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Kinetics and thermodynamics of oil extraction from South African hass avocados using hexane as a solvent

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ABSTRACT

This study evaluated the yield, kinetic and thermodynamics parameters of the oil extraction process from South African Hass Avocados using Hexane as a solvent. The avocado oil was extracted through the solid-liquid process at different temperatures. The thermodynamic parameters that were evaluated and modelled in this study were studied under constant volume, pressure and temperature conditions during extraction experiments. The enthalpy, entropy and Gibbs free energy were the parameters studied. The extraction was done at four different temperatures 40 °C, 50 °C, 60 °C and 70 °C. The kinetic model found that the extraction reaction was first-order reaction and the increase in temperature increased the oil yield from 169.20 g/L at 40 °C to 210.73 g/L at 70 °C after 3 h of extraction. The activation energy found was E_a = 127.30 KJ/mol, the thermodynamic parameters under the transition theory at 70 °C were $\Delta S^{\neq}$ = 70.06 J/mol.K, $\Delta H^{\neq}$ = 124.44 KJ/mol, $\Delta G^{\neq}$ = -23.91 KJ/mol. The standard thermodynamic parameters of the process at 70 °C were ΔH = 0.09 KJ/mol, ΔS = 70.06 J/mol.K and ΔG = -7.19 KJ/mol. These indicated that the extraction of avocado oil is an irreversible reaction and the reaction is endothermic. Furthermore, it was proven that the reaction is spontaneous.

1. Practical application

The results of this study prove the application of mathematical and engineering theory to actual practice. The proof of these models will allow process engineers to be able to use the models that fit the process to predict actual production yields and estimate the energy needed per gram of oil. These estimates will help in managing process costs control. The results of the study may be used as data to help design engineers with unit operations equipment's sizing and process design. Furthermore, the data and models can be used as a guide for implementing process control in the oil extraction process.

2. Introduction

Avocado oil is a known product around the world as it has grown with use in different industries. The oil is produced from the avocado fruit, which is a fruit with high oil content, found to have been the main component of its dry weight (Ozdemir and Topuz, 2004). The avocado fruit is mainly consumed as a fruit itself and because of this, it was not considered to be grown as a primary source of oil. Therefore avocado oil has been generally produced from the fruits rejected by the fresh fruit trade (Woolf et al., 2009). Avocado oil has been an important raw material in the cosmetic industry due to its high skin penetration properties and its high vitamin E content (Woolf et al., 2009). Therefore, with the increase in demand for avocado oil, the production of the oil has been explored with different extraction processes such as traditional mechanical cold pressing, aqueous extraction which uses water and centrifugal force, solid-liquid extraction which makes use of organic solvents and the biological extraction which uses biological enzymes (Qin and Zhong, 2016). According to Topalla and Gecgel (2000), solid-liquid extraction is the most common and efficient extraction process for producing vegetable and seed oils. The studies of reaction kinetics and thermodynamics have been done on the extraction of oils from different oil sources (Aktar and Adal, 2019; Amin et al., 2010; Sulaiman et al., 2013; Santos et al., 2015). This study aims to further add and contribute to this existing literature and also compare the kinetics of avocado oil extraction from this study to that of other extraction

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Nomenclature

Symbols

A	Arrhenius constant (min^{-1})
C_A	Concentration of avocado oil at time t (g/L)
C_{A0}	Concentration of avocado oil at time 0 (g/L)
e	Euler's number
E_a	Activation energy (KJ/mol)
ΔG	Change in Gibbs free energy (KJ/mol)
ΔH	Change in enthalpy (KJ/mol)
k	Reaction rate constant (min^{-1})
K	Equilibrium constant
n	Reaction order
R	Universal gas constant (8.3145 J/mol.K)
ΔS	Change in Entropy (J/mol.K)
t	Extraction time (min)
T	Temperature (°C & K)
X_A	Oil fraction at time t
X_{A0}	Oil fraction at time 0
Y_T	Oil concentration percentage extracted
Y_U	Oil concentration percentage unextracted

kinetics and thermodynamics of oil extraction from waste coconut and found the reaction to be a first-order reaction, also endothermic, irreversible and spontaneous reaction.

The aim of this work was to determine the reaction kinetics and the thermodynamic parameters of avocado oil extraction through a solid-liquid extraction process with hexane as solvent. Fick's law and Van't Hoff's model were both selected to test their suitability in describing and explaining the experimental data on the kinetics and thermodynamic parameters of the avocado oil extraction process at different temperatures. Fick's law was chosen to prove whether it is suitable to explain the theory of diffusion of oil from the avocado solid to the hexane liquid with experimental data. Van't Hoff's model was chosen to prove whether it is suitable to describe the relationship between changes in temperature with the change in equilibrium constant with the experimental data of avocado oil extraction. The results of this study were also compared to other research studies to evaluate the models used.

3. Methodology / materials and method

3.1. Raw materials

The raw material chosen for this study was the Hass avocado variety grown locally in South African farms. These farms are situated in the north eastern part of the country in provinces of Limpopo, Mpumalanga

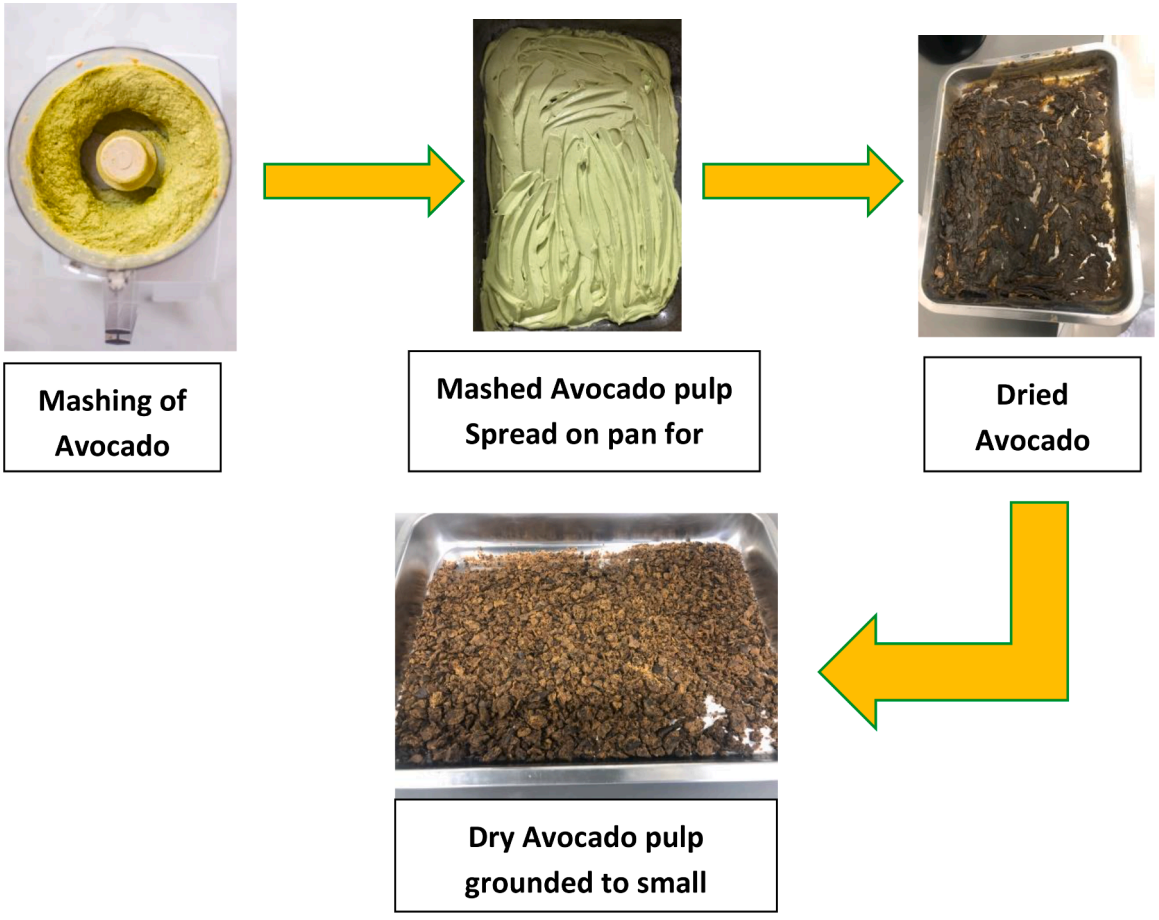

Fig. 1. Avocado pulp pretreatment process.

processes. Topalla and Gecgel (2000) studied the kinetics of extraction of sunflower seed oil and they found an increase in extraction with an increase in temperature and they also found that the extraction process was irreversible and spontaneous. Sulaiman et al. (2013) studied the and Kwa-Zulu Natal. This variety of avocado was chosen based on its abundance and availability, it is said to be the most grown avocado variety in South Africa. According to Nelson (2010) from the South African avocado growers association (SAAGA), approximately 70% of

Fig. 2. Extraction using Soxhlet.

the avocados trees in South Africa are of the Hass variety.

The avocados used in this study were sourced from the market wholesaler and kept under controlled temperature to slow the ripening process. The avocado fruits were then kept at ambient temperature of 20 °C - 24 °C in the laboratory for 5 days to have a natural ripening. The avocados sourced are of the same brand and grower. The ripened fruits were peeled and deseeded; the mesocarp (flesh) was meshed up into a paste using a food blender as shown in Fig. 1. The paste was placed in pans and dried for 48 h in an oven at 70 °C. The temperature of 70 °C was selected as the highest possible temperature safe enough to avoid thermal oxidation of the oil during pretreatment. Ortiz Moreno et al. (2003) conducted an avocado oil extraction where dehydration of the pulp was done at 70 °C under vacuum. The vacuum was made to prevent auto-oxidation and the temperature of 70 °C was safe enough to not result in thermal oxidation. The dry avocado paste was grounded and stored in a closed cupboard to avoid direct light.

During the preliminary experiments, the average oil content of the avocados was determined through an exhaustive extraction using the Soxhlet extraction method as shown in Fig. 2. . This confirms what Kumar (2015), (Satriana et al., 2019), Ozdemir & Topuz (2004) research claim that the Soxhlet extraction was found to be the exhaustive solvent extraction method to give the maximum extraction. According to Kumar (2015), the Soxhlet operation makes use of fresh solvent every time there is contact between solid and liquid since the solvent and the solid are not in constant contact. Therefore, the solid and liquid never reach equilibrium. The maximum amount of oil content found in the Hass avocados at maturity was found to be an average of 67.07% of the fruit dry weight.

Hexane (Science World, Cape Town, South Africa. CAS 110–54–3) was the organic solvent chosen to be used for extraction in this study. This choice was based on different reasons, the first reason was the properties of the solvent itself in extracting avocado oil. Hexane is a non-polar solvent and this makes it eligible to extract oil which is also non-polar, from literature it was known that “like dissolves like” so non-polar dissolves non-polar compounds (Kumar, 2015). The second reason was the eligibility of the solvent, which was based on a resolution made by the joint committee of the United Nations Food and Agricultural Organisation and the World Health Organisation (FAO/WHO). The committee decided that only 17 organic solvents were allowed to be used for food and personal care products. These solvents are known as GRAS (Generally Regarded as Safe) solvents. The other reason will have to do with the chemical characteristics of the solvent. According to Kumar (2015), the choice of solvent should be selected based on the availability, price, properties like boiling point to allow easy recovery with evaporation, toxicity, solvent power and it should be non-hygroscopic.

3.2. Oil extraction

The avocado oil extraction was done based on the conditions of the preliminary experiments that were done with Soxhlet extractor prior as shown in Fig. 2. The avocado oil was extracted with hexane (Science World, Cape Town, South Africa. CAS 110–54–3) at a constant liquid to solid ratio of 3.05 mL hexane/gram of dry avocado, which was found to have been a favourable ratio in the previous research (Mgoma et al., 2019). The three necked 500 mL round flasks were used for extractions as a batch reactor. One opening was used for the condenser, the other opening was used for the thermometer and the other had a stopper which was opened for sampling every 10 min intervals. The extractions were done at four different temperatures 40 °C, 50 °C, 60 °C and 70 °C , respectively, for three hours at each temperature. The experimental runs were conducted in duplicate to compare and ensure the reliability of the results. The concentration of the oil extracted was monitored and recorded over time. The oil concentration in the solution was measured by extracting 3 mL from the solution using a pipette into a glass beaker; the beaker was then placed in an oven to allow the solvent to evaporate. The beakers were then removed from the oven, allowed to cool down and then reweighed. The difference in weight over time was observed and recorded.

The mass of mesocarp used for extractions was 50 g samples with 152.67 mL of hexane as a solvent for all experiments. In all the experiments, the solvent was first poured into the flask and heated up to the desired temperature. Then the dried avocado mesocarp would be added and extraction would commence. After three hours of extraction the

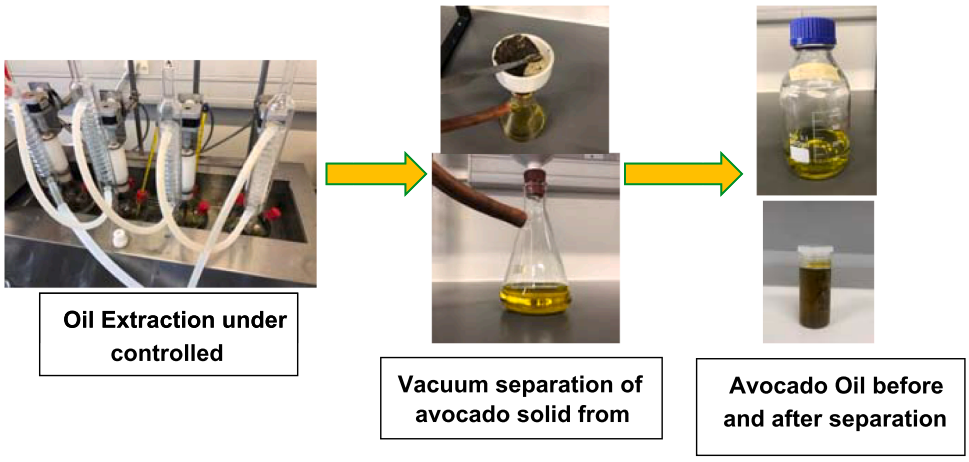

Fig. 3. Oil Extraction under controlled temperatures and separation of oil from solid and solvent.

Table 1
Oil concentration yield over time at different temperatures.

Time (min)	Oil Concentration Yield (g.L^{-1})			
	40 °C	50 °C	60 °C	70 °C
0	0	0	0	0
10	75.1250	92.8250	96.3000	113.5500
20	78.0000	114.9500	117.6000	139.9000
30	95.0750	129.6500	132.5250	152.2500
40	106.5000	138.6750	142.1250	168.6500
50	117.1250	142.8500	152.5250	177.5250
60	125.8000	154.1750	159.5750	181.5250
90	143.6750	166.4500	171.7000	196.6500
120	152.2750	174.4500	180.0000	198.7500
150	163.3000	179.7500	188.5250	207.1250
180	169.2000	189.0250	192.6750	210.7250

solid and solution were separated using the Buchner funnel and filter paper with aid of a vacuum as shown in Fig. 3 . The liquid solution was also further separated by distilling the solvents using the Buchi rotary evaporator (Buchi Co., Switzerland). The oil was collected in a glass beaker and put in an oven to remove any remaining solvent that was not recovered. The oil was then placed in a bottle and kept at ambient temperature for further analysis.

4. Results and discussion

4.1. Yield of oil over time at different temperatures

From the preliminary experimental runs done of the oil extraction with hexane; the results guided the runs of these sets of experiments. Extraction was done only with South African avocados of the same ripeness as explained in the methodology. The concentration yield of the oil in the liquid phase was compared between the four different temperatures and the plot was generated. Table 1 and Fig. 4 represent the data from the experiments conducted at four different temperatures over 3 h each.

4.2. Effects of temperature on the oil yield

Fig. 4 shows the effect of temperature in the extraction process of avocado oil. The results show that the increase in temperature enhances the yield of oil and the rate at which the oil is extracted. This means that the increase in temperature results in the increase in the rate of reaction, which we can conclude that the temperature is directly proportional to the extraction yield and rate of extraction. This agreed with the results of studies done by Amarante et al. (2014) and Sulaiman et al. (2013) of oil extraction at different temperatures. As seen in Table 1, the rise of temperature from 40 °C to 70 °C raised the final oil concentration yield by over 40 g/L from 169.2 g/L to 210.73 g/L. Furthermore, the rate of extraction is increased by the increase in temperature, the oil extracted in the first 10 min of extraction increases from 75.13 g/L at 40 °C to 113.55 g/L at 70 °C, which is also the difference of almost 40 g/L.

The solubility of the material which is being extracted will increase with the increase in the temperature as it is being extracted (Richardson et al., 2002). Fig. 4 also shows the effect of time during the extraction process. The extraction continues in favour of the forward reaction over time as the oil diffuses from the solid into the liquid phase (Richardson et al., 2002). However, it is also found that as time increases the rate of extraction decreases and the reaction tends to go into a state of equilibrium. This is elaborated by the shape of the curve, which moves from being steep to become flat. The trend of the plot shows that the concentration gradient decreases as the avocado solid tends to exhaustion over time. This confirms Fick's law in diffusion that the rate of diffusion is driven by the concentration difference of the solute between feed and the solvent (Richardson et al., 2002).

According to the mass transfer mechanism of solid-liquid extraction, the start of the extraction is dominated by washing, which extracts the

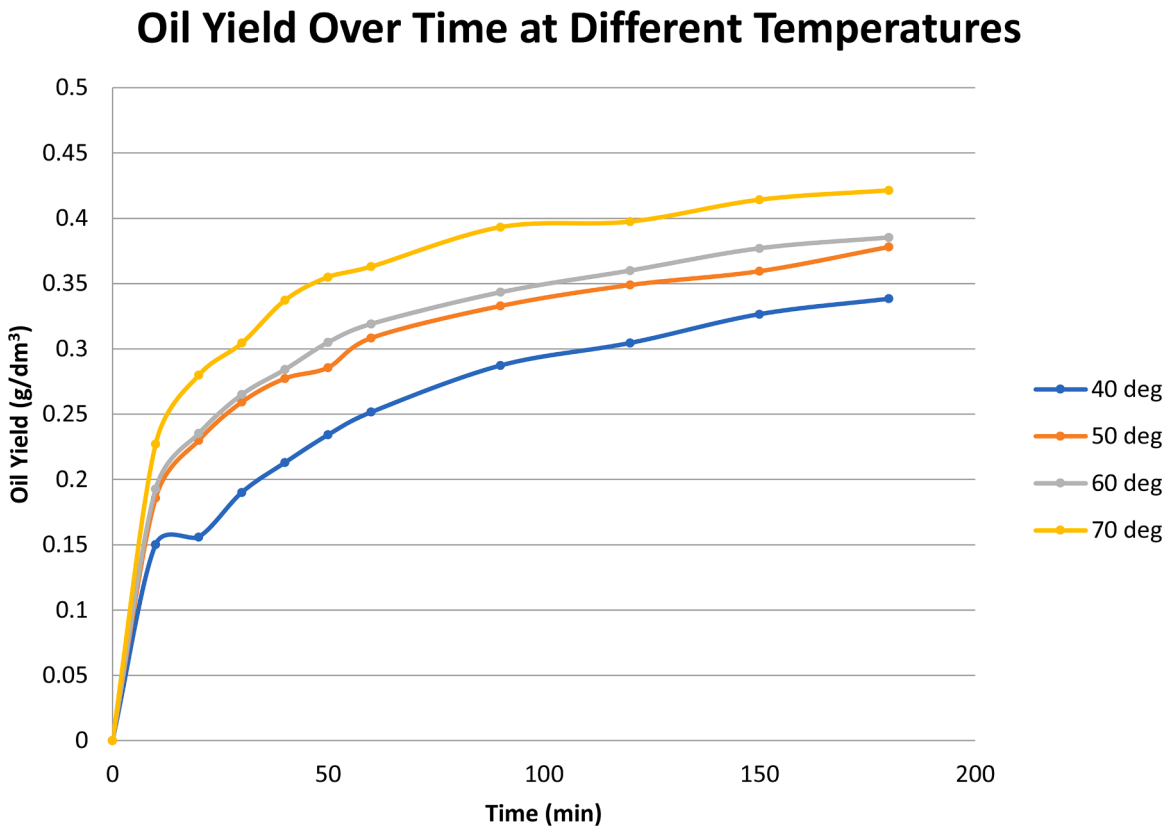

Fig. 4. Oil Concentration yield over time at different temperatures.

Table 2
Extraction rate constants at different temperatures.

T (°C)	k (min^{-1})
40	0.0015
50	0.0044
60	0.0103
70	0.1382

solute from the exposed surface of the solid. The extraction then further proceeds by diffusion where the solute diffuses from the inside of the solid particles into the liquid phase. This step of diffusion is described and explained by Fick's law, which states that; if a concentration difference exists, the rate of transfer of a component is proportional to the product of the molecular diffusivity and the concentration gradient (Richardson et al., 2002).

4.3. Reaction kinetics

The oil extraction process is a process controlled by diffusion due to its concentration gradient of the oil in the liquid phase (Santos et al., 2015) which is also considered the driving force for extraction. Since this process is controlled by diffusion it can therefore then be related to Fick's law and as a result, Fick's second law equation can be rearranged (Eq. (1)) (Santos et al., 2015). This results in the rate of concentration in an unsteady state process as follows:

$$\frac{dC}{dt} = kC^n \tag{1}$$

The equation may also be rearranged into a form that includes mole/mass fractions of the yield and written as follows:

$$\frac{dC_A}{dt} = k[C_{A0}(1 - X_A)]^n \tag{2}$$

Where C_{A0} is the oil concentration in the solid at time 0; and X_A is the oil fraction at time t. Then k is the extraction rate constant and n is the reaction order.

However, since the batch reactor was used for this study with constant volume and the data shows that the reaction is irreversible and can be based on one reactant. Therefore, an assumption that the rate of reaction is a function of the concentration of only one reactant can be made (Fogler, 1999). The rate of reaction can then be determined by the following equation:

$$\frac{dC_A}{dt} = -C_A\frac{dX_A}{dt} \tag{3}$$

To determine the reaction (extraction) rate constant from experimental data by making use of a differential method of analysis; both the reaction (extraction) rate constant and the reaction order can be calculated (Fogler, 1999). The equation can be linearized by taking a natural logarithm on both sides of the equation to be in the form of a straight line function:

$$\ln\frac{dC_A}{dt} = n\ln C_A + \ln k \tag{4}$$

According to Fogler (1999), the reaction rate constant can be determined graphically using the differential method. This method makes use of a linearized equation that when simplified be in the form of $Y = mx + C$. Therefore, from the data obtained from experiments, it was possible to plot the graphs of the logarithm of the change in concentration over time [ln dC/dt] against the logarithm of the concentration [ln C] at different temperatures. The slope of these plots gives us the order of the reaction and the intercept of the plot gives us the ability to determine the reaction rate constant. The results of the reaction (extraction) rate constant obtained at different temperatures are shown in Table 2 :

Fig. 5 at different temperatures shows that the plots have different slopes and intercepts. When comparing these trends it was found that different temperatures have different reaction rates, which was evident that the increase in temperature led to an increase in extraction rate constant, k. Table 2 depicts the results of the reaction rate constants at different temperatures and an increase in reaction rate constant was observed with the increase in temperature. According to Amarante et al. (2014) the increase in extraction temperature increases the solubility of the solvent and decreases the viscosity of both the solute and the solvent, which helps facilitate the mass-transfer process.

The regression (R^2) of all the functions shows apercentage of above 90%, which means that over 90% of the data points on all the functions fall in the regression lines. The results, however, show that there is a variation in reaction orders. It can be obseved that the extraction at 60 °C and 70 °C have the first-order reaction; whereas the extraction at 40 °C and 50 °C are still in the first-order but they tend to the second-order reaction, respectively.

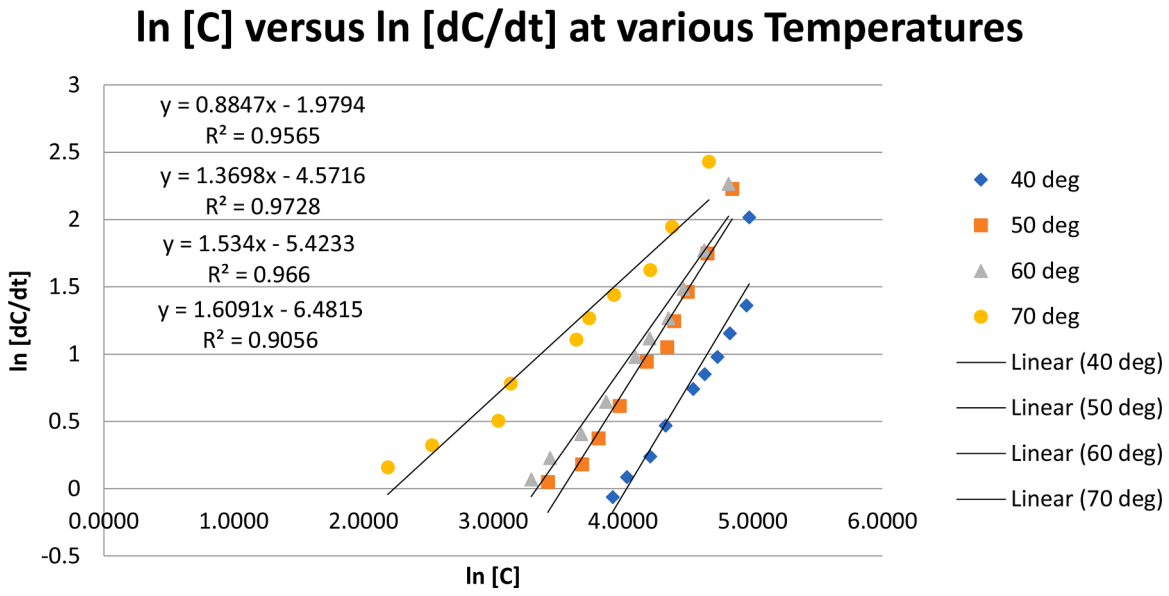

Fig. 5. Plot of ln C against dC/dt to determine the extraction rate constant and reaction order.

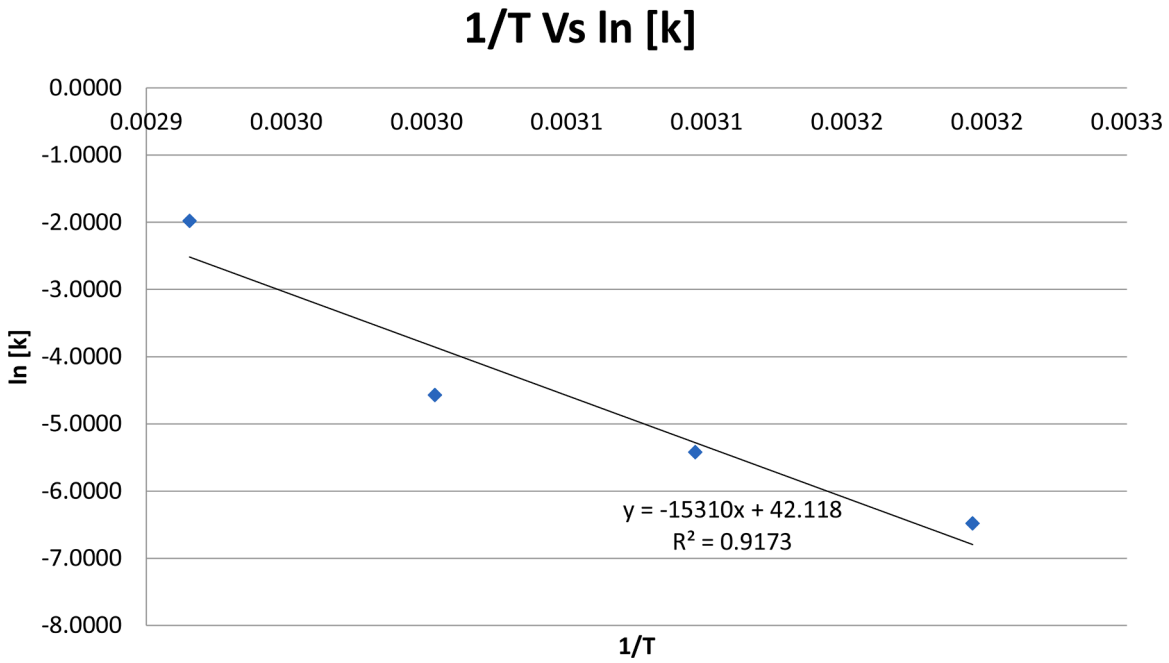

Fig. 6. Plot of ln k against 1/T to determine the activation energy of the system.

4.4. Thermodynamic models

The thermodynamic models used in this study were carefully selected to be those that would apply to the conditions in which the experiments were performed. For the conditions of constant volume and constant temperature, the Van't Hoff's model (Eq. (5)) may be applied to help determine the Enthalpy and the Entropy of a system (Amarante et al., 2014). According to Atkins & Paula (2006), Van't Hoff's model relates the equilibrium constant of a system to the changes in temperature. From the second law of thermodynamics; the Gibbs' free energy derived from the Gibbs and Helmholtz energies model at constant temperature can be calculated with the use of Eq. (6).

$$\ln K = -\frac{\Delta G}{RT} = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \tag{5}$$

$$\Delta G = \Delta H - T\Delta S \tag{6}$$

4.5. Determining the activation energy

The activation energy of the extraction reaction can be determined using the Arrhenius equation which is found to be:

$$k = Ae^{-E_a/RT} \tag{7}$$

Where E_a is the activation energy, R is the universal gas constant, A is the Arrhenius constant and T is the temperature where k is the reaction rate constant. The activation energy and the Arrhenius constant can also be determined graphically by linearizing and simplifying the Arrhenius equation (Mills et al., 1993). The linearized Arrhenius equation is found to be in the following form:

$$\ln k = \frac{-E_a}{R}\left(\frac{1}{T}\right) + \ln A \tag{8}$$

The equation can be seen to also be having the form of a straight line $Y = mx + C$. Therefore we can plot ln k against (1/T). This also means that according to Eq. (8) , the activation energy can be determined from the slope of the plot and the Arrhenius constant can be determined from the intercept.

Fig. 6 is a plot of ln k against 1/T; the regression of the plot allowed the activation energy and the Arrhenius constant to be calculated. The activation energy was found to be, E_a = 127.2950 KJ/mol and the Arrhenius constant, $A = 1.9571 \times 10^{18}$ min^{-1} which can also be said to be $A = 3.2618 \times 10^{16}$ S^{-1}.

Table 3
Activation Thermodynamic parameters.

T (°C)	ΔS≠ (J/mol.K)	ΔH≠ (KJ/mol)	ΔG≠ (KJ/mol)
40	70.8185	124.6926	−22.0415
50	70.55702	124.6094	−22.6653
60	70.30351	124.5263	−23.2865
70	70.0575	124.4431	−23.9053

4.6. Calculating the activation thermodynamic parameters

These parameters and constants now allow the activation thermodynamic parameters to be determined. The activation thermodynamic parameters were calculated according to the transition state theory using the following equations:

$$A = \frac{RT}{Nh}e^{\Delta S^{\neq}/R} \tag{9}$$

$$\Delta H^{\neq} = E_a - RT \tag{10}$$

$$\Delta G^{\neq} = \Delta H^{\neq} - T\Delta S^{\neq} \tag{6}$$

Note the inequality sign on the entropy, enthalpy and Gibbs energy terms, which state that these parameters were calculated in transition state. Where N is the Avogadro's constant, and h is the plank's constant from Eq. (9). These parameters were calculated according to each absolute temperature and they are as shown in the Table 3 :

The results, in this case, show that there is positive entropy and negative Gibbs free energy. The indication of changes in enthalpy and entropy being positive means that the extraction process is endothermic (Stolen and Grande, 2004). These activation thermodynamic results during extraction also indicate that there is a rise in the disorder of the solid-oil-hexane system because the oil is transferred from a solid phase to a liquid phase (Amarante et al., 2014).

Table 4
Equilibrium data at different temperatures.

Temp (°C)	1/T	Y_T	ln Y_T	Y_U	K
40	0.003195	51.66414	3.9448	15.40586	3.3535
50	0.003096	57.7176	4.0556	9.35243	6.1714
60	0.003003	58.8321	4.0747	8.237926	7.1416
70	0.002915	64.3435	4.1642	2.726474	23.5995

Furthermore, it was also found that the change in activation free energy or the Gibbs free energy calculated using Eq. (6) to be negative. The negative change in Gibbs free energy means that the reaction takes place spontaneously (Amarante et al., 2014). It can therefore then be confirmed that the extraction of oil from the avocado mesocarp with hexane as solvent takes place spontaneously at temperatures between 40 °C and 70 °C.

4.7. Calculating the standard thermodynamic parameters

The standard thermodynamic parameters were calculated using the Van't Hoff's model with Eq. (5). These parameters were calculated using the equilibrium data of the extraction process.

Table 4 shows the summary of equilibrium values at different extraction temperatures. This equilibrium data was used to plot the inverse of temperature in Kelvin against the natural log of the oil yield at that temperature. The plot (Fig. 7) gives a straight line and its slope represents the standard enthalpy of the system, ΔHR (Amin et al., 2010). The standard change in enthalpy of the system was found to be $\Delta H =$ 0.0876 KJ/mol for an avocado oil extraction using hexane.

According to the results in Table 5, which were determined from the Van't Hoff's model and the equilibrium constant equation, it was found that the enthalpy was positive, which explains that the avocado oil extraction process is an endothermic reaction; which proves that there was energy applied to the reaction. The study also determined the standard entropy of the extraction process at different temperatures. The results of the entropy found were all positive for the temperatures that were studied. The positive standard entropy of the system confirms that the extraction reaction is an irreversible reaction (Amin et al., 2010; Bevan and Science, 2000). The study also found the results of the standard Gibbs free energy to be negative for all the temperatures studied. A negative Gibbs free energy indicates that the extraction reaction is a spontaneous reaction at that temperature (Stolen and Grande, 2004).

According to the study by Amarante et al. (2014) and the one conducted by Sulaiman et al. (2013); the results of their studies agree with the results of this study with avocado mesocarp. Amarante et al. (2014) studied the extraction of castor oil from waste castor cake and Sulaiman et al. (2013) studied and optimized the extraction of coconut oil from waste coconut. These two studies explored the chemical thermodynamic parameters of the extraction processes and the results of their studies were compared with those of this study with avocado. The comparison of these studies was found to have agreed; which meant that the results of this study agreed with the thermodynamic laws. The extraction reactions were all endothermic because of the positive change in enthalpy, the reactions were all found to have been irreversible because of the positive change in entropy and the reactions were all found to have been spontaneous because of the negative change in Gibbs free energy.

The results of this study were compared with those of Amarante et al. (2014) and Sulaiman et al. (2013) because they were extractions from the fruit/vegetable mesocarp (flesh) and not that of seeds oil. The extractions were all done using organic solvents that are acceptable as GRAS solvents. The studies were reported by Liauw et al. (2008); Topalla and Gecgel (2000) and Santos et al. (2015) shows that it was also found that the results of this study also agreed with some of their studies done with seed oils. However, according to Santos et al. (2015), Topalla

Table 5
Standard thermodynamic parameters, equilibrium constant (ΔK), entropy (ΔS) and Gibbs energy (ΔG) at different temperatures.

Temp (°C)	ΔK	ΔS	ΔG
40	3.3535	10.3406	−3.1490
50	6.1714	15.4030	−4.8876
60	7.1416	16.6089	−5.4432
70	23.5995	26.5395	−9.0154

Enthalpy $\Delta H = 0.0876$ KJ/mol.

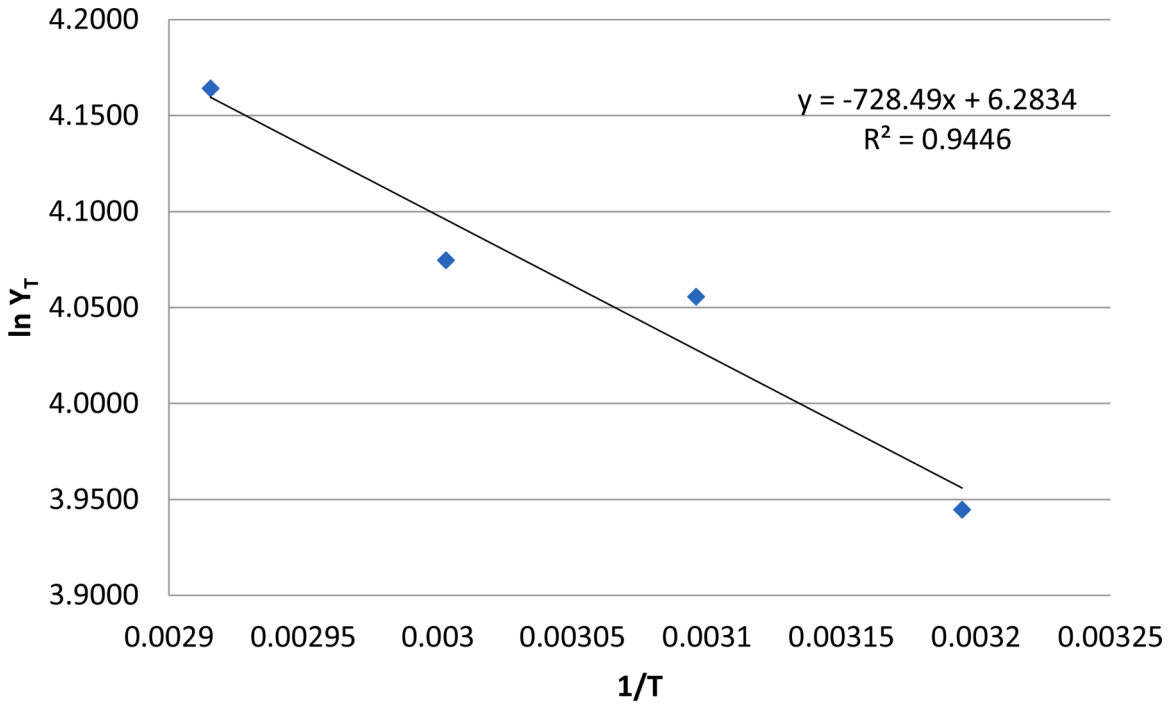

Fig. 7. Plot of 1/T against the ln Y_T to determine the standard enthalpy of the system.

and Gecgel (2000) and Liauw et al. (2008); it was found that with seed oils, the particle size and moisture content of the seeds have a significant influence in the Gibbs energy which overall have an influence in the spontaneity of the reaction.

The anticipated challenge to this process in industrial scale is that it will not be an ideal process as results found in lab scale. The reaction conversion and efficiency is anticipated to be different in an up-scale due to the type of reactor design features and the solid to liquid interaction. However, these challenges can be overcome by altering the process conditions until the desired conversion and kinetics are reached. The other challenge anticipated is the loss in energy and material due to drying and pulverizing the dry solids. This will then affect the energy and material balances of the process.

5. Conclusion

The study has confirmed the kinetics of the extraction of oil from avocado flesh through a batch solid-liquid process using hexane as a solvent with a solid to liquid ratio of 3.05 mL/g. The process was also found to have been feasible at temperatures between 40 °C and 70 °C. The study confirmed that the rise in extraction temperature results in a rise in the rate of extraction and the yield of the oil extracted. The kinetic study of the process showed that the increase in temperature gave an increase in the extraction rate constant. The difference of 30 °C in temperatures from 40 °C to 70 °C was found to have had an increase in yield of over 40 g/L from 169.2 g/L to 210.73 g/L. This work also concluded that extraction of avocado oil took place by both washing and diffusion steps; where Fick's law proved to successfully describe the diffusion process of oil from the avocado flesh.

Avocado oil extracted through solid liquid extraction technique is mostly used for the cosmetics industry and oil extracted using a cold mechanical press and aqueous technique is used for culinary. Therefore, the oil extraction studied in this paper will be commercialized as it is the one that produces a higher yield. Solid liquid solvent extraction is the most common extraction technique in commercial industries because of its efficiency. Therefore, the data found from the research may help size a reactor/extractor using the reaction kinetics data. The data found from Fick's law with mass transfer and equilibrium data help with the operating parameters of the extraction process. The thermodynamic parameters will help guide the operations as well in order to favour forward irreversible and spontaneous reactions.

The conclusion was reached that the use of Van't Hoff's model proved to be a suitable model and it successfully described the relationship between the changes in the equilibrium constant with the change in temperature. The thermodynamic parameters proved that the experimental results agreed with the theory of second and third law of thermodynamics as was expected regarding the change in enthalpy, entropy and Gibbs free energy. At elevated temperatures of 40 °C to 70 °C, the change in enthalpy were found to be positive, which indicates that, the process is endothermic, thus confirming that the energy was added to the system. The change in entropy was also found to have been positive which indicates that the extraction reaction is irreversible. The Gibbs free energy was calculated at all extraction temperatures and were all found to have been negative. This according to the second law of thermodynamics, which is described by the Gibbs and Helmholtz energies, indicates that the extraction reaction is spontaneous. It was also found from the results that the increase in temperature decreases the Gibbs energy; this means that the increase in extraction temperature increases the spontaneity of the reaction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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