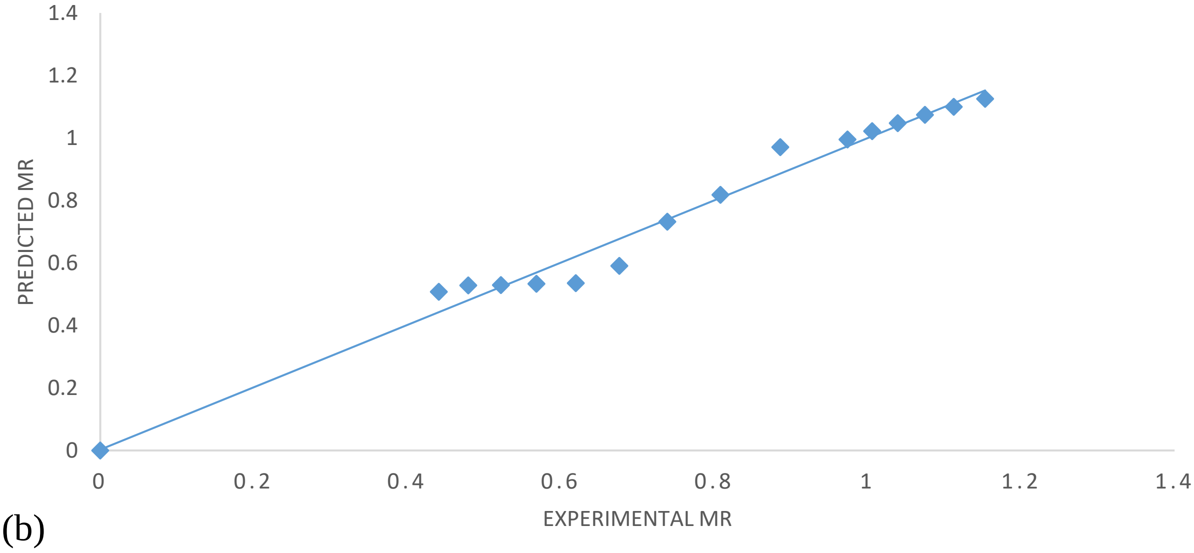


Figure 2: Plots showing the comparison between the experimental and the various model-predicted moisture ratios at drying temperatures of (a) 40 °C (b) 50 °C (c) 60 °C (d) 70 °C.

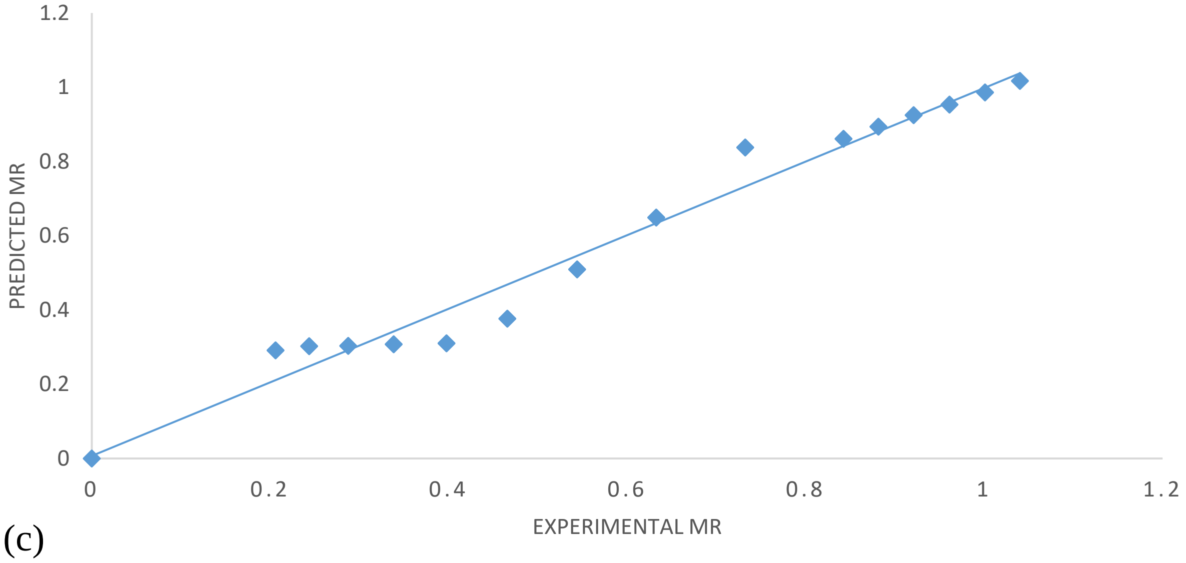
Among the five mathematical models assessed, the Avhad and Marchetti model demonstrated the closest fit to the experimental data, having R^2 values of 0.9787, 0.9817,0.9834 and 0.9944, RMSE values of 0.0406, 0.0459, 0.0525, and 0.0383, and MSSE values of 0.0016, 0.0021, 0.0027, and 0.0014 at the different temperatures (40, 50, 60, and 70 °C) respectively for palm kernel drying process. The R^2 values (0.9944) across the four temperatures for the Avhad and Marchetti model were closest to 1 when compared to other models utilized. The model also has the lowest RMSE value of 0.0383 and MSSE value of 0.001467 for the palm kernel drying at 70 °C. Based on these reasons, the Avhad and Marchetti model was selected as the best drying kinetic model that best describes the drying behaviour of palm kernel. The correlation between the experimental and the Avhad and Marchetti model-predicted moisture ratio at the different temperatures is shown in Figure 3(a – d).


PREDICTED MR
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
EXPERIMENTAL MR

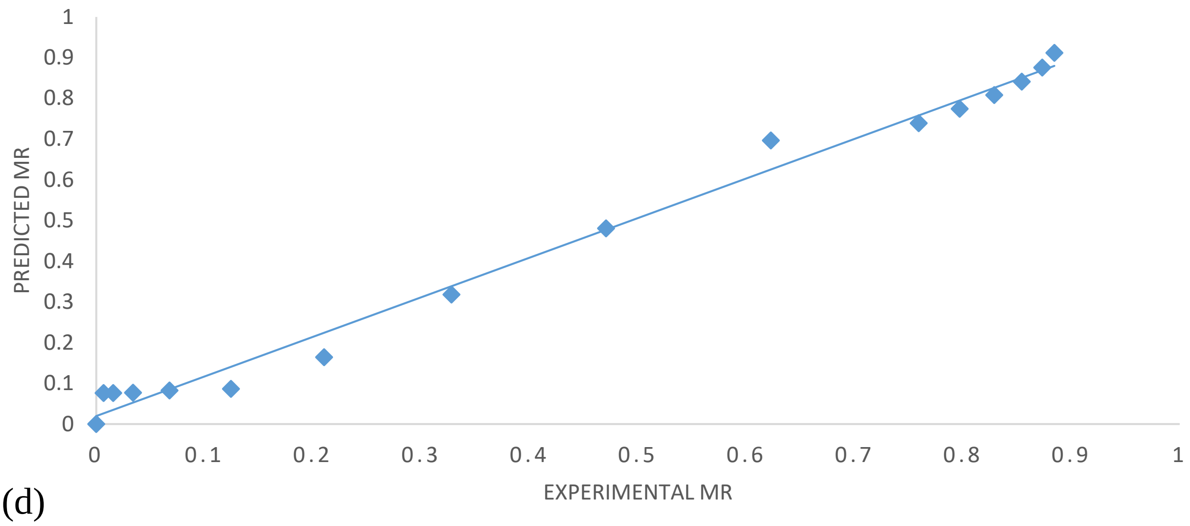
(a)


PREDICTED MR
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
EXPERIMENTAL MR

(b)


PREDICTED MR
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
EXPERIMENTAL MR

(c)



(d)

Figure 3: Plots of Predicted against Experimental Moisture Ratio using Avhad and Marchetti model at (a) 40 °C, (b) 50 °C, (c) 60 °C, and (d) 70 °C

3.2 Determination of activation energy

The activation energy is a crucial parameter that must be determined to ascertain the ease of drying of the material. It is the energy necessary to cause the extraction of moisture from the material being dried [33]. Typically, the magnitude of the activation energy is correlated with the inherent properties of the material being dried. Therefore, if water molecules are tightly bound within the material's structure, their removal becomes more challenging [34]. Large activation energy implies higher difficulty in moisture removal from the material during drying. The plot of lnk against T^{-1} based on Avhad and Marchetti's drying kinetic model is shown in Figure 4, from which the activation energy was calculated from the slope of the graph. The activation energy of the palm kernel drying process was 32.59 kJ/mol. The activation energy for the drying of the palm kernels was found to be lower than values reported for some other food products as shown in Table 3.

The lower activation energy is an indication that minimal energy is required for moisture removal from palm kernels compared to other food products. This also means that the moisture removal process from the kernels can happen efficiently even at relatively lower temperatures and less external energy input is required to drive the drying process. This can lead to energy savings and lower operating costs for drying facilities. Again, drying at lower temperatures reduces the risk of heat damage to the palm kernels. This is particularly important for maintaining the quality of the kernels, including their nutritional content, flavor, and appearance. With lower activation energy, the drying process can proceed more rapidly, leading to shorter processing times. This can increase throughput and overall efficiency in production.

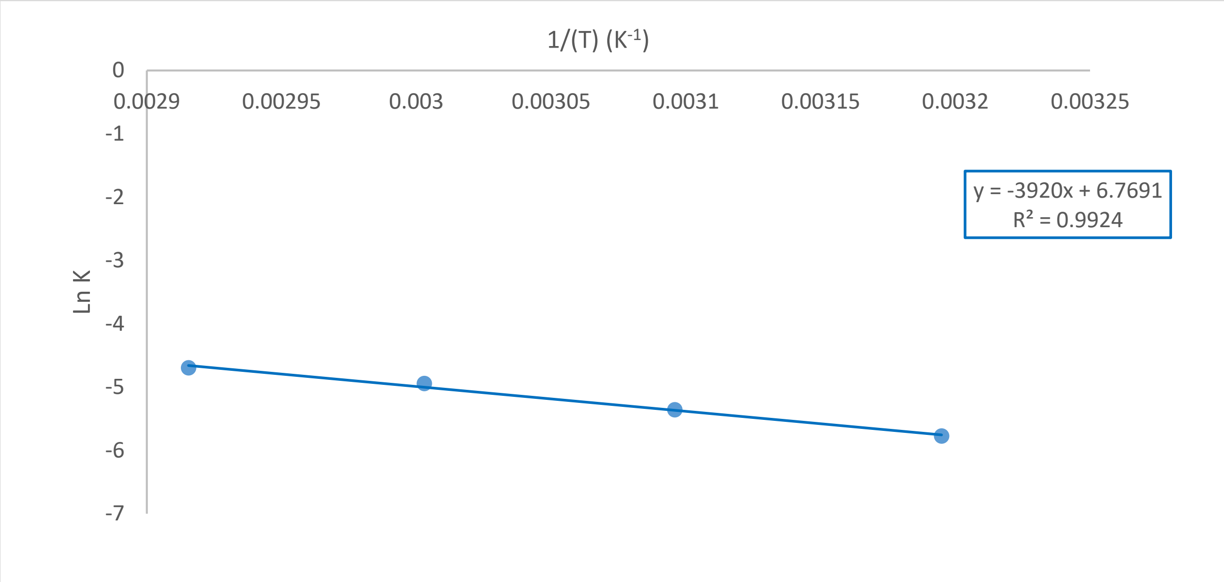


Figure 4: A plot of Lnk against (T^{-1}) based on Avhad and Marchetti drying kinetic model

Table 3: Comparison of the activation energy obtained in this study with some reported values

Material being dried	E_A (kJ/mol)	Reference
Palm kernel	32.6	This study
Basil	33.2	[35]
Mint	82.9	[36]
pumpkin	35.6	[37]

4.0.Conclusion

This study has successfully investigated and modelled the drying behaviour of Dura species of palm kernels at harvest moisture content under varying temperatures (40 – 70 °C). A faster moisture removal rate at higher temperatures was observed, which slowed down over time due to decreasing moisture content. Avhad & Marchetti, Logarithmic, and Henderson & Pabis models demonstrated better agreement with the experimental data compared to others. Avhad & Marchetti's model, however, excelled above others, particularly at 70 °C ($R^2 = 0.9944$), accurately representing drying kinetics across all temperatures. Based on the Avhad & Marchetti model, an activation energy of 32.59 kJ/mol was obtained for the drying process, indicating the ease at which moisture is removed from palm kernel in contrast to other agricultural products which have relatively higher activation energy. This can lead to energy savings and reduced operational costs in industrial drying operations of palm kernel

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