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Research Article

Modeling of the Extraction Kinetics of Oil from Safou Pulp (*Dacryodes edulis* H.J. Lam) by Heating in Hexane with Stirring

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Abstract

The continuous extraction of oil from safou pulp in hot hexane with stirring was studied. Two factors were considered: the method with two modes, M1 and M2, respectively without and with prior preheating of the solvent, and the temperature with two modes as well, 90 and 105°C for M1, and 50 and 70°C for M2. The results showed that continuous extraction by direct contact of the substrate with the solvent yields lower results compared to Soxhlet extraction, which has the advantage of regenerating the pure solvent each time, leading to more efficient recovery of the solute. However, the extraction rate is proportional to the preheating of the solvent, temperature, and agitation of the system, compared to previous results. The extraction curves exhibit the usual pattern of solid-liquid extraction of plants, with an ascending phase followed by stabilization. The temperature stabilization phase was not observed. The experimental curves validate the Peleg model, but not the first-order kinetic model. The oil is extracted by elution and diffusion. Peleg's lines, t/Yt = 0.01855t + 0.13074 at 90 °C and t/Yt = 0.02076t + 0.05839 at 105 °C for method M1, and t/Yt = 0.01842t + 0.03657 at 50 °C and t/Yt = 0.01934t + 0.02647 at 70 °C for method M2, characterizing the extraction process, confirm the previous conclusions. The initial extraction rates, respectively equal to 7.65, 17.13, 27.34, and 37.77 %.min^{-1}, are proportional to the extraction temperature and higher when the solvent is preheated. The activation energy values, 61.31 kJ.mol^{-1} for method M1 and 14.88 kJ/mol for method M2, clearly show the benefit of preheating the solvent before starting the extraction.

Keywords: Safou pulp; oil extraction; heating; Stirring; Kinetic; Modeling.

Introduction

The safou, a non-conventional oilseed (Silou, 2014) originating from the Gulf of Guinea, is a fruit highly valued by local farming populations. The oil from its pulp, which ranges between 40 and 65% of the dry matter (Silou *et al.*, 1991; Silou, 1996; Kengué, 2002; Bopoundza *et al.*, 2020), contains over 95% palmitic, oleic, and linoleic acids in total (Omoti and Okyi, 1987; Kiakouma and Silou, 1987;

Tchendji *et al.*, 1987; Kinkéla and Bezard, 1993; Kapseu and Tchiegang, 1994; Bopoundza *et al.*, 2020). Studies on the kinetics of its transformation are recent (Massamba *et al.*, 2012; Silou *et al.*, 2022; Lipinda *et al.*, 2023; Binaki *et al.*, 2024). The study by Silou *et al.* (2022), which performed refractometric extractions at room temperature by maceration and hot Soxhlet extraction by depletion, showed that the oil is extracted according to the Peleg model with both methods and according to first-order kinetics with the Soxhlet method. The study indicated that the oil is extracted in two stages: rapid elution from the cells broken during grinding and slow diffusion from the intact cells; and that the validation of the first-order kinetics only through hot Soxhlet extraction suggests, during this process, the neglect of the elution phase in favor of diffusion.

Indeed, the mass transfer during solid-liquid extraction, as in the case of safou, is a process that depends on several stages. In general, this mass transfer mechanism occurs in four stages: solvent diffusion into the solid matrix, solute dissolution in the solvent, diffusion of the solute-rich solution toward the outer surface of the solid, and transfer of the enriched solution from the solid phase to the liquid phase (Rakotonirina *et al.*, 2018). The first stage is the fastest and can thus be neglected compared to the other three. The second is the slowest compared to the other processes when the solute is a solid. However, when the solute is a liquid that has a higher affinity with the solvent (miscible), this stage is fast for the solute fixed on the walls of the inert solid and slow for the solute inside the cells, becoming slower as the cell walls are less permeable. Practically, the slowness of this step is minimized by grinding the substrate (Mafard and Béliard, 1993; Mohamed, 2007). Turning it into powder allows for the destruction of a significant portion of the cell walls, thereby facilitating mass transfer during the extraction from the substrate to the solvent (Pifferi and Vaccari, 1983; Gao and Mazza, 1996; Landbo and Meyer, 2001). Grinding is thus an operation that reduces extraction duration by minimizing the time required for the different solid-liquid extraction steps. In addition, proper agitation of the mixture minimizes the fourth stage and also facilitates the extraction of the remaining solute in the intact cells.

Apart from time, the extraction rate is also a function of temperature. It influences extraction efficiency; the higher the temperature, the more the solvent increases its diffusion capacity while its surface tension and viscosity decrease (Sparr Eskilsson and Björklund, 2000). Therefore, it is difficult to simply determine the influence of temperature on extraction.

Temperature thus appears as a very important parameter in the extraction process of plant active ingredients. Its increase can shorten the duration of active ingredient extraction by minimizing certain steps (Türker and Erdogdu, 2006). By increasing the solvent's diffusion capacity, this slow step can become fast and completely merge with elution, potentially resulting in first-order kinetics, combining elution and diffusion. Therefore, a contradictory view to the conclusion drawn by Silou *et al.* (2022) regarding the first-order kinetics validated by hot Soxhlet extraction arises.

These interpretations indicate that the study of extraction processes requires a rigorous methodology. Understanding the different processes is essential for implementing an appropriate application. The extraction conditions and process monitoring must be well studied to achieve satisfactory results. Thus, in this study, unlike the one conducted by Silou *et al*. (2022), we focus on modelling the hot solvent extraction of oil from safou pulp (Dacryodes edulis) with agitation, considering two factors: the extraction method and temperature, each with two modes.

Material and Methods

Plant material

The studied safou (50 fruits) were purchased at the Total market (Brazzaville). These safou came from Madzia (Pool department). The fruits were of grade II, the most common grade in the sub-region. They were washed and then pitted. The obtained pulp was then dried in an oven at 105°C for 24 hours, and subsequently ground.

Methods

1- Determination of the Oil Content of the Studied Safou Pulp

The oil content $(OC)_0$ of the studied safou pulp was determined by Soxhlet extraction (3 trials) for 3 hours with 350 mL of hexane (Mampouya *et al.*, 2013). The mass m_1 of the pulp used for each extraction was 50 g. After extraction, the extract was dried with sodium sulfate, the solvent was evaporated under vacuum, and any remaining solvent traces were removed by drying the oil in an oven at 105°C for 6 hours. The obtained oil was weighed (m_2), and the oil content $(OC)_0$ was determined using the formula:

$$(OC)_0 = \frac{m_2}{m_1} x100 \quad (1)$$

2- Experimental Oil Extraction

Two methods were used to extract oil from the safou pulp:

- The first method, labeled M1, involved mixing the ground pulp with the solvent at room temperature and then placing the mixture in the oven at the desired temperature.
- The second method, labeled M2, involved preheating the solvent to the extraction temperature before adding the ground pulp.

The extractions were carried out at temperatures of 90 and 105°C using method M1 and, due to solvent evaporation caused by preheating before mixing with the plant material, at temperatures of 50 and 70°C using method M2.

For each extraction, seven bottles were used, with 5 g of pulp powder (m_1) introduced into each bottle containing 30 g of hexane. The bottles were sealed, shaken for 10 seconds, and then placed in the oven. The samples were taken at times 1 min, 30 min, 60 min, 90 min, 120 min, 150 min and 180 min. At each specified time, one bottle was removed from the oven, and the remaining bottles were shaken for 10 seconds and then returned to the oven. This process continued until all seven bottles were exhausted.

At each removal, the bottle's contents were filtered, and the solvent in the resulting solution was evaporated in the oven at 105°C for 24 hours. The obtained oil was weighed (m_2), and the yield y_t was determined using the formula:

$$y_t = \frac{m_2(t)}{m_1} x100 \quad (2)$$

3- *Modeling of Oil Extraction from Safou Pulp*

There are numerous studies on the modeling of mass transfer kinetics in plant products. Several models have been used to explain mass transfer processes during the processing of plant products, such as drying (Awotona *et al.*, 2020; Yildirima, 2017; Charmongkolpradit and Luampon, 2017; Fang *et al.*, 2015; Khawas *et al.*, 2015; Porniammongkol *et al.*, 2014), oil extraction (Limpida *et al.*, 2024; Satriana *et al.*, 2023; Silou *et al.*, 2022), and rehydration (Quicazan *et al.*, 2012; Turhan *et al.*, 2002).

In this work, two models were used as a basis for the kinetic study of oil extraction (desorption) from safou pulp: the first-order kinetic model and the Peleg model (Silou *et al.*, 2022).

For the first-order kinetic model, the oil content at each moment is evaluated in the extract, which can correspond to the yield of our extraction over time, while in the Peleg model, it refers to the oil content in the sample.

If total extraction is considered, the yield at t_∞ (y_∞) corresponds, by extrapolation, to the initial oil content $(OC)_0$ of the samples. Moreover, the oil content $(OC)_t$ of the studied samples at time t is given by equation 3.

$$(OC)_t = (OC)_0 - y_t \quad (3)$$

Following the above, the mathematical expressions of these two models adapted to the study data are written as:

First-order Kinetic Model		Peleg Model	
$\boldsymbol{y_t = (OC)_0\left(1 - e^{-kt}\right)}$	(4)	$(OC)_t = (OC)_0 - \frac{t}{k_1 + k_2 t}$	(5)

Whose linearized mathematical expressions are:

First-order Kinetic Model		Peleg Model	
$\boldsymbol{\ln\left(\frac{1}{1-\frac{y_t}{(OC)_0}}\right) = kt}$	(6)	$\frac{t}{(OC)_0 - (OC)_t} = k_1 + k_2 t$	(7)

By setting $X_t = \frac{y_t}{(OC)_0}$ and $Y_t = (OC)_0 - (OC)_t = y_t$ (see Eqn. 3), the first-order kinetic and Peleg equations simplify.

First-order Kinetic Model		Peleg Model	
$\boldsymbol{\ln\left(\frac{1}{1-X_t}\right) = kt}$	(8)	$\frac{t}{Y_t} = k_1 + k_2 t$	(9)

The curve of $\ln\left(\frac{1}{1-X_t}\right) = f(t)$ is a straight line with a slope of k (min^{-1}) (first-order kinetic constant) passing through the origin, and the curve of $\frac{t}{Y_t} = f(t)$ is a straight line with a slope of k_2 (%$^{-1}$) (Peleg capacity constant) and an intercept of k_1 (min.%$^{-1}$) (Peleg kinetic constant).

The desorption rates (R) can be obtained using the first derivatives of equations (4) and (5) for these two models.

First-order Kinetic Model		Peleg Model	
$\boldsymbol{R_1 = \frac{dy_t}{dt} = -(OC)_0 . k . e^{-kt}}$	**(10)**	$\boldsymbol{R_2 = -\frac{d(OC)_t}{dt} = \frac{k_1}{(k_1 + k_2 t)^2}}$	(11)

The first-order kinetic rate constant 1 k and the Peleg constant k_1 are related to the initial extraction rates $(R_1)_0$ and $(R_2)_0$ by the mathematical expressions:

First-order Kinetic Model		Peleg Model	
$\boldsymbol{(R_1)_0 = \left(\frac{dy_t}{dt}\right)_{t_0} = -(OC)_0 . k}$	**(12)**	$\boldsymbol{(R_2)_0 = -\left(\frac{d(OC)_t}{dt}\right)_{t_0} = \frac{1}{k_1}}$	(13)

The Peleg capacity constant k_2 is related to the minimum accessible oil content $(OC)_e$ of the samples. At t_∞, Peleg's equation (5) provides the relationship between $(OC)_e$ and k_2:

$$(OC)_\infty = (OC)_e = (OC)_0 - \frac{1}{k_2} \quad (14)$$

This minimum accessible oil content represents the amount of oil not extracted during the process and indicates the efficiency of the extraction.

4- *Determination of Activation Energy (Ea)*

The activation energy (Ea in kJ/mol) is the minimum energy required to initiate the extraction process (Kurji *et al.*, 2019). Its determination is done by plotting the curve of *lnk* or *lnv* as a function of temperature T. If the resulting plot is a straight line, the slope gives the value of $\frac{Ea}{R}$ (Elenga *et al.*, 2011).

Approximately, the activation energy *Ea(app)* can be obtained between two temperatures T_1 and T_2 when the rate constants k_1 and k_2 or the rates R_1 and R_2 at the two temperatures are known:

$$Ea(app) = \frac{R.ln\frac{k_2}{k_1}}{\frac{1}{T_1}-\frac{1}{T_2}} = \frac{R.ln\frac{R_2}{R_1}}{\frac{1}{T_1}-\frac{1}{T_2}} \quad (15)$$

5- *Statistical Analysis*

The statistical analysis was performed using Excel 2010 and OriginPro 2021 software.

Results and Discussion

Oil Content of The Studied Safou Pulps

The oil content of the studied safou pulps is shown in Table 1. These pulps exhibit a characteristic content found in the literature (> 55%), which makes safou an oilseed with undeniable food potential, given its composition in fatty acids (FAs) and triacylglycerols (TAGs) (Umoti and Okyi, 1987; Kiakouma and Silou, 1987; Tchendji *et al.*, 1987; Kinkéla and Bezard, 1993; Kapseu and Tchiegang, 1996; Bopoundza *et al.*, 2020).

Table 1: Oil Content of the Studied Safou Pulps

Test	1	2	3	Average	Standard deviation
$(OC)_0$ (%)	57,43	56,99	57,68	57,37	0,35

Experimental Oil Extraction from Safou Pulp

The monitoring of oil extraction from safou pulp using the two methods M1 and M2 yielded the results shown in Table 2. The oil contents of the studied pulps are similar to those reported in the literature for solvent extraction (Dzondo-Gadet *et al.*, 2004, 2005). The extraction yields are 91.16%, 84.19%, 93.78%, and 89.77% relative to the initial average oil content $(OC)_0$ at 90, 105, 50, and 70°C, respectively. These yields are lower than those achieved by Soxhlet extraction, where the solvent, continuously regenerated in a pure state in the cartridge, regains its original properties and efficiently recovers the material to be extracted (the oil), even the most adsorbed, from the pulp.

The Table 2 shows that the two methods yield different results. The results obtained with method M1 clearly indicate the latency period required for heating the system when starting the extraction at room temperature. At 90 °C, 77% of the oil is extracted more than 45 minutes later, and at 105°C, 77% is extracted after 30 minutes, whereas the same oil content was extracted within the first minute using method M2. These results are consistent with scientific theories suggesting that the temperature of the solvent significantly impacts solid-liquid extraction processes (Turker *et al.*, 2005; Chambers *et al.*, 1996). Higher temperatures facilitate the diffusion of the solvent into the substrate and increase its solubility, making it easier to extract the oil contained in the intact cells (method M2), thereby enabling the simultaneous progression of both elution and diffusion extraction processes. Fig. 1 clearly shows the depletion of the plant matrix by method M2 compared to method M1 as early as the 60th minute of extraction, marked by the stabilization of both extraction curves, while those for method M1 continue to increase until the 90th minute at 105°C and until the 120th minute at 90°C.

Table 2: Oil Extraction Yields (%) from Safou Pulp as a Function of Time and at Different Temperatures

Times (min)	M1		M2	
	at 90°C	at 105°C	at 50°C	at 70°C
0	0	0	0	0
1	35.7	35.1	44.4	43.1
30	39.7	44.02	48.8	47.1
60	49.4	44.5	51.2	51.7
90	45.0	47.1	52.8	50.1
120	51.4	45.7	53.5	51.0
150	52.6	47.2	53.7	51.3
180	52.3	48.3	53.8	51.5

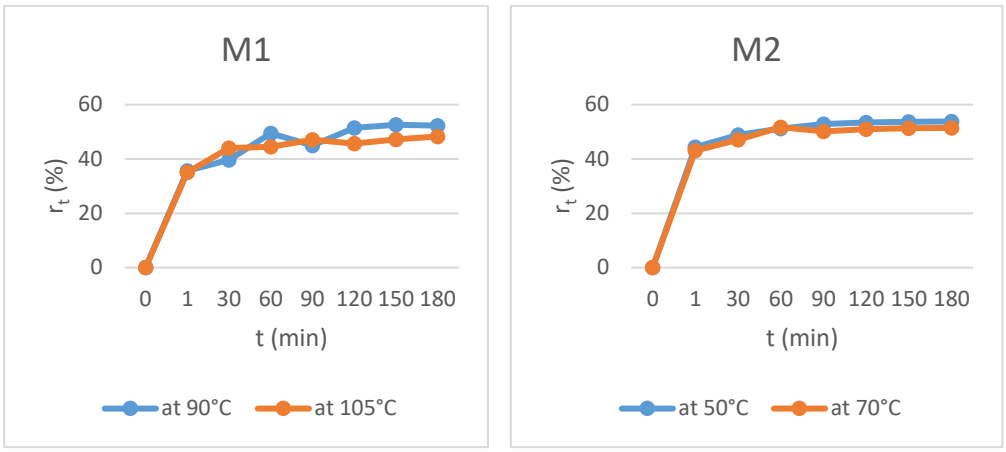


Fig. 1: Extraction Kinetics Curves of Oil Using the Two Methods

The two extraction curves (50°C and 70°C) for method M2 show stabilization after the 90th minute of extraction, indicating an equilibrium between the extract and the plant material, while those of method M1 continue to grow until the 120th minute. This part of the extraction, where the slope of the curve gradually decreases, corresponds to the progressive disappearance of the washing (elution) phase in favor of the diffusion phase. The extraction curves for method M1 exhibit significant fluctuations. These fluctuations could also be due to the latency time taken by the system to heat up, as they are observed at both temperatures, 90 and 105°C. Method M2, leading to the extraction of more than 77% of the oil within the first minute, minimizes these fluctuations. This observation shows that the extraction duration of plant material by solvent at a given temperature is reduced when the solvent-substrate mixture is performed at the considered temperature, especially as the solvent is heated. The heating step is not observed. A hotter solvent enhances the extraction yield by permeabilizing the cell walls through denaturation, increasing the solubility of the substances to be extracted, increasing the diffusion coefficients, and reducing its viscosity.

Observing the results obtained by Silou *et al.* (2022), this study provides better yields compared to the two Soxhlet extractions with the same solvent and maceration with bromo-1 naphthalene. The oil yields obtained in this study, from the first minute, far exceed those obtained after hours by these two methods, comparable to the Soxhlet extraction after about 130 minutes, despite the regeneration of pure solvent by this method. These two extractions, without agitation, compared to this study, confirm scientific theories: good agitation minimizes the transfer of the solute-enriched solution contained in the solid phase to the liquid phase and also facilitates the extraction of the remaining solute within the intact cells (Sparr Eskilsson and Björklund, 2000). Moreover, maceration lasts about 4 to 10 days, while decoction (agitation due to boiling) requires only short contact times, around ten minutes (Groubert, 1984). It follows from this study that, besides the grinding of the safou pulps, preheating the solvent and agitating the mixture increase the extraction yield.

Beyond the fluctuations observed in method M1, the curves showing the evolution of extraction yields over time for these two methods (Fig. 1) have a characteristic appearance of an extraction curve for a metabolite from a plant matrix, presenting two phases (ascending and stationary) and resemble those of most authors (Meziane *et al.*, 2006; Zghaibi *et al.*, 2020; Silou *et al.*, 2022; Satriana *et al.*, 2023) who have conducted continuous metabolite extraction. These curves show three extraction stages:

- During the first stage (from t = 0 to 30 minutes for method M1 and to 1 minute for method M2), the sorption rate is very fast, with the extraction yield rising from 0 to over 69% at 90°C and over 76% at 105°C for method M1, and over 77% at 50°C and over 75% at 70°C for method M2. This behavior can be explained by:
  - Easy access to the solute by the solvent due to the denaturation of the substrate cells during grinding,
  - The presence of a richer solid phase,
  - The effect of heat on the solvent, which promotes the solubility of the solute,
  - The unavailability of active sites on the safou.

The predominant step is elution.

- During the second stage (30 to 120 minutes at 90°C and beyond 180 minutes at 105°C for method M1, and 1 to 90 minutes at 50°C and 60 minutes at 70°C for method M2), the extraction rate decreases significantly. The extraction yield increases from 69.20% to 89.59% at 90°C and from 76.70% to more than 84.19% at 105°C for method M1, and from 77.39% to 92.03% at 50°C and from 75.12% to 90.11% at 70°C for method M2. This behavior can be explained by:

- The scarcity of interstitial solute and the increasingly difficult access of the solvent to the solute within the intact cells,
- The progression of the extraction (increasing time), making the active sites on the safou more available (unsaturation),
- The depletion of the solid phase.

There is a coexistence of both extraction stages, with the first elution and diffusion being predominant.

- During the third stage (time greater than 120 minutes at 90°C and not observable at 105°C for method M1, and greater than 90 minutes for extraction at 50°C and greater than 60 minutes for extraction at 70°C for method M2), the extraction rate drops to zero, and equilibrium is reached. This behavior can be explained by:

  - The unsaturation of the matrix (safou),
  - The balance between the number of active sites transitioning from the solid phase to the liquid phase (extraction).

In conclusion, this kinetic study shows the existence of two (2) stages:

- The first stage corresponds to a rapid extraction of the oil, depending on the extraction technique and the matrix used,
- And the second (third stage), where the curve levels off, which corresponds to the maximum possible yield achieved, indicating equilibrium between the substrate and the extract.

The heating stage of the plant material, during which no safou oil extraction occurs, is not observed.

Modeling of Pulp Oil Extraction

The data used to plot the oil extraction curves from safou pulp using the two methods (M1 and M2) with Peleg's model and first-order kinetics are presented in Tables 3 to 6.

The validation curves for these two models are shown in Fig. 2 and 3.

The values of the coefficients of determination or correlation (R^2), as well as the estimated parameters, which help interpret the results, are presented in Table 7.

Table 3: Data used to plot the curves of these kinetic models at 90°C (M1)

Time (min)	0	1	30	60	90	120	150	180
y_t(%)	0	35.7	39.7	49.4	45.0	51.4	52.6	52.3
$(TH)_t=(TH)_0-y_t$	57.37	21.67	17.67	7.97	12.37	5.97	4.77	5.07
$X_t=y_t/(TH)_0$	0	0.62	0.69	0.86	0.78	0.90	0.92	0.91
$\ln(1/1-X_t)$	0	0.97	1.17	1.97	1.51	2.30	2.53	2.41
$Y_t=y_t$	0	35.7	39.7	49.4	45.0	51.4	52.6	52.3
t/Y_t	–	0.03	0.76	1.21	2	2.33	2.85	3.44

Table 4: Data for plotting these kinetic models at 105°C (M1)

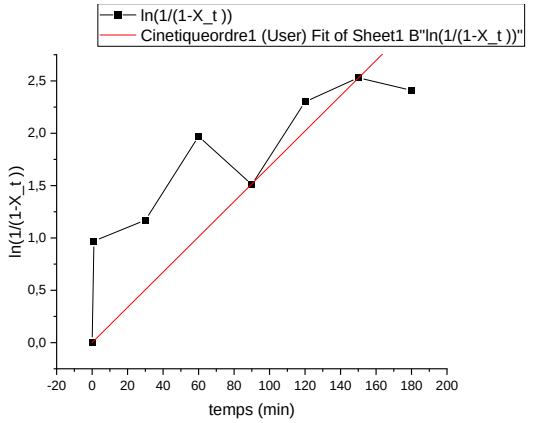
Time (min)	0	1	30	60	90	120	150	180
y_t(%)	0	35.1	44.0	44.5	47.1	45.7	47.2	48.3
$(TH)_t=(TH)_0-y_t$	57.37	22.27	13.37	12.87	10.27	11.67	10.17	9.07
$X_t=y_t/(TH)_0$	0	0.61	0.77	0.78	0.82	0.80	0.82	0.84
$\ln(1/1-X_t)$	0	0.94	1.47	1.51	1.71	1.61	1.71	1.83
$Y_t=y_t$	0	35.1	44.0	44.5	47.1	45.7	47.2	48.3
t/Y_t	–	0.03	0.68	1.35	1.91	2.63	3.18	3.73

Table 5: Data for plotting these kinetic models at 50°C (M2)

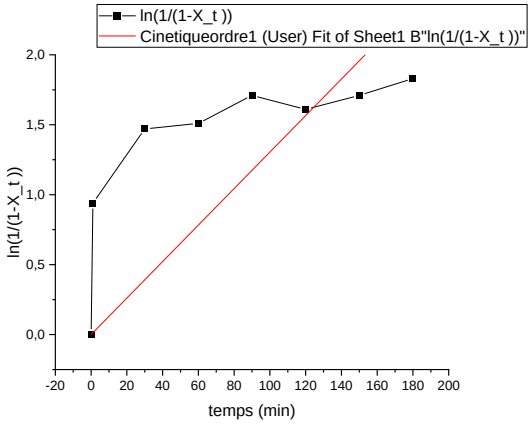
Time (min)	0	1	30	60	90	120	150	180
y_t(%)	0	44.4	48.8	51.2	52.8	53.5	53.7	53.8
$(TH)_t=(TH)_0-y_t$	57.37	12.97	8.57	6.17	4.57	3.87	3.67	3.57
$X_t=y_t/(TH)_0$	0	0.77	0.85	0.89	0.92	0.93	0.94	0.94
$\ln(1/1-X_t)$	0	1.47	1.90	2.21	2.53	2.66	2.81	2.81
$Y_t=y_t$	0	44.4	48.8	51.2	52.8	53.5	53;7	53.8
t/Y_t	–	0.02	0.61	1.17	1.70	2.24	2.79	3.35

Table 6: Data for plotting these kinetic models at 70°C (M2)

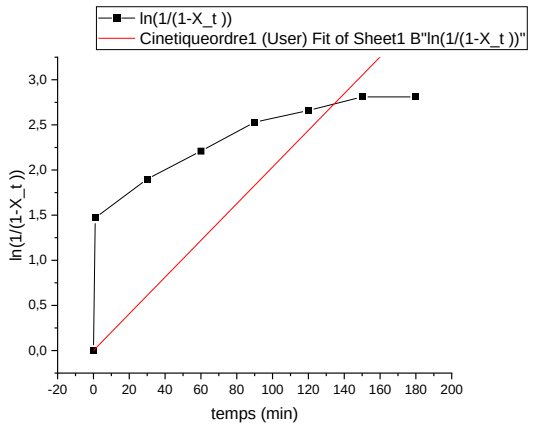
Time (min)	0	1	30	60	90	120	150	180
y_t(%)	0	43.1	47.1	51.7	50.1	51.0	51.3	51.5
$(TH)_t=(TH)_0-y_t$	57.37	14.27	10.27	5.67	7.27	7.37	6.07	5.87
$X_t=y_t/(TH)_0$	0	0.75	0.82	0.90	0.87	0.89	0.89	0.90
$\ln(1/1-X_t)$	0	1.39	1.71	2.30	2.04	2.21	2.21	2.30
$Y_t=y_t$	0	43.1	47.1	51.7	50.1	51.0	51.3	51.5
t/Y_t	–	0.02	0.64	1.16	1.80	2.35	2.92	3.50



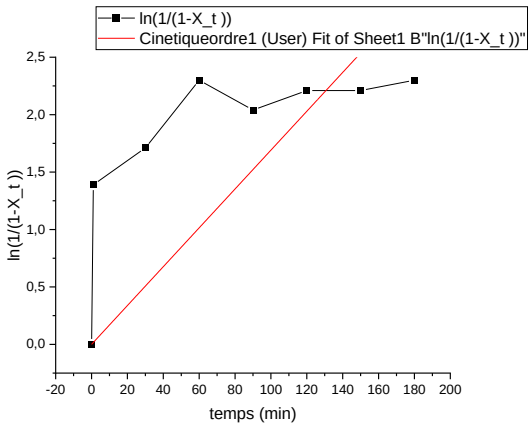
a) Validation test at 90°C (M1)



b) Validation test at 105°C (M1)



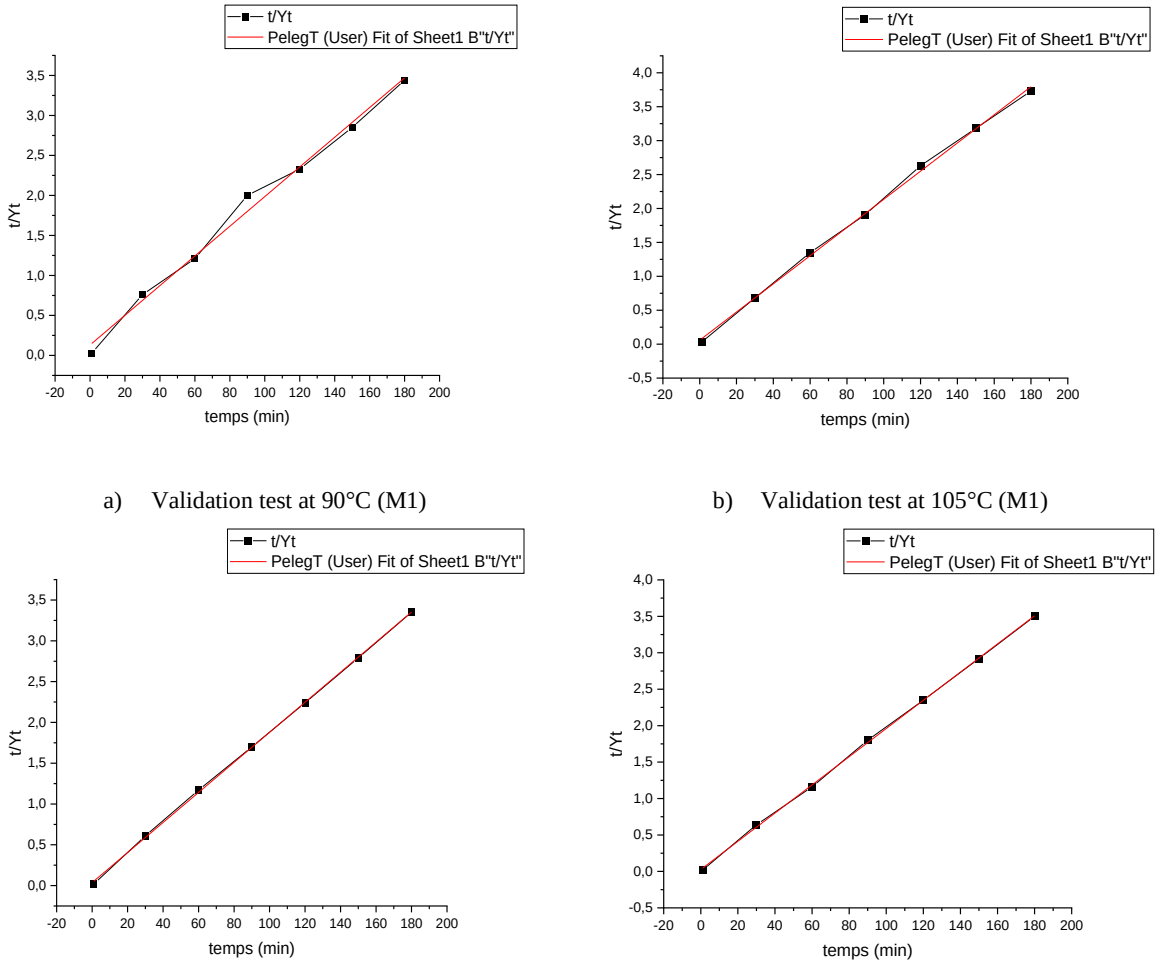
c) Validation test at 50°C (M2)



d) Validation test at 70°C (M2)

Fig. 2: Pseudo first-order kinetic model

These results show that the extraction of oil from safou pulp using both methods M1 and M2 validates Peleg's model, with R^2 values ranging from 0.9924 to 0.9997 and χ^2 values between 0.0005 and 0.0132. The first-order kinetic model is not validated. These findings are consistent with the results obtained by Silou *et al.* (2022) for continuous solvent extraction with the same plant material. The values of k_1 and k_2 obtained using this model, when plotting the curves $t/Y_t = f(t)$ (Fig. 2 and 3) with the experimental data, allow for the derivation of the mathematical expressions of the lines for this model (Eqn. 9) and the determination of the minimum accessible oil content of the samples $(TH)_e$ (Eqn. 14) and the initial extraction rate $(R_2)_0$ (Eqn. 13).



a) Validation test at 90°C (M1)

b) Validation test at 105°C (M1)

c) Validation test at 50°C (M2)

d) Validation test at 70°C (M2)

Fig. 3: Peleg model

Table 7: Statistical data for the two models studied

Methods	**Parameters**			
	first-order kinetic model		**Peleg model**	
M1 at 90°C	k	0.01684 ± 0.00218	k_1	0.13074 ± 0.07866
			k_2	0.01855 ± 7.27242E-4
	χ^2	0.39074	χ^2	0.01323
	R^2	0.48367	R^2	0.99237
M1 at 105°C	k	0.01305 ± 0.00235	k_1	0.05839 ± 0.03818
			k_2	0.02076 ± 3.52996E-4
	χ^2	0.45289	χ^2	0.00312
	R^2	-0.2251	R^2	0.99856
M2 at 50°C	k	0.02033 ± 0.00325	k_1	0.03657 ± 0.01569
			k_2	0.01842 ± 1.45032E-4
	χ^2	0.86632	χ^2	5.26299E-4
	R^2	0.0442	R^2	0.99969
M2 at 70°C	k	0.01691 ± 0.00322	k_1	0.02647 ± 0.01862
			k_2	0.01934 ± 1.72096E-4
	χ^2	0.8493	χ^2	7.41045E-4
	R^2	-0.38168	R^2	0.9996

Table 8: Peleg equations and values of $(TH)_e$ and $(R_2)_0$ validating the oil extraction.

Methods	Mathematical expression	$(OC)_e$ (%)	$(R_2)_0$ (%/min^{-1})
M1 at 90°C	$t/Y_t = 0.01855t + 0.13074$	3.46	7.65
M1 at 105°C	$t/Y_t = 0.02076t + 0.05839$	9.20	17.13
M2 at 50°C	$t/Y_t = 0.01842t + 0.03657$	3.08	27.34
M2 at 70°C	$t/Y_t = 0.01934t + 0.02647$	5.66	37.77

These results confirm scientific theories. The initial extraction rate $(R_2)_0$, which characterizes the rate of mass transfer from the solid to the liquid, is proportional to the extraction temperature and higher when the solvent is preheated. The values of k_2 also increase with temperature. Preheating the solvent is therefore a favorable criterion for the extraction of oil from safou pulp, which is increasingly facilitated by higher temperatures.

The experimentally accessible minimum oil contents, which are 5.07%, 9.07%, 3.57%, and 5.87% (Tables 3, 4, 5, and 6) respectively at 90°C (M1), 105°C (M1), 50°C (M2), and 70°C (M2), differ by less than 15% from the calculated values obtained using Peleg's model (Table 8), except for the extraction at 90°C with method M1, where fluctuations increase the deviation to over 40% compared to the previous value of 4.77%, resulting in a difference of 27%.

These results confirm the occurrence of the extraction in two stages and lead to a formal second-order kinetics, thus validating Peleg's model.

Activation Energy

The activation energies for extraction using the two methods M1 and M2, validated by Peleg's model and determined approximately using the initial extraction rates R_0 through Eqn. 15, are 61.31 kJ/mol and 14.88 kJ/mol, respectively. These energy values indicate that the oil is more easily extracted by method M2 than by method M1, suggesting that preheating the solvent is favorable for extracting oil from safou pulp.

Table 9: Activation energy values for oil extraction from various plants (Satriana *et al.*, 2023).

Vegetal	Ea (kJ/mol)
Oil extraction from Chlorella vulgaris	39.66
Oil extraction from avocado pulp	47.51
Oil extraction from mint leaves	55.11
Extraction of oils from 10 different plants	79-104
Avocado oil after	99.60

Conclusion

The extraction of oil from safou pulp using hexane follows scientific principles. Preheating the solvent yields the best results, as does agitation of the system, when compared to the study by Silou *et al.* in 2022 using Soxhlet extraction with the same solvent and maceration with bromo-1-naphthalene on the same fruit.

Furthermore, similar to the findings of Silou *et al.*, the extraction of oil from safou pulp using the two methods, M1 and M2, validates Peleg's model but not the first-order kinetic model. The oil is extracted through elution and diffusion. The k_1 and k_2 values obtained using this model are, for method M1, 0.131 min.%$^{-1}$ and 0.019 %$^{-1}$ at 90°C and 0.058 min.%$^{-1}$ and 0.01 %$^{-1}$ at 105°C; for method M2, 0.037 min.%$^{-1}$ and 0.018 %$^{-1}$ at 50°C and 0.026 min.%$^{-1}$ and 0.019 %$^{-1}$ at 70°C. The initial extraction rates, which are proportional to the extraction temperature and solvent preheating, are 7.65, 17.13, 27.34, and 37.77 %·min^{-1}, respectively. The experimentally accessible minimum oil contents differ by less than 15% from the values calculated using Peleg's model.

The activation energies for oil extraction are significantly different. The value for method M2, 14.88 kJ/mol, is much lower than that for method M1, 61.31 kJ/mol, and is close to values found in the literature, clearly indicating the benefit of preheating the solvent before starting the extraction.

Authors' Contribution

FC Bopoundza, AF Binaki & T Silou designed the research plan; FC Bopoundza, ET Biassala, JA Siassia Massamba & T Silou performed experimental works & collected the required data. FC Bopoundza, AF Binaki, ET Biassala, BW Loumouamou, SN Ngueko & JA Siassia Massamba analysed the data; & prepared the manuscript. FC Bopoundza, ET Biassala & T Silou critically revised and finalized the manuscript. Final form of manuscript was approved by all authors.

Conflict of Interest

The authors declare that there is no conflict of interest with present publication.

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