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Kinetics and Mass Transfer Studies of Nigerian Cashew Nutseed Oil (CNSO) Production

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Abstract— *To improve the efficiency of oil recovery from Cashew Nutseeds (CNS) and optimize extraction conditions, it is important to understand the kinetics and mass transfer processes of the oil extraction. This study investigated the mass transfer and kinetic parameters governing the extraction of oil from Nigerian Cashew Nuts using n-hexane as a solvent. Experimental analyses were conducted to determine the influence of temperature (313.15K, 318.15K, 323.15K, 328.15K, and 333.15K) and extraction time (50, 60, 70, 80, and 90 minutes) on the yield of oil. Results revealed that at 313.15K, oil yields of 10.56%, 12.78%, 14.21%, 16.11%, and 17.28% were recorded at the different extraction times accordingly, and a similar trend was observed at all temperatures used in this study. This indicated that across all temperature levels, yield exhibits a positive correlation with extraction time, suggesting that prolonged extraction enhanced the yield of Cashew Nutseed Oil (CNSO). A comparative assessment of experimental data and the corresponding predictions from the Power model over the five different time intervals revealed a deviation of < 1.4% suggesting a high degree of agreement between the Power model and the experimental data. By comparing the coefficient of determination (R^2) values, findings revealed that the first-order kinetics dominated with (R^2) values > 0.96 across all temperature levels with a power index, n, ranging between 0.5666 and 0.8369, which is < 1. The calculated mass transfer coefficients, k_m, using Fick's diffusion model, varied between 0.4010 and $0.5627 min^{-1}$ across all temperature levels with a standard deviation of $0.1046 min^{-1}$, indicating a moderate variability in the observed values with diffusion-controlled mass transfer. Temperature significantly influenced oil yield from CNS, and optimization strategies can enhance industrial-scale oil production efficiency; hence, future studies should incorporate activation energy calculations using the Arrhenius equation to further elucidate the thermodynamic aspects of the process.*

Keywords— *Cashew Nutseed Oil, Mass transfer, kinetics, Diffusion model, Order of reaction, reaction rate*

I. INTRODUCTION

Composite industrial materials are increasingly being utilised to reduce reliance on fossil fuels and focus on safer, more eco-friendly alternatives [1]. Materials that are renewable or feedstocks, derived from plant and animal sources, have an unlimited supply and can regenerate over time. These renewable resources are more environmentally friendly and sustainable than non-renewable resources like coal, natural gas, and petroleum, making them cost-effective and naturally replenished [2,3]. Processing cashew apples result in the production of Cashew Nutseed Oil (CNSO), which is one renewable resource from plants [4,5].

The abundance of cashew nuts in many tropical regions, especially in Nigeria, has led to the recognition of its potential oil source with numerous applications in the food, cosmetic, and pharmaceutical industries [6].. CNSO has been utilized in numerous polymer-based industries, with its primary use being in the production of brake linings and clutch facings for the automotive industry. According to the International Trade Centre in 2010, Nigeria is a top producer of 958,000 metric tons of cashew nuts. One of the primary byproducts that are obtained in cashew processing industries is Cashew Nutseed Oil (CNSO) [1,6].

As the demand for natural and sustainable alternatives to petroleum-based products grows, more and more attention is being given to the extraction of oil from various plant sources [7,8].. CNSO extraction is a complex process that can be affected by many factors, including extraction technique, solvent type, extraction time, temperature, and seed particle size. Maximizing yield and quality necessitates efficient oil extraction techniques. Hence, different extraction methods are utilized, with each having its own advantages and disadvantages. The most common extraction technique used is the solvent extraction [9]. Oil from seeds is dissolved with high efficiency using a suitable solvent, n-hexane solvent extraction is frequently employed due to its low boiling point and non-polar nature, making it easy to separate after extraction, and due to its low toxicity, high efficiency, and selectivity [10,11]

Various studies have been conducted using cashew nuts and kernels for oil production. Synthesis and production of Cashew Nut Shell Liquids (CNSL) resins were carried out by [4]. The study revealed that the resins produced had properties that resembled those of commercial resins. [12] conducted studies on oil extraction from Nigerian cashew nuts using petroleum ether. The kinetics and thermodynamics properties of the process were investigated. The conclusion was that applying conventional and modified power models can be beneficial in the design analysis of extraction systems and help prevent man-hours from being wasted. Similarly, [13] experimentally investigated the kinetics and thermodynamics of oil extraction from Ghanaian cashew kernels using hexane and revealed that major fatty acid compositions were identified in the oil characterization: oleic acid and linoleic acid.

To improve the efficiency of oil recovery and optimize extraction conditions, it is crucial to understand the mass transfer phenomenon and kinetics of the oil extraction process using a readily available solvent [9]. Kinetic studies investigate the rate of oil extraction, reaction orders, and rate constants associated with the process, while the mass transfer studies involve determining the mass transfer coefficient as it determines the efficiency rate of mass transfer between the biomass and the extracting solvent.[8]. This study involves the extraction of oil from Nigerian cashew nuts using n-hexane, determining the effect of time on the percentage yield of oil and in detail the kinetic, and mass transfer of the oil extraction process. The focus of the investigation is to examine cashew nuts as a potential oil source, providing a sustainable and renewable alternative to petroleum-based oils. Gaining knowledge about the kinetic and mass transfer processes involved in extracting oil from cashew nut seeds would be advantageous for optimizing processes and controlling product quality.

II. MATERIALS AND METHODS

2.1 Materials

Some of the major materials and equipment for this study include: Grinded Cashew Nutseed (CNS), Specific gravity bottle, Distilled water, Oven, Weighing balance, Soxhlet Extractor, Heating mantle, Simple distillation apparatus, Hot Plate, Stop watch, Beaker, pH meter, Picnometer, ASTM 300 Capillary tube, n-hexane

2.2 Methods

2.2.1 Oil Extraction Process

The procedure for the extraction of oil from the Cashew Nutseeds (CNS) is as reported by [4,12]. The CNS was washed thoroughly with distilled water to remove dirt, dust, pesticide residue, and other impurities. The nuts were cut open to expose the seeds and sundried for two weeks. Thereafter, the seeds were ground to powdered form and sieved to a uniform particle size of 1.88 mm. The oil extraction process was carried out in Soxhlet apparatus using n-Hexane as the solvent at a constant sample weight of 50g, seed particles of size 1.88 mm, and solvent volume of 250 ml. The kinetics of CNS oil extraction process wasalso studied at a constant sample weight of 50g, seed particles of size 1.88 mm and solvent volume of 250 ml, while the temperature was varied from 313.15K – 333.15K in the interval of 5K and extraction varied from 50 - 90 minutes at the interval of 10 minutes.

50g of the sample was placed in the thimble of the extractor and 250 ml of n-hexane was poured into a round-bottom flask. The flask was heated via a mantle set at 313.15K to extract the oil in the seed particles. The extracted oil +solvent was collected and distilled at 341.15Kwhich is the boiling point of pure hexane to separate the solvent (hexane) from the extracted oil. The distilled oil was weighed and the yield was calculated. The effect of temperature and extraction time on oil yield was carried out at temperatures of 313.15K, 318.15K, 323.15K, 328.15K, and 333.15Kand extraction times of 50, 60, 70, 80, and 90 minutes.

The percentage oil yield was calculated using the expression below:

$$Y = \frac{W_O}{W_C} \times 100 \qquad (1)$$

Where;
Y - the oil yield (%)
W_O- the weight of pure oil extracted (g)
W_C- the weight of the sample of ground cashew nut seed used in the experiment.

2.2.2 Model Development

Models were developed for both the kinetics and mass transfer of oil extraction as shown below according to the work of [12,13,14]

Kinetics Studies of Oil Extraction from CNS

In this study, the power model was used to investigate the extraction process of Cashew Nutseed Oil (CNSO).

Power Model

The power model is expressed as:

$$Y = kt^n \qquad (2)$$

Where:
Y = Percentage of oil yield (%)
$k = characteristic\ constant\ (min^{-1})$
t = Extraction time (min)
n = Diffusion exponent

The rate constant and power index were determined by integrating both sides of Equation (2) as follows:

$$\text{In Y} = \text{In k} + \text{n In t} \qquad (3)$$

Hence, a plot of In Y against In t gives a slope equivalent ton and intercept as k.

Where: k is the characteristic constant incorporating the active coefficients, while the power index,n, is the diffusion exponent, which indicates the transport mechanism of oil, and it is less than 1 (n < 1) in most oil extraction processes [14].

2.2.3 Order of the extraction process

Using the first, second, and third-order kinetic models, the sequence of the extraction procedure was assessed. Integrated rate laws were used to plot the graphs, where the slopes of the graphs represent the kinetic constants (k) as shown:

First-Order equation:

$$In\left(\frac{(A)}{(A)_0}\right) = -akt \qquad (4)$$

$$In(A) = -ak.t + In[A]_0 \qquad (5)$$

Second-Order equation:

$$\frac{1}{[A]} - \frac{1}{[A]_0} = akt \qquad (6)$$

$$\frac{1}{[A]} = ak.t + \frac{1}{[A]_0} \qquad (7)$$

Third-Order equation:

$$\frac{1}{[A]^2} - \frac{1}{[A]_0^2} = 2ak.t \qquad (8)$$

$$\frac{1}{[A]^2} = 2ak.t + \frac{1}{A_0^2} \qquad (9)$$

2.2.4 Rate of Extraction

The model used for calculating the yield for the rate of extraction from first-order kinetics is as reported in Emmanuel et al., 2024:

$$Y = Y_e(1 - e^{-kt}) \qquad (10)$$

Where:
Y = the yield at time t
Y_e = the maximum yield (equilibrium yield)
K = the rate constant
t = the extraction time

2.2.5 Mass Transfer Studies

Three types of diffusion coefficients are considered in the process of oil extraction from CNS:

- Internal diffusion coefficient within the solid particles (biomass)

- Coefficient of free molecular diffusion in the boundary layer on the surface of the particle
- Coefficient of convective diffusion in liquid phase around the particle [14,15].

Moreover, the extraction of oil from CNS has the following stages:

- The hydrodynamic state of the n-hexane washing the CNS particles determines how well the solvent (n-hexane) penetrates the pores of the particles.
- Mass transfer by the dissolution of the oil which is through a semipermeable membrane,
- Transfer of the oil from the surface of the CNS particles into the solvent. This is primarily due to convective diffusion [14,16], which is dependent on the hydrodynamic circumstances of washing the particles with n-hexane.

Accordingly, by mathematical modeling:

The mass of CNS entering per unit time in the solvent, m_e, is determined by the expression:

$$\Delta m_e = \frac{V_e dC_e}{dt} \tag{11}$$

Mass of biomass oil extracted per unit time:

$$-\Delta m_b = K(C_b - C_e).F \tag{12}$$

Where: F is the volume surface of solid particles. Then the material balance equation can be written in the form:

$$-\Delta m_b = \Delta m_e \tag{13}$$

Combining equations (11) and (12) gives:

$$\frac{V_e dC_e}{dt} = K(C_b - C_e).F \tag{14}$$

Initially, $\tau = 0$, hence;

$$C_b = C_e \tag{15}$$

Where:

C_b and C_e is the concentration of oil in the biomass particles and extractant (solvent) respectively.

However, analytically, Fick's Law describes the diffusion of a solute from a solid phase (biomass - CNS) into a solvent (n-hexane). The mass transfer coefficient (k_m) can then be determined using Fick's First Law (steady state diffusion) as:

$$J = -D\frac{dC}{dx} \tag{16}$$

Where;

J = diffusion flux (kg/m^2.s)

D = Diffusivity or diffusion coefficient (m^2/s)

$\frac{dC}{dx}$ = concentration gradient (kg/m^3.m)

But, the mass transfer coefficient (k_m) is the ratio of the flux to the driving force (concentration difference);

$$J = k_m\,(C_s - C_b) \tag{17}$$

Where;

C_s = concentration of oil in the solvent (kg/m^3)

C_b = bulk concentration of oil in the biomass (kg/m^3)

Now, comparing equations (16 and 17) gives the relationship between Fick's First Law and the mass transfer coefficient to the diffusivity expressed as:

$$k_m = \frac{D}{\delta} \tag{18}$$

Where;

K_m = mass transfer coefficient (m/s)

D = diffusion coefficient (m^2/s)

δ = boundary layer thickness (m)

Furthermore, the mass transfer coefficient, k_m, can also be expressed as:

$$\frac{dC_s}{dt} = k_m(C_o - C_s) \tag{19}$$

Where;

C_s – oil concentration in solvent at time, t

C_o – initial oil concentration in biomass

Solving the equation (19) gives:

$$C_s(t) = C_0\,(1 - e^{-kt}) \tag{20}$$

Equation (20) predicts how oil concentration increases over time

However, experimentally, mass transfer coefficient, k_m is obtained by plotting In $(C_0 - C_s)$ versus time, where the slope gives k_m.

$$k_m = -\frac{d}{dt}\,In\,(C_0 - C_s) \tag{21}$$

In this study, the model used to obtain the mass transfer coefficient, k_m, is according to that reported in [13], where:

$$\frac{dC}{dt} = k_m \times (C_o - C_t) \tag{22}$$

Integrating and rewriting Equation (22)gives:

$$-In\left(\frac{C_o - C_t}{C_o}\right) = k_m t \tag{23}$$

Where:

$C_o$and C_t represent mass concentrations of CNSO at C_o = 90 min and C_t at time, t whereas $K_m$represents the mass transfer coefficient.

In terms of yield of CNSO, Equation (23) can be expressed as:

$$-In\frac{Y_f - Y_t}{Y_f} = k_m t \tag{24}$$

Where $Y_f$and Y_t represent percentage oil yield at 90 minutes and percentage yield at t minutes.

III. RESULTS AND DISCUSSION

Operational factors such as temperature and processing time are crucial in most chemical industries. [7,10,17]. The quality of the yield and products is significantly affected by these factors. For a better understanding and optimization of the extraction process, it is essential to conduct kinetics and mass transfer studies to extract oil from CNS [13.18]. These studies were conducted using a particle size of 1.88mm, a solvent volume of 250ml, and different extraction times and temperatures.

3.1 Oil Yield at various extraction times and temperatures

Equation (1) was employed to obtain the percentage yield of CNSO at different extraction times and temperatures, as demonstrated in Table 1 and Figure 1. The extraction process at various temperatures (313.15K, 318.15K, 323.15K, 328.15K, and 333.15K) resulted in an increase in oil yield with time. The evaluation of CNSO is based on the percentage of oil recovered after distillation processes, which increased as the extraction time increased. [13,14,19] reported similar findings in the literature. Extraction times of 50 to 90 minutes at a 10-minute interval and temperature of 313.15K yielded oil of 10.56%, 12.78%, 14.21%, 16.11%, and 17.28%, respectively. Similarly, at 333.15K, yield of 21.04%, 22.65%, 24.79%, 26.52%, and 28.86%. Were recorded at the same time interval. The yield compared to that of [12] has a slight deviation of 0.32%. This might be due to differences in extraction times (20 – 60 minutes) and extraction solvent (petroleum ether).

TABLE 1: Extraction time and Temperature variation on yield

Extraction time (mins)	**Temperature (K)/% Yield**				
	313.15K	**318.15K**	**323.15K**	**328.15K**	**333.15K**
50	10.56	13.21	16.13	20.11	21.04
60	12.78	15.01	18.23	21.45	22.65
70	14.21	16.98	19.86	23.1	24.79
80	16.11	18.21	21.13	25.71	26.52
90	17.28	19.1	22.97	27.99	28.86

The variation of yield (%) as a function of extraction time (minutes) across five different temperatures indicates an increasing trend with longer extraction times for all temperature conditions. Across all temperature levels, yield exhibits a positive correlation with extraction time, suggesting that prolonged extraction enhances the yield. This observation aligns with diffusion-driven mass transfer principles, where increased thermal energy facilitates the dissolution and release of target compounds. This trend suggests that temperature enhances extraction efficiency, possibly due to improved solubility and diffusion rates [20,21]. This finding suggests that optimizing extraction time and temperature can significantly impact yield efficiency. While higher temperatures enhance yield, excessive heating may lead to thermal degradation of thermally sensitive compounds [22]. From the results, the highest percentage of oil yield was obtained at 333.15K and 90 min of extraction time, which aligns with literature according to the works conducted by [13] with 0.05% deviation.

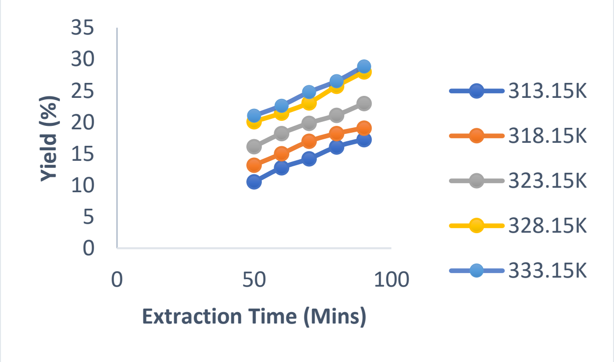

Figure 1: Percentage yield as a function of extraction time and temperature

The plot in Figure 1 also indicates that an increase in the temperature is proportionate to the percentage yield; however, a continuous increase in the temperature might lead to the extraction of undesirable compounds [16].

3.2 Rate of extraction of oil

It was revealed from the plot of the rate of oil extraction (g/Min) from CNS versus extraction time (Figure 2) that at the initial stage of extraction, the rate of oil extraction is directly proportional to time. This implied that, the mass transfer rate was highest at the onset of extraction. For instance, at 313.15K, the rate of extraction obtained is 0.122g/min, but as the extraction time increased to 90 minutes, the rate of oil extraction decreased to 0.192g/min. At the onset of the extraction, the oil present near the surface of the CNS was readily available for extraction, and the solvent efficiently dissolved and removed the oil, however, as time increased, the amount of oil in the CNS available for extraction decreased as well. This was also observed in the works of [14,23,24] where a decrease in the rate of oil extraction was recorded as time progressed.

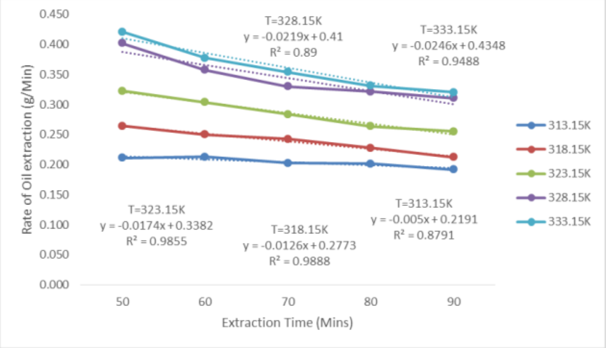

Figure 2: Rate of oil extraction Vs Extraction Time

In the mathematical modeling of the extraction process, the yield can be described by equation (10)

The initial linear increase in yield corresponds to the period where e^{-kt} is small, meaning that the yield increases nearly with time. As the extraction proceeds, e^{-kt} Approach 1, indicating that maximum yield has been reached. The slope of the plot in Figure 2for all the temperatures (313.15K, 318.15K, 323.15K, 328.15K and 333.15k is negative (-0.005, -0.0126, -0.0174, -0.0219 and -0.0246, respectively) which means that the extraction rate was decreasing with an increase in extraction time. Similar trend was observed in the investigation carried out by [23,25].

3.3. Determination of Power Model Constants

The power index n and the constant coefficient of oil extraction were determined by inserting experimental findings into equation (3). Figure 3 represents the relationship between k-values, extraction time and temperatures, where the values of k and n were obtained by comparing the linear regression equation in Figure 3 to equation (3) at the different temperatures and the extraction times used for this study.

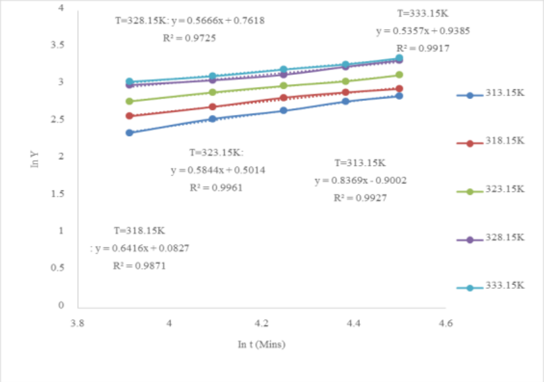

Figure 3: Relationship between n and k values

Consequently, at 313.15k, n and k were obtained as 0.8369 and 0.4065min$^{-1,}$ respectively. Substituting these values into the power model (equation 2) gives: $Y = 0.4065t^{0.8369}$. Similarly, at 333.15K, n and k were obtained from the regression line in Figure 3 as 0.5357 and 0.9385min$^{-1,}$ respectively which gives the percentage yield at that temperature as; $Y = 2.556t^{0.5357}$. The characteristic constant, k, and the diffusion exponent n, are temperature dependent and from the kinetic models, it was revealed that R^2 values are all > 95% which indicates a good fit between the experimental and model data. This is consistent with the works of [12,13] with R^2 values > 97% in the kinetic models obtained in their studies. The fitted regression equations exhibit high determination coefficients (R^2> 0.95), confirming a strong correlation between In Y and In t. These findings suggest that the extraction kinetics follow the power-law model, which is often associated with diffusion-controlled processes [12,18,26].

A range of 3 - 4 has been reported for power index or diffusion exponent n by various authors: pumpkin [27] and aegyptiaca kernel [28] though for higher temperatures and different solvents. [29] at extraction time of 60 minutes and at a temperature of 60^{o}C obtained 0.84 and 0.81 as the diffusion exponent, n, and characteristic constant, k as 0.8917 and 1.2575 min^{-1} for Laffa Cylindrical and Hura crepitan seed oils respectively. The diffusion exponent, which indicates the transport mechanism of oil in this study, was less than 1 for all temperatures and extraction times. This aligns with the studies carried out by [14, 16, 30] where it was reported that the power index is usually less than 1 ($n < 1$) in most oil extraction processes.

3.3.1 Analysis of the Comparison Between Experimental Data and Power Model

Table 2 presents a comparative assessment of experimental data and the corresponding predictions from a power model over the five different time intervals, ranging from 50 to 90 minutes at 10 minutes intervals. Additionally, the percentage difference between the experimental data and the model predictions is recorded.

TABLE 2. Experimental and Power Model data at 333.15K

S/No	Time (Mins)	Experimental data	Power model	Deviation (%)
1	50	21.04	20.78	1.20
2	60	22.65	22.91	1.15
3	70	24.79	24.89	0.40
4	80	26.52	26.73	0.03
5	90	28.86	28.47	1.35

At the temperature of 333.15K, both the yield obtained from experiment and that of the power model values exhibit a consistent increase over time, indicating a consistent trend in the observed phenomenon. The experimental values increase from 21.04 at 50 minutes to 28.86 at 90 minutes, while the power model predictions follow a similar trajectory from 20.78 to 28.47. The close proximity of these values suggests that the power model effectively captures the behavior of the experimental data.

The deviation percentage quantifies the discrepancy between the experimental and model values. Across the five observations, the deviations remain relatively low, ranging between 0.03% and 1.35%. The lowest deviation (0.03%) occurs at 80 minutes, indicating a near-exact fit at this point. The highest deviation (1.35%) is observed at 90 minutes, suggesting a slight divergence between the model and experimental data at higher time intervals. However, all deviations remain within an acceptable range, confirming the robustness of the power model. This indicated a high degree of agreement between the power model and the experimental data. The deviations remain below 1.4% for all time intervals, suggesting that the Power model provides a reliable approximation of the actual experimental trends. This aligned with that reported by [12, 14, 31].

3.3.2.Reaction Order of the Oil Extraction Process

The order of reaction in extraction kinetics is crucial for understanding the rate-determining steps and optimizing process efficiency. This study evaluates the reaction order using equations (5, 7 and 9),and comparing the coefficient of determination (R^2) values for first, second, and third-order kinetic models at different temperatures. The coefficient of determination (R^2) serves as a statistical metric for selecting the most appropriate model and to establish the dominant kinetic order that governs the extraction process.

TABLE 3. Kinetic models and R^2 values at different temperatures

S/No	Temperature (K)	Kinetic Model and R^2 values		
		1st Order	**2nd Order**	**3rd Order**
1	313.15	$y = 0.0122x + 1.7848$ $R^2 = 0.9739$	$y = -0.0018x + 0.5066$ $R^2 = 0.9536$	$y = -0.0014x + 0.2426$ $R^2 = 0.9418$
2	318.15	$y = 0.0093x + 2.1431$ $R^2 = 0.9627$	$y = -0.0012x + 0.4435$ $R^2 = 0.9492$	$y = -0.0009x + 0.1905$ $R^2 = 0.9422$
3	323.15	$y = 0.0085x + 2.3738$ $R^2 = 0.9854$	$y = -0.001x + 0.4055$ $R^2 = 0.9763$	$y = -0.0007x + 0.1602$ $R^2 = 0.9707$
4	328.15	$y = 0.0084x + 2.5683$ $R^2 = 0.9972$	$y = 0.0084x + 2.5683$ $R^2 = 0.9922$	$y = -0.0005x + 0.1381$ $R^2 = 0.9962$
5	333.15	$y = 0.0079x + 2.6502$ $R^2 = 0.9987$	$y = -0.0008x + 0.3666$ $R^2 = 0.9976$	$y = -0.0005x + 0.1316$ $R^2 = 0.9961$

In this study, the kinetic models and R^2 values corresponding to first, second, and third-order kinetic models were determined across five different temperatures (313.15K – 333.15K) as represented in Table 3. The model with the highest R^2 value at each temperature was considered the best fit for the extraction kinetics [12, 13, 18, 32]. At lower temperatures (313.15K – 318.15K), the first-order kinetic model exhibits the highest R^2 values (0.9739 and 0.9627), indicating that extraction kinetics likely follow first-order behavior. However, at higher temperatures (328.15K – 333.15K), the difference between first, second, and third-order R^2 values becomes less significant, suggesting that higher temperatures may promote mixed-order or complex kinetic behavior. This trend aligns with previous studies where increased temperature influences solute diffusion and mass transfer efficiency [25].

The dominance of first-order kinetics at lower temperatures suggests that the extraction rate depends primarily on the concentration gradient of solutes. As temperature increases, enhanced solute solubility and diffusion may contribute to more complex reaction orders, possibly due to secondary interactions [26]. These results emphasize the need for temperature optimization in extraction processes to maintain kinetic efficiency while avoiding degradation effects.

3.4 Mass Transfer Studies

The mass transfer coefficient was evaluated according to the method reported by Baidoo, et al. (2024). Mass transfer through convection and diffusion controls the extraction process due to variations in the oil concentration. In the seed, diffusion is more common than advection in the solvent [16]. It is necessary to analyze and explain the mass transfer process using a diffusion model because the solid particle concentration is unknown [21].

The time of extraction in the liquid phase changes with the oilmass concentration according to equation (20).

From equation (24), aplot of In$\left\{\frac{Y_f}{Y_f-Y_t}\right\}$against time across the different temperatures is as shown in Figures 4 (a), (b), (c), (d) and (e) give a linear graph where the mass transfer coefficients, k_m, at the different temperatures were obtained as the slope (Table 4)

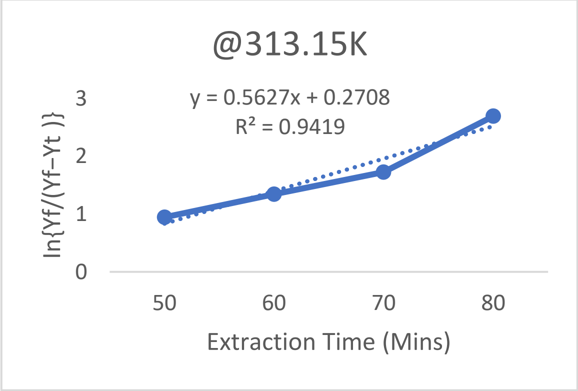

Figure 4(a): relationship between k_m and temperature

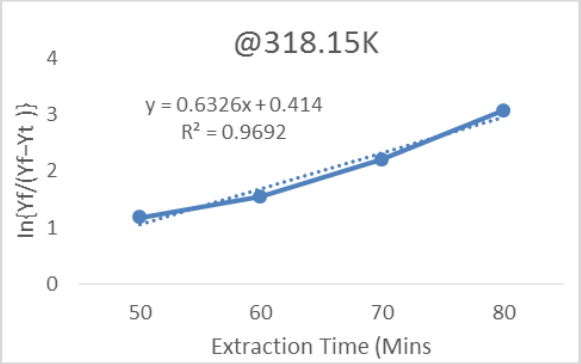

Figure 4(b): relationship between k_m and temperature

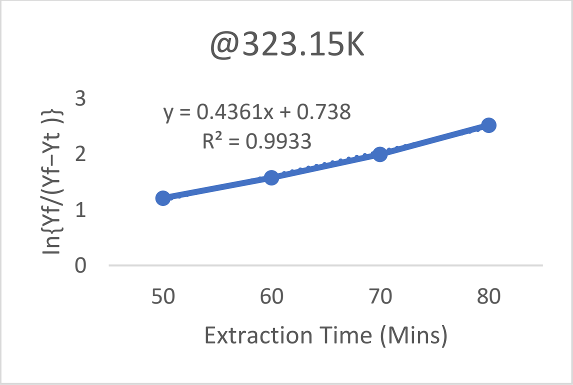

Figure 4(c): relationship between k_m and temperature

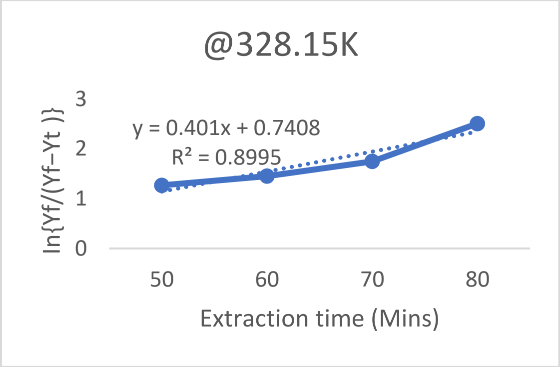

Figure 4(d): relationship between k_m and temperature

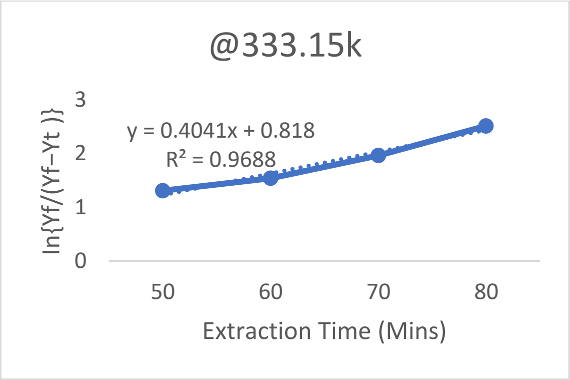

Figure 4(e): relationship between k_m and temperature

TABLE 4: Mass transfer coefficients, k_m,at various temperatures

S/No	Temperature (K)	Mass transfer coefficient, K_m, (Min^{-1})	R^2 Values
1	313.15	0.5627	0.9419
2	318.15	0.6326	0.9692
3	323.15	0.4361	0.9933
4	328.15	0.4010	0.8995
5	333.15	0.4041	0.9688
	Mean	0.4873	0.9545
	Std. Dev.	0.1046	0.0357

The coefficient of mass transfer, k_m, increased proportionally as temperature increased due to the reduced barrier to the mass transfer at the solid-liquid interface as represented in Table 4. Several studies conducted on the extraction of oil support this relationship: Tulshie et al. 2019, revealed that using ethanol as a solvent and extracting oil from jatropha seeds at a temperature range of 303K – 333K decreased the mass transfer coefficient. [13, 20, 33] reported similar trends in their investigations.

K_m values showed a general decreasing trend with increasing temperature, except for a peak at 318.15K (k_m=0.6326Min^{-1}). The lowest k_m value was observed at 333.15K (K_m=0.4041Min^{-1}). While an increase in temperature typically enhances mass transfer due to increased molecular activity, the observed increase in k_m at 318.15K could be attributed to other factors such as changes in fluid properties or system dynamics. The R^2 values are consistently high, ranging from 0.8995 to 0.9933, indicating a strong correlation between the experimental data and the model used. The highest R^2 value was observed at 323.15K (R^2=0.9933), while the lowest is at 328.15K (R^2=0.8995). The mean K_m value is 0.4873 Min^{-1}, with a standard deviation of 0.1046 Min^{-1}, indicating moderate variability in the data. The mean R^2 value is 0.9545, with a standard deviation of 0.0351, reflecting a consistently high goodness of fit.

There exists a complex relationship between temperature and mass transfer coefficients [34,35]. Experimental results in this study on the mass transfer coefficient, K_m, at various temperatures, along with the corresponding R^2 values, revealed the relationship between temperature and the mass transfer coefficient, which is a key parameter in oil extraction from biomass and in general chemical and process engineering.

IV. CONCLUSION

The findings suggest that optimizing extraction time and temperature can significantly impact on the yield efficiency in the oil extraction process from CNS. While higher temperatures enhance yield, excessive heating may lead to thermal degradation of thermally sensitive compounds. The extraction kinetics predominantly follow a first-order reaction model, with minor deviations at higher temperatures. The dominance of first-order kinetics at lower temperatures suggests that the extraction rate depends primarily on the concentration gradient of solutes. As temperature increases, enhanced solute solubility and diffusion may contribute to more complex reaction orders, possibly due to secondary interactions These results emphasize the need for temperature optimization in extraction processes to maintain kinetic efficiency while avoiding degradation effects. The observed results trend aligned with the Fickian diffusion model, where higher temperatures accelerate mass transfer but also lead to saturation effects, reducing the time dependence of extraction efficiency. While an increase in temperature typically enhances mass transfer due to increased molecular activity, the observed decrease in km at higher temperatures (above 318.15 K) could be attributed to other factors such as changes in fluid properties or system dynamics. Understanding the reaction order provides valuable insights into optimizing extraction conditions and improving process efficiency. Future work should incorporate Arrhenius-based activation energy calculations to further validate the kinetic mechanisms and thermodynamic properties of the extraction process.

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Conflict of Interest

The authors declare no conflict of interest in this study.

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