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KINETIC AND THERMODYNAMIC STUDIES OF TURMERIC OIL EXTRACTION PROCESS USING SOXHLET EXTRACTION

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Abstract

Turmeric oil is internationally commercialized for used in food and pharmaceutical processing, the growing demand necessitates low-cost and time save methods for extraction of the oil. This study assessed the kinetic and thermodynamic of the extraction of Maro turmeric oil with hexane as a solvent and determines the prime

Keywords: Turmeric, hexane, oil extraction, kinetic and thermodynamic

INTRODUCTION

Turmeric (*Curcuma longa*) is a valuable medicinal plant widely recognized for its bioactive compounds, particularly curcuminoids and essential oils, which exhibit significant antioxidant, antimicrobial, and anti-inflammatory properties (Prathapan *et al.,* 2019). The extraction of turmeric oil is a critical step in utilizing these bioactive components for applications in pharmaceuticals, cosmetics, and food industries (Azmir *et al.,* 2013; Sagar *et al.,* 2018). Various extraction techniques have been explored, including Soxhlet extraction, hydrodistillation and supercritical fluid extraction, each with distinct advantages and limitations (Jesus *et al.,* 2020; Nguyen & Nguyen, 2018).

extraction temperature and time that give high oil yield compared to the traditional method of oil extraction with low yield. The extraction was done at four altered temperatures 323K, 333K, 343K and 353K, Fourier Transform Infrared (FT-IR) was used to characterized the oil. From the results, the prime oil extraction temperature were 343K and 353K, increase in temperature increase the volume of oil yield. The FT-IR spectrum exposed that turmeric oil contains alkane, alkene, alcohol, aldehydes, ketones and phenols functional groups. Six kinetics models which include: first order, second order, pseudo-first order, pseudo-second order, intra-particle diffusion model and power law model were used for the study. The extraction process was found to follow pseudo-second order kinetic with correlation coefficient (R^2) of above 0.91. The thermodynamics analysis exposed that turmeric oil extraction has positive enthalpy (19.8791kj/mol), implying an endothermic process, while positive entropy (6.609×10^{-3} kj/molK) showed the extraction is high randomization. The positive Gibbs free energy (15.1948 to 15.3930 kj/mol) displays turmeric oil extraction process is non-spontaneous.

Figure 1; Turmeric Rhizome (Azmir *et al.,* 2013).

Soxhlet extraction is one of the most efficient methods for recovering essential oils from plant materials, particularly when using non-polar solvents like hexane, which enhances the solubility of lipophilic compounds (Al-Farsi & Lee, 2008; Jokić *et al.,* 2010). The kinetics of the extraction process provides crucial insights into mass transfer mechanisms, helping optimize operational parameters such as extraction time and solvent-to-solid ratio (Ghasemzadeh *et al.,* 2017; Lim & Nadarajah, 2015). The rate of extraction is influenced by factors such as temperature, particle size, and solvent diffusion, making kinetic modeling essential for process optimization (Pan *et al.,* 2003; Vongsak *et al.,* 2013).

Thermodynamic studies enable a deeper understanding of the feasibility and spontaneity of the extraction process by evaluating parameters such as enthalpy (H), entropy (S), and Gibbs free energy (G) (Da Porto *et al.,* 2012; Karthikeyan *et al.,* 2021). A positive enthalpy change indicates an endothermic process, requiring heat input for efficient extraction, while entropy changes help determine molecular interactions between the solvent and turmeric matrix (Mohdaly *et al.*, 2010; Machado *et al.,* 2015). These thermodynamic insights are crucial for scaling up extraction processes in industrial applications (Sagar *et al.,* 2018).

This study examine the kinetic and thermodynamic aspects of turmeric oil extraction using Soxhlet extraction with hexane as the solvent. By analyzing extraction rates and dynamism changes accompanying with the process, this research contributes to optimizing extraction conditions for maximum oil yield and quality. The findings provide valuable data for improving industrial extraction processes and enhancing the efficiency of bioactive compound recovery. Hence, this study focuses on kinetic and thermodynamic studies of oil extraction by soxhlet apparatus. Other research were compared with the present study.

MATERIALS AND METHODS

The materials used in the experiment include turmeric rhizomes, hexane (solvent) made in Merck KGA, 64271 Darmstadt Germany with CAS No 110-54-3. The following laboratory equipment and apparatus were used in the study; Soxhlet apparatus used were made in china, round bottom flask 500- 1000ml capacity, heating mantle, thermometer, mortar, filter paper and Fourier Transform Infrared (FT-IR)

Sample Collection and Preparation

Wet rhizome of turmeric for the study were procured from Maro, Kajuru LGA, Kaduna State. The Turmeric were identified by the researcher with the assistance of a botanist in Biological Sciences Department, Kaduna State University. The voucher number were deposited at the National Root and Crops Research Institute Maro Sub-station, Kajuru LGA, Kaduna State, Nigeria. The turmeric rhizomes were stored in brown envelope and transported to Federal University Dustin ma, Katsina State, Nigeria for preparation.

The wet turmeric rhizomes was washed with tap water, followed by distilled water. The cleaned samples were dried at 310K – 313K for 21 days inside laboratory. The dried turmeric were chop into uniform size with mortar and pistil. Chop dried turmeric were converted into powder. The sample was sieve through 0.5 – 1 mm mesh to ensure uniform particles.

Procedure of Oil Extraction

The turmeric oil extraction was done based on the conditions of the experiments with Soxhlet extractor as shown in Figure 2;

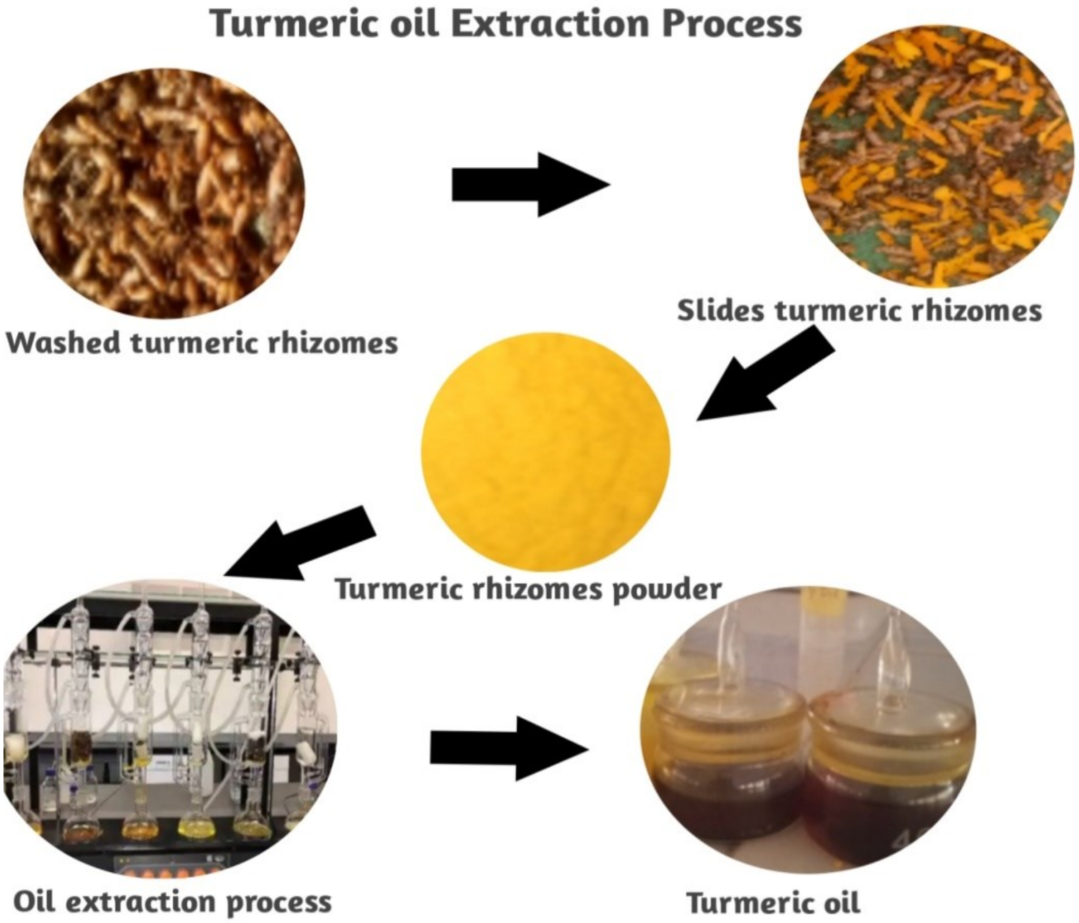

Figure 2; Turmeric oil Extraction Process (Source; laboratory work 2024).

The operational procedure conditions include;

Temperature: The operating temperature for extraction was varied from 323K, 333K, 343K and 353K.

Extraction time: The term extraction time is used for the duration of time it takes for extraction of oil. In this study, the experiments were carried out for 60, 90,120,150,180, 210, 240, 270, 300 and 330 minutes of extraction time.

Ratio of turmeric to solvent: The ratio of turmeric to solvent used was 20 gram of turmeric sample to 250ml of solvent. The yield of turmeric oils is expressed in equation 1 and 2

$$\text{Mass of oil (g) extracted} = \text{mass of oil and container} - \text{mass of container} \quad 1$$

$$\text{Concentration (g/L)} = \frac{Mass\ of\ oil\ \ in\ g}{Volume\ of\ solvent\ in\ 250ml} \times 1000 \quad 2$$

$$Volume\ of\ oil\ (L) = \frac{Mass\ of\ oil\ \ in\ g}{\text{Concentration (g/L)}} \quad 3$$

To Determine the Effect of Temperature on the Extraction of Turmeric oil: The effect of temperature on the extraction of turmeric oil was assessed by keeping the sample ratio constant at 20 gram of turmeric sample to 250ml of solvent, time at 60 minutes, and temperature varied from 323K, 333K, 343K and 353K.

To Determine the Effect of Time on the Extraction of Turmeric oil : The extent of extraction of turmeric oil using hexane were studied as a function time. The sample ratios were kept constant at 20 gram of turmeric sample to 250ml of solvent. Time of extraction was varied at the range of 60, 90, 120, 150, 180, 210, 240, 270, 300 and 330 minutes at different temperature varied from 323K, 333K, 343K and 353K.

To Determine the Order of Reaction for the Experiment: Six kinetic models were used to study the extraction of turmeric oil. These include;

First Order Kinetic Model

First order kinetic model propose is

$$\text{Log}\, c_t = \left(\frac{-k}{2.303}\right)\text{t} + \log C_O \quad 4$$

Where C_t and C_0 are the concentrations of the solute at time t and initial concentration (g/dm^3), respectively and k_1 is the first order rates constant, (Min^{-1}). If the first-order kinetics is applicable to the extraction, then the plot of log Ct versus t of equation (4) above will give a linear relationship with ($\frac{-k}{2.303}$) and log C_0 as slope and intercept .

Second-Order Kinetic Model

Second-order kinetic propose is $\frac{1}{Ct} = k_2 t + \frac{1}{Co}$ **5**

Where C_0 and C_t (g/cm^3) are the concentration of solute at time t and initial concentration respectively, and k_2 is the rate constant of second order. If the second-order kinetics is applicable to the system, then the plot of $\frac{1}{Ct}$versus t of equation (**5**) will give a linear relationship with k_2 and $\frac{1}{Co}$as slope and intercept.

Pseudo-First Order Model

$$\log(q_e - q_t) = \left(\frac{-k'}{2.303}\right)t + \text{loq}\, q_e \qquad \mathbf{6}$$

If the first- pseudo order kinetics is applicable to the system, then the plot of log (q_e- q_t) versus t of equation (**6**) will give a linear relationship with $(\frac{-k'}{2.303})t$ and Log q_e as slope and intercept respectively.

To distinguish kinetic equations based on extraction capacity from solution concentration, **Lagerangrean's** first order rate equation has been called pseudo first-order.

Pseudo-Second-Order Model

$$\log(q_t - q_e) = \left(\frac{k'_2}{2.303}\right)\text{t} + \text{loq}\, q_e \qquad 7$$

If the kinetic is applicable to the system, then the plot of log (q_e- q_t) versus t of equation (7) above will give a linear relationship with log q_e and $(\frac{k'2}{2.303})$ as slope and intercept respectively.

Intra-Particle Diffusion Model

$$\frac{q}{t} = k_i d^{1/2} \qquad 8$$

The logarithm form of the equation (8) is given as:

$$log\ q_t = log\ k_i d + 0.5 \log t \qquad 9$$

Where K_id is the intra-particle diffusion rate constant. According to equation (9), a plot of log versus 0.5 log t gives a straight line with a positive intercept for intra particle diffusion controlled process.

Power Law Model

Power law model is used for the diffusion of an active agent through non-smelling devices and is described by equation below

$q = B\,t^{n}$10

Logarithmic form; $log_{q} = \log \mathrm{B} + \mathrm{n}\log \mathrm{t}$ 11

Where, B is a constant incorporating the characteristics of the carrier-active system, and n is the diffusional exponent, indicative of transport mechanism.

$ln_{q} = ln_{B} + n\, ln_{t}$ 12

By plotting ln_{q} *against* ln_{t}, the intercept is obtained as ln_{B}, while n is the slope.

To Determine the Thermodynamic Parameters

The thermodynamic parameters will be determined by employing the equations;

$\Delta G° = -\mathrm{RT\,In\,k}$ 13

but $\Delta G° = \Delta H° - T\Delta S°$ 14

we can rewrite it as $-RT\,In\,k = \Delta H^{0} - T\Delta S^{0}$

$\mathrm{In\,k} = \frac{\Delta S°}{R} - \frac{\Delta H°}{RT}$ 15

Where ΔS° =Standard Entropy change

R = Gas Constant = 8.314 J/molK

ΔH° = Standard Enthalpy change

T = Absolute temperature (K)

ΔG° = Standard change in Gibb's Free energy

k = Rate constant

By plotting In k Vs$\frac{1}{T}$, the values of ΔH° is the slope and ΔS° will be the intercepts, hence ΔG° was calculated from equation (14).

The rate constant of a chemical reaction is dependent on the absolute temperature. It means that temperature affects the rate of reaction. The expression that gives the relationship between rate constant and temperature is known as the Arrhenius equation. If the rate constant is known, then this equation can calculate the activation energy or vice.

The temperature dependence of the rate constant (k) is expressed as follows:

$k = A_{e}\left(\frac{-Ea}{RT}\right)$ 16

Here 'A' is the proportionality constant, known as the frequency factor, 'Ea' is the activation energy, 'R' is the gas constant, 'T' is the absolute temperature, and 'e' is the base of the natural logarithm.

Taking the logarithm in the above equation, we get;

$In\,k = In\,A + In\,e\,\left(\frac{-Ea}{RT}\right)$ 17

$$In\,k = In\,A - \frac{Ea}{RT}(In_e) \qquad 18$$

$$In\,k = In\,A - \frac{Ea}{RT}(because\ In_e\ = 1) \qquad 19$$

Converting to a common logarithm, we get

$$\log k = logA - \frac{Ea}{2.303R}\frac{1}{T} \qquad 20$$

$$\log k = \frac{-Ea}{2.303R}\frac{1}{T} + \log A \qquad 21$$

By plotting log k Verses $\frac{1}{T}$, the activation energy Ea is the slope and the pre-exponential function (A) will be the intercept.

RESULTS AND DISCUSSION

Turmeric Oil FT-IR Analysis

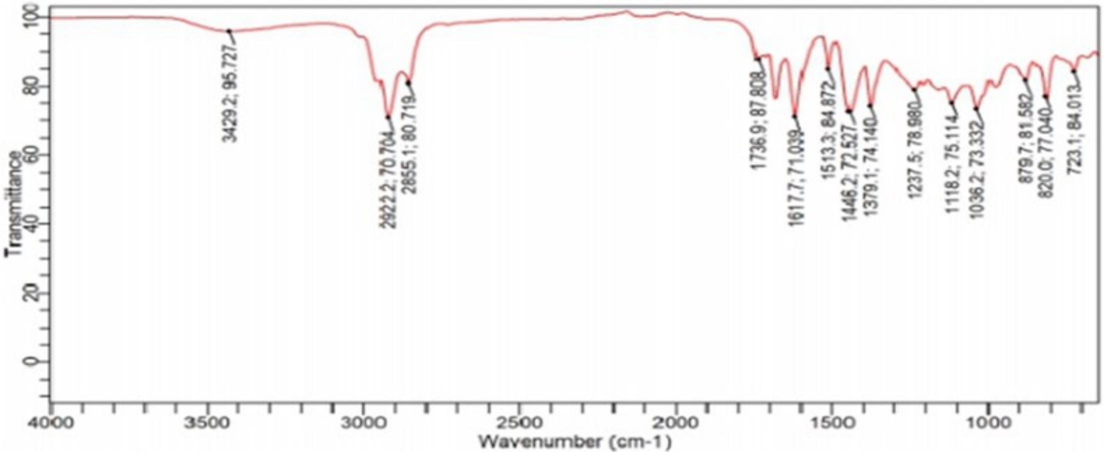

Figure 3: FT-IR spectrum of Turmeric oil. (Source; laboratory work 2024).

Turmeric oil is a complex molecule because the FT-IR spectrum has more than 5 absorption band.

Table 1; Interpretation of Turmeric oil FT-IR

Peak number	Wave number (cm^{-1}) Observed	Literature	Functional group	Class of compound
1	723.10	1000–650	C - H bending	Bending vibration of Alkene.
2	820.01	1000–650	= C - H bending	Bending vibration of Alkene.
3	879.65	1000–650	=C - H bending	Bending vibration of Alkene

Peak number	Wave number (cm^{-1}) Observed	Literature	Functional group	Class of compound
4	1036.20	1320 -1000	C - O stretching	Stretching vibration of alcohol, carboxylic acid, ester, ethers.
5	1118.20	1320 -1000	C -O stretching	Stretching vibration of alcohol, carboxylic acid, ester, ethers.
6	1237.48	1320 -1000	C - O stretching	Stretching vibration of alcohol, carboxylic acid, ester, ethers.
7	1379.12	1370–1350	C - H bending	Bending vibration of Alkane
8	1446.21	1500–1400	C - C Stretching (in ring)	Stretching vibration of Aromatic compound
9	1513.30	1550–1475	N - O stretching	Asymmetric Stretching vibration of nitro compounds.
10	1617.66	1650–1580	C = N bending	Bending vibration of Amine.
11	1736.94	1740–1720	C = O stretching	Stretching vibration of Aldehyde, saturated aliphatic.
12	2855.14	3000–2850	C - H stretching	Stretching vibration of Alkane.
13	2922.23	3000 - 2850	C - H stretching	Stretching vibration of Alkane.
14	3429.15	3500–3200	O - H stretching	Stretching vibration of Alcohol and phenols.

(Source; laboratory work 2024).

The oil extracted was characterized using FT-IR and from the spectrum, turmeric oil contains; Alkane, alkene, alcohol, carboxylic acid, ester, ethers, aromatic compound, nitro compound, amine group, aldehyde and saturated aliphatic compound. This findings is similar to Emmanuel *et al.,* (2024) study on cashew karnel.

Effect of Temperature on the Extraction of Turmeric oil

Table 2; Effect of Temperature on the Extraction of Turmeric oil:

Temperature (K)	Volume (cm^3)
323	69.50
333	80.00
343	97.00
353	120.00

(Source; laboratory work 2024).

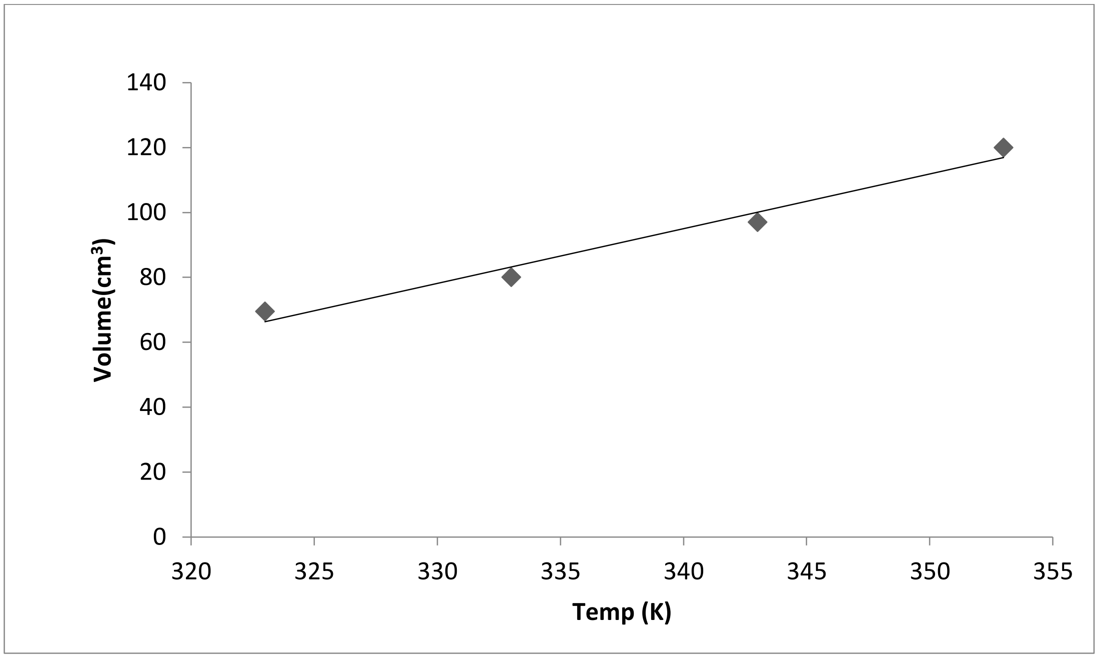

Figure 4: A graph of Effect of Temperature on the Extraction of Turmeric oil. (Source; laboratory work 2024).

The concentration of the extracted oil was found to be prime with 97cm^3 at 343K and 120cm^3 at 353K. Increase in temperature lead to increase in volume of oil extracted, hence, temperature is directly proportional to the volume of oil extracted. This agreed with the results of studies done by Emenike *et al.,* (2022) on nut seed.

Effect of Time on the Extraction of Turmeric oil

Table 3; Effect of Time on the Extraction of Turmeric oil

Time (mins)	Volume (cm³)			
	323K	**333K**	**343K**	**353K**
0	0.00	0.00	0.00	0.00
60	1.00	3.00	3.50	4.00
90	2.50	3.50	4.50	5.50
120	4.00	4.00	6.00	7.00
150	4.50	5.00	7.50	8.50
180	5.00	6.50	8.50	10.0
210	7.50	7.00	9.50	12.50
240	9.00	10.50	11.00	14.00
270	10.5	12.00	13.00	17.00
300	11.50	13.50	15.50	20.50
330	13.00	15.00	18.00	21.00

(Source; laboratory work 2024).

The volume of the extracted oil was found to be prime with 18.00cm³ at 343K and 21.00cm³ at 353K. Increase in time lead to increase in volume of oil extracted, hence, time is directly proportional to the volume of oil extracted. This agreed with the results of studies done by Emenike *et al.* (2022) and Shaun *et al.,* (2021) of oil extraction at different temperatures of nut seed and hass avocados respectively.

Order of Reaction of Turmeric oil Extraction Process

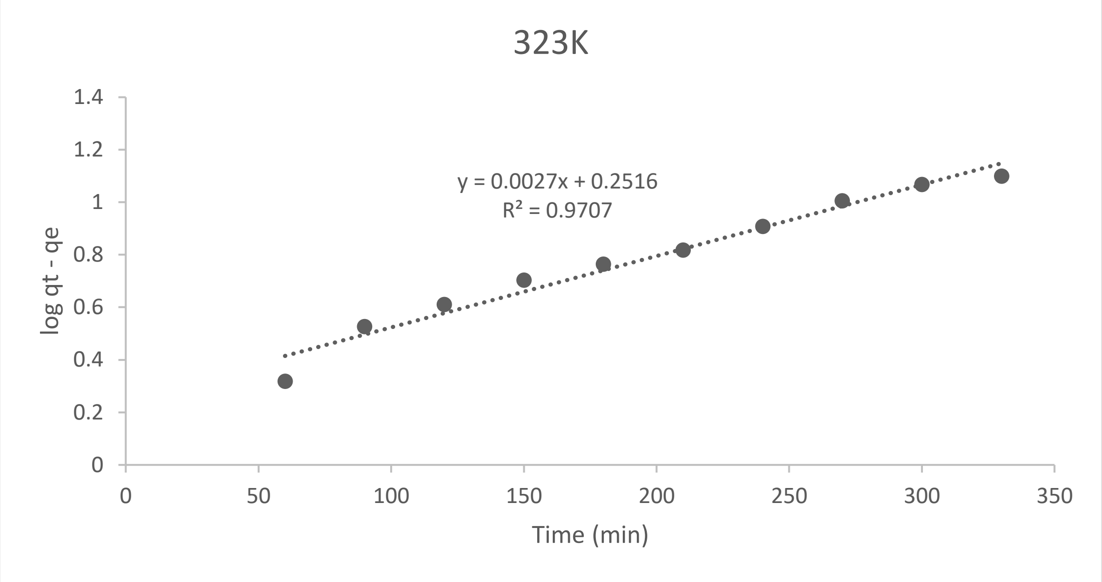

Figure 5; Graph for pseudo second order kinetic model of turmeric oil extraction at 323K. (Source; laboratory work 2024).

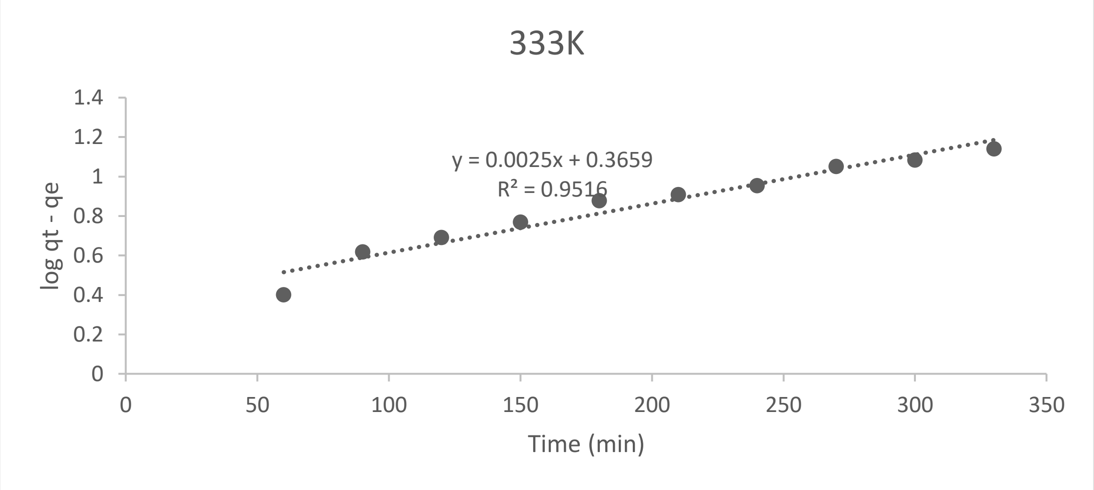

Figure 6; Graph for pseudo second order kinetic model of turmeric oil extraction at 333K. (Source; laboratory work 2024).

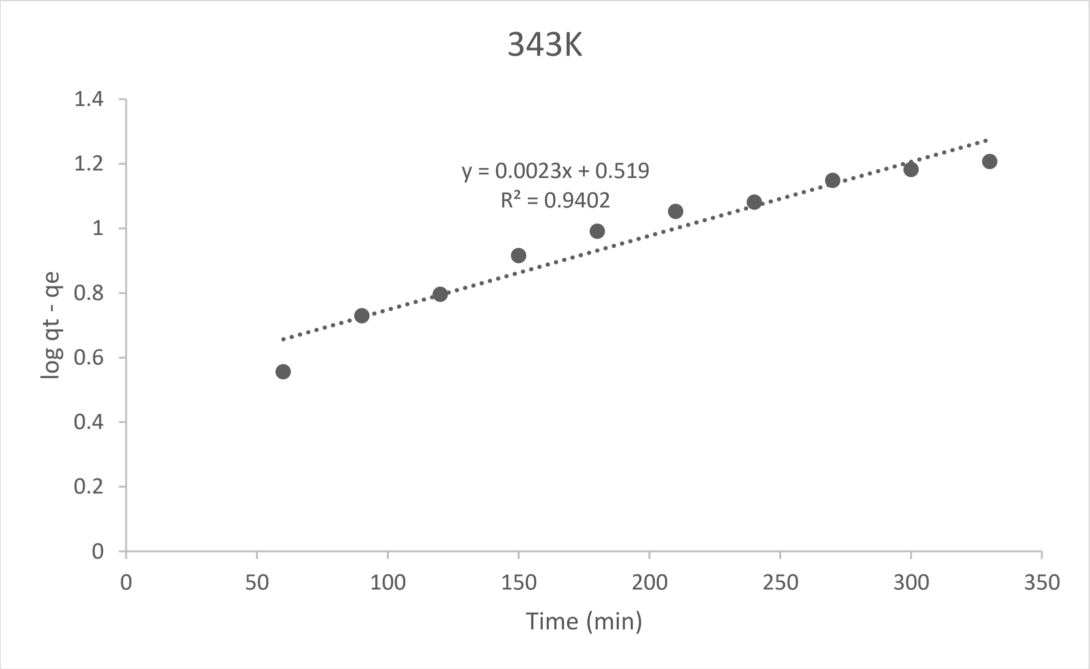

Figure 7; Graph for pseudo second order kinetic model of turmeric oil extraction at 343K. (Source; laboratory work 2024).

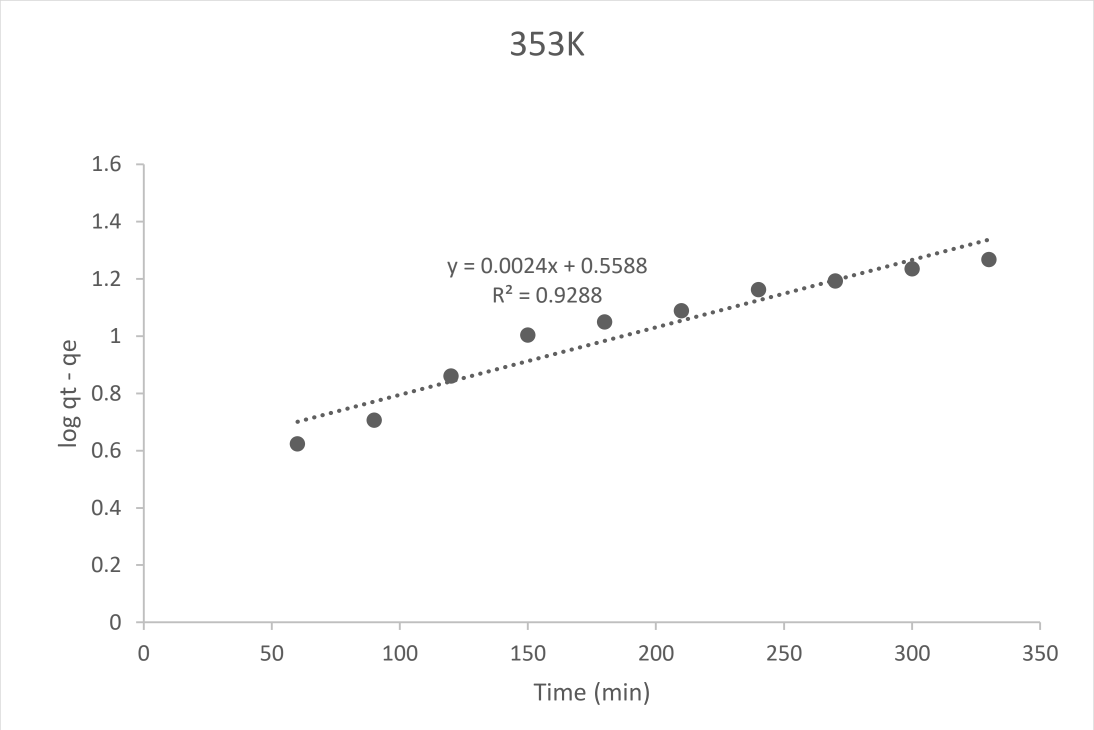

Figure 8; Graph for pseudo second order kinetic model of turmeric oil extraction at 353K. (Source; laboratory work 2024).

Table 4; Summary of Turmeric oil Kinetic Model Values

	First Order				**Second Order**				**Pseudo First Order**		
T K	**k_1 (10^{-3})**	**C_o (10^{12})**	**R^2**		**k_2**	**C_O (10^{12})**	**R^2**		**k'_1 (10^{-3})**	**qe(10^{12})**	**R^2**
323	6.2181	2.0488	0.9707		0.0001	4.6296	0.6409		5.5272	1.4167	0. 5576
333	5.7575	2.1577	0.9516		0.0009	3.0303	0.6771		6.4484	1.5167	0. 6467
343	7.3696	4.4844	0.7172		0.0007	2.9412	0.7219		5.2969	2.5852	0. 9402
353	5.2969	2.9478	0.9349		0.0005	8.0000	0.6287		5.5272	2.6193	0. 8630
Pseudo Second Order				Intra Particle Diffusion Model				Power Law Model			
T K	**k'_2 (10^{-3})**	**q_e (10^{12})**	**R^2**		**k_{id} (10^{-3})**	**I**	**R^2**		**B (10^{-3})**	**N**	**R^2**
323	6.2181	1.7848	0.9707		1.6118	0.4839	0.8898		7.1636	0.1206	0.7165
333	5.7575	2.3222	0.9516		1.3816	0.5810	0.8535		5.7731	0.3659	0.9516
343	5.2969	3.3036	0.9402		1.1513	0.7204	0.8238		5.3099	0.5190	0.9402
353	5.5272	3.6208	0.9288		1.3816	0.7669	0.8086		5.7731	0.5588	0.9288

(Source; laboratory work 2024).

From the regression (R^2) values, the oil extraction process was pseudo second order kinetic model. A pseudo second order reaction occurs when a second order reaction involves a reactant that is present in excess, making its concentration effectively constant throughout the reaction. From the experiment, hexane as a solvent is present is excess and the concentration is constant throughout the extraction process. Pseudo second order model due to its relevance in describing chemisorption (chemical adsorption) phenomena, make it suitable for the study of essential oil extraction from plant materials (Zhang *et al.,* 2018). The rate constants for turmeric oil extraction ranged from to 0.0052969g/l min^{-1} to 0.0062181g/l $min^{-1.}$ A relatively low rate constant implies that the extraction kinetics are governed by slower adsorption and desorption interactions, consistent with the characteristics of pseudo second-order behavior, where chemisorption typically plays a significant role (Rahman *et al.,* 2018).

Furthermore, the adherence to pseudo second order kinetics emphasizes the importance of considering both external and internal mass transfer resistances during the extraction. Factors such as particle porosity, the solubility of oil constituents, and solvent diffusivity all interplay to affect the extraction kinetics observed. In practical terms, optimizing these factors through precise control of process conditions could enhance the overall efficiency of the soxhlet extraction (Ali *et al.,* 2020; Wang *et al.,* 2021). The pseudo-second order kinetic model offers a robust framework for understanding and optimizing the extraction of essential oils. By accounting for chemisorptive interactions and process conditions, pseudo second order kinetic model enables enhanced control and predictability of extraction processes, which is essential for both small-scale and industrial applications (Ahmed *et al.,* 2022).

Thermodynamic studies of Turmeric oil Extraction Process

Table **5**: Thermodynamics Data Analysis

1/T (10^{-3})	Ink	log k
3.0960	-5.6803	-2.3963
3.0030	-5.7573	-2.2498
2.9150	-5.3406	-2.2460
2.8330	-5.1981	-2.1275

(Source; laboratory work 2024).

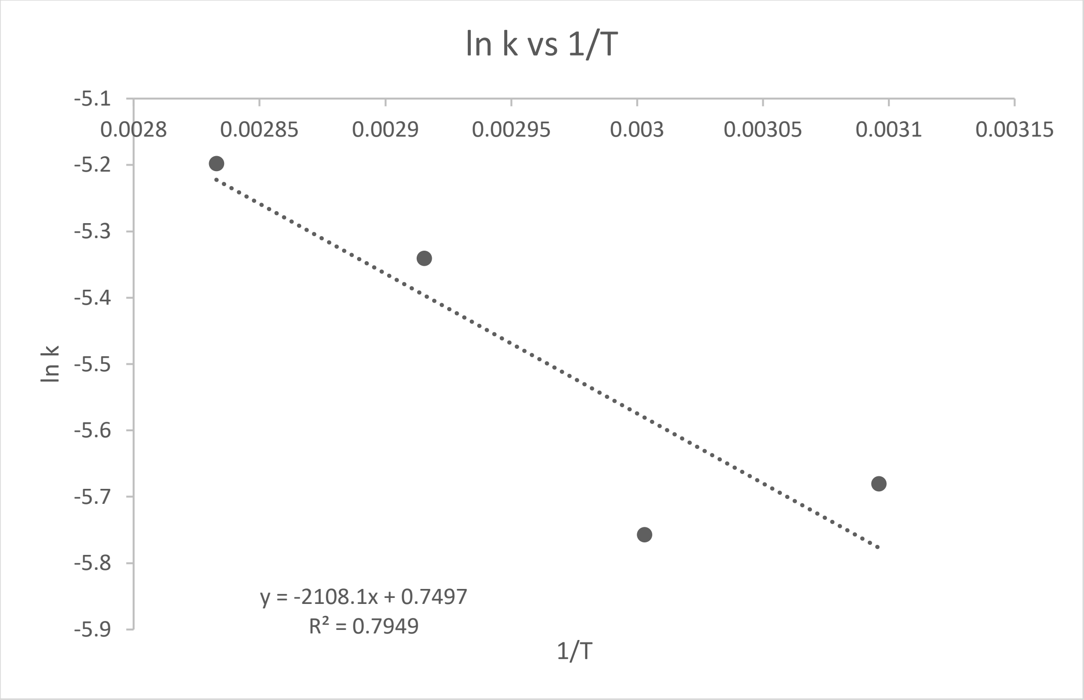

Figure 9; Graph of Ink vs 1/T for turmeric oil extraction process. (Source; laboratory work 2024).

From the above graph the following thermodynamic parameters for turmeric oil extraction process are obtain from the slope and intercept.

$$Ink = \frac{\Delta S^{o}}{R} - \frac{\Delta H^{o}}{RT}$$

$Slope = -\frac{\Delta H^{o}}{R}$ $,\Delta H^{o} = slope \times - R = -2108.1 \times -8.3145\, j/molK$

ΔH^o = 17527.79745 j/mol= 17.5278 kj/mol

Intercept = $\frac{\Delta S^{o}}{R}$, ΔS^o = Intercept × R = 0.7497× 8.3145 j/molK

ΔS^o = 6.60919605 j/molK = 0.006609 kj/molK

Using $\Delta G^{o} = \Delta H^{o} - T\Delta S^{o}$ we obtain free Gibb's energy at different temperature

ΔH^o = 17527.79745 j/mol and ΔS^o = 6.60919605 j/molK

At 323K **ΔG^o = 17527.79745 – 323 (6.60919605)** **ΔG^o = 15393.02712585 j/mol** **ΔG^o = 15.3930 kj/mol**	At 343K **ΔG^o = 17527.79745 – 343 (6.60919605)** **ΔG^o = 15260.84320485 j/mol** **ΔG^o = 15.2608 kj/mol**
At 333K **ΔG^o = 17527.79745 – 333 (6.60919605)** **ΔG^o = 15326.93516535 j/mol** **ΔG^o = 15.3269 kj/mol**	**At 353K** ΔG^o = 17527.79745 – 353 (6.60919605) ΔG^o = 15194.75124435 j/mol ΔG^o = 15.1948 kj/mol

(Source; laboratory work 2024).

To calculate the values of activation energy and the pre-exponential function (A), Arrhenius equation $\log k = \frac{-Ea}{2.303R}\frac{1}{T} + \log A$ was used.

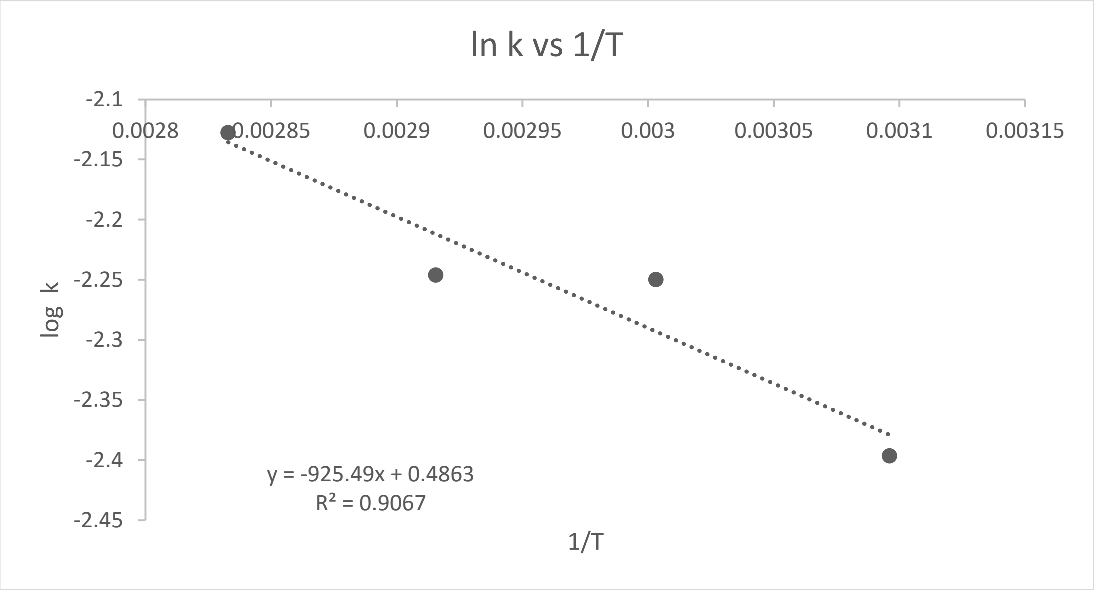

Figure 10; Graph of Log k vs 1/T for turmeric oil extraction process. (Source; laboratory work 2024).

$$log\ k\ =\ \frac{-Ea}{2.303\ R}\frac{1}{T} + Log\ A$$

$$Slope\ = \frac{-Ea}{2.303\ R}, Ea\ =\ slope\ \times\ 2.303\ \times\ -R$$

$$=\ -925.49\ \times\ 2.303\ \times\ (-8.3145\ j/molK)$$

Ea = 17721.554151315 j/molK. = 17.7216 kj/molK.

Intercept = Log A

A = Antilog of intercept = $10^{0.4863}$ = 3.06407929381

Table 6; Summary of Thermodynamics Properties

SAMPLE	A	Ea (kj/mol K)	ΔH°(kj/mol)	ΔS° (kj/molK)	ΔG° (kj/mol)			
					323K	333K	343K	353K
TURMERIC OIL	+3.0641	+17.7216	+17.5278	+0.006609	+15.3930	+15.3269	+15.2608	+15.1948

(Source; laboratory work 2024).

The Arrhenius factor (or pre-exponential factor) for turmeric oil is 3.0641min-^{1} indicates the frequency of effective collisions or successful interactions between reactant molecules during the oil extraction process. This moderate Arrhenius factor suggests that the interaction between the solvent and turmeric matrix is relatively effective, contributing to a steady rate of extraction under soxhlet apparatus set up (Nguyen *et al.,* 2019). Activation energy (Ea) represents the minimum energy required for a chemical reaction to proceed. The relatively low activation energy of observed for turmeric oil extraction suggests that the process occurs with moderate energy input. This relatively low activation energy +17.7216kj/molK suggests that turmeric oil extraction can proceed at moderate temperatures, reducing the overall energy input necessary for the process (Sharma & Gupta, 2022). The soxhlet extraction process relies on the solvents repeated refluxing and interaction with the solid turmeric matrix, facilitating the release of oil compounds. A low activation energy aligns well with the continuous contact and solubilization processes enabled by the extraction technique (Fang *et al.,* 2021).

The positive enthalpy change (ΔH) +17.5478kj/mol for turmeric oil extraction process, indicates that the extraction of turmeric oil is an endothermic process. This indicates that the process absorbs heat from its surroundings to break bonds within the turmeric matrix and facilitate oil release (Smith & Jones, 2018). In an endothermic reaction, temperature plays a pivotal role in driving the extraction forward. This behavior suggests that increasing the temperature of the extraction process could lead to improved yields due to increased molecular motion and enhanced interactions between the solvent and turmeric matrix (Barbosa & Mendes, 2020). The positive value of ΔH aligns with findings from other plant oil extractions, where thermal energy input is necessary to disrupt plant cell structures, release volatile compounds, and dissolve them into the extraction solvent (Sulaiman & Abdullah 2017). Thus, optimizing the temperature range for Soxhlet extraction is critical for maximizing turmeric oil yield while ensuring energy efficiency. The soxhlet extraction process ensures a consistent heat supply, making it well-suited for endothermic extractions of turmeric oil.

The entropy change (ΔS) measures the change in disorder within the system during the oil extraction process. The positive entropy value +0.006609kj/molK indicates an increase in randomness as turmeric oil transitions from its bound state within the plant matrix to a more dispersed state in the solvent. This increase in entropy is consistent with the disruption of cellular structures and the subsequent release and diffusion of essential oil compounds (Martinez & Hall, 2019). The positive entropy change suggests that the process is favored by an increase in molecular randomness, which facilitates the solubilization and diffusion of turmeric oil molecules into the extraction solvent. This behavior is desirable in extraction processes, as it indicates that the system naturally progresses toward a state of higher disorder, driven by interactions between the solvent and the turmeric matrix (Nguyen *et al.,* 2019).

Gibbs free energy (ΔG) is a critical thermodynamic parameter that indicates the spontaneity of a process. The ΔG values for the oil extraction process at various temperatures are as follows: +15.3930kj/mol at 323K, +15.3269kj/mol at 333K, +15.2608kj/mol at 343K and +15.1948kj/mol at 353K. The positive ΔG values at each temperature indicate that the extraction process is non-spontaneous under standard conditions. However, the decrease in ΔG values with increasing temperature in turmeric oil extraction process suggests that the process becomes more thermodynamically favorable at higher temperatures (Lin & Chen, 2017). This behavior is consistent with the endothermic nature of the reaction, where higher temperatures provide the necessary energy input to overcome thermodynamic barriers and drive the process forward (Zhao *et al.,* 2019).

The gradual decrease in ΔG values, from 323K to 353K, in turmeric oil extraction process indicates an improvement in the feasibility of the extraction process as the temperature increases. This trend suggests that temperature optimization is crucial for enhancing the extraction efficiency of turmeric oil using the Soxhlet apparatus (Ahmad *et al.,* 2016). The observed ΔG values highlight the importance of maintaining an appropriate temperature range to maximize yield and energy efficiency.

Table 7; Comparison of Thermodynamic Parameters for Different Plants Oil Extraction

∆H (kj/mol)	∆S (kj/mol.K)	∆G (kj/mol)	Oil source (plant)	Reference
28.17	0.234	-3.90 to -8.91	Pumpkin seed	Nwabanne (2012)
11.19	0.033	0.24 to 0.57	Coconut seed	Sulaiman *et al.,* (2013)
7.83	26.62	-0.86 to -1.31	Watermelon seed	Olakunle *et al.,* (2014).
29.20	0.092	0.45 to -13.83	*Thevetiaperuviana* seed	Jabar *et al.,* (2015)
15.02	45.52	1.62 to -0.10	Jatropha seed	Dos Santos *et al.,* (2015).
11.70	0.260	-2.49 to -1.95	Bitter gourd seed	Umamaheshwari and Reddy (2016).
372.05	1.290	-26.64 to -52.35	*Colocynthis vulgaris schrad*seed	Agu *et al.,* (2018)
27.62	0.087	-0.02 to -1.32	Cashew nut seed	Eminike *et al.,* (2022).
17.5278	0.007	15.19 to 15.39	Turmeric rhizome	Present study

CONCLUSION

The kinetic and thermodynamic studies of extraction of oil from Maro turmeric rhizomes by soxhlet extraction method using hexane as solvent was carried out and characterized. The maximum volume of oil extracted was found at 343K and 353K, hence as the temperature increase the volume oil extracted increases. The FT-IR spectrum reveal that turmeric oil contains alkane, alkenes, alcohol, aldehydes, ketones, esters and carboxylic acids. Among the six kinetic model studied, pseudo-second order was found to best fit the experimental data obtained with correlation coefficient above 0.91. From the data of the thermodynamics parameters obtained, the process was seen to be endothermic, high entropy and non - spontaneous.

Contribution to Knowledge

The outcomes of this study verify the application of mathematical and engineering concept to actual practice. The evidence of these models will allow practice engineers to use the pseudo second order kinetic model that fit the process to predict actual production yields and estimate the energy needed per gram of oil. These assessments will help in managing process costs control. The outcomes of the study may be used as data to help design engineers with unit operations equipment's sizing and process design. Additionally, the data and model can be used as a guide for employing process control in the oil extraction process.

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Author Contributions

Allems G. A choose the topic with the approval of **Siaka A. A**. The conceptual frame work and methodology was written by **Allems G. A** and **Siaka A. A**. The experiment and manuscript was conducted and written by **Allems G. A**. Manuscript Review and editing was done by **Siaka A. A.**

Conflict of interest

The authors affirmed that no conflicting interest or personal associations that could have appeared to impact the work reported in this paper.

Nomenclature Symbols

A = Pre- exponential factor or Arrhenius constant (min^{-1})
Ea = Activation energy (kj /mol)
ΔH = Change in enthalpy (kj /mol)
ΔS = Change in Entropy (J/mol.K)
ΔG = Change in Gibbs free energy (kj /mol)
k = Reaction rate constant (min^{-1})
R = Universal gas constant (8.3145 J/mol.K)
C_t= Concentration of turmeric oil at time t (g/L)
C_0 = Concentration of avocado oil at time 0 (g/L)
q_e= Extraction capacity at equilibrium (min)
q_t= Extraction capacity at equilibrium time t (min)

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