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Valorization of palm oil mill effluent via enhanced oil recovery as an alternative feedstock for biodiesel production

Yee Mun Tang [a,*], Kok Tat Tan[b] and Lai Peng Wong [a]

[a] Department of Environmental Engineering, Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, Jalan Universiti Bandar Barat, 31900 Kampar, Perak, Malaysia

[b] Department of Petrochemical Engineering, Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, Jalan Universiti Bandar Barat, 31900 Kampar, Perak, Malaysia

*Corresponding author. E-mail: even2501@1utar.my

YMT, 0000-0001-8568-3055; LPW, 0000-0002-9172-5183

ABSTRACT

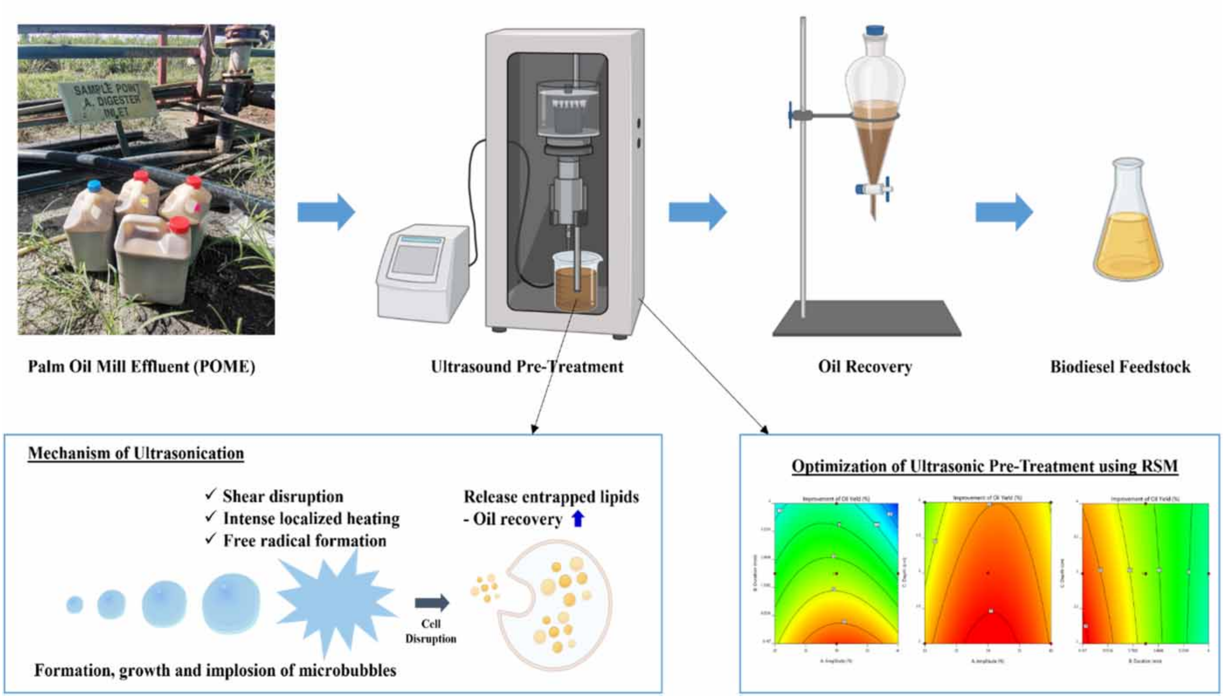
Residual oil from palm oil mill effluent (POME) can be valorized into value-added products like biofuel. However, the complex structure in POME limits the full recovery of intracellular lipids. To address this challenge, low-frequency ultrasonication was used as a pre-treatment prior to oil recovery to improve the yield by liberating the entrapped oil via the cell disruption technique. This study focused on optimizing the ultrasound conditions (i.e., ultrasonication amplitude, ultrasonication duration, and probe immersion depth) to maximize the improvement of oil recovery yield using response surface methodology. The optimized conditions were 30.074% ultrasonication amplitude, 0.167 min ultrasonication duration, and 2 cm probe immersion depth. This resulted in an additional 42.50% improvement in oil recovery yield over non-ultrasonicated POME, which is in close agreement with the model prediction. Additionally, a cost–benefit analysis was incorporated to determine the feasibility of ultrasonication for enhancing oil recovery. The study also explored the synthesis of biodiesel from POME-recovered oil and characterized the fuel attributes according to American Society for Testing and Materials- and European Standards-prescribed procedures. The attributes of biodiesel produced from POME-recovered oil are comparable to those of palm-based biodiesel in Malaysia, demonstrating its potential as an alternative source for biodiesel production.

Key words: biodiesel, oil recovery, palm oil mill effluent, response surface methodology, ultrasonication, valorization

HIGHLIGHTS

- An optimized study for ultrasound-enhanced oil recovery from palm oil mill effluent (POME) using response surface methodology was conducted.
- Cost–benefit analysis revealed that ultrasound pre-treatment is a viable process.
- POME-recovered oil was used for biodiesel production via a two-step esterification and transesterification process.
- Biodiesel produced from POME-recovered oil met the fuel characteristics requirement of local and international standards.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The growth of the palm oil industry is proliferating, particularly in Southeast Asia, due to the rising demand from the food and beverage, oleochemical, and biodiesel industries. Concurrent with this surge in production, a tremendous amount of industrial wastewater, known as palm oil mill effluent (POME), is also generated. According to the source from Oil World (2021), the global crude palm oil (CPO) production in 2021 was 78.5 million tons, generating more than 235 million tons of wastewater, which is currently an underutilized biomass. POME is an acidic high-strength waste with a high concentration of solids and organic content that is detrimental to the environment if discharged indiscriminately. POME also contains a notable amount of oil and grease (O&G) ranging from 130 to 18,000 mg/L (Kamyab *et al.* 2018), an untapped resource that industries have largely neglected without realizing its effects and potential.

Ever since the global depletion of fossil fuels and the rise in environmental pollution, there has been significant research dedicated to biodiesel as an eco-friendly and renewable alternative fuel. Commonly, edible oil is the leading resource for the manufacturing of biodiesel. Nevertheless, the utilization of edible oil invariably sparks controversy and establishes a conflict between the availability of food and fuel. As the world evolves toward sustainability, researchers and stakeholders are striving to explore the conversion of waste into biofuel, one of which is by reutilizing the residual oil recovered from POME for biodiesel production. This approach to waste oil utilization is particularly beneficial as it reduces waste discharge and disposal while supporting circular economy initiatives. Several methods have been investigated for recovering the oil from POME (Ahmad *et al.* 2003; Faisal *et al.* 2016; Mohamed Anuar *et al.* 2020). However, the complex and relatively resistant impurities in POME limit the full recovery of intracellular O&G (Wan Sharifudin *et al.* 2015). This reduces the efficiency of oil recovery and contributes to resource wastefulness in the long term. To offset this reluctance, pre-treatment with a cell disruption approach is thus required prior to oil recovery.

Ultrasonication is an acoustic green technology that can induce physical, chemical, and biological effects on the sonicated materials (Show & Wong 2012). The use of ultrasonic irradiation technology has piqued the interest of researchers in environmental remediation due to the promising results in enhancing sludge biodegradability. Wong *et al.* (2017) discovered that sonicated POME contains more soluble organic matter than non-sonicated POME, whereas Isa *et al.* (2020) revealed that POME pre-treated with ultrasound improved biogas production by 21.5% due to increased biodegradability. The cavitation phenomenon induced by the propagation of ultrasonic waves has been associated with the effects such as shear disruption, intense localized heating, and free radical formation (Mamvura *et al.* 2018). Considering that the oil is entrained in the POME particles, ultrasonication treatment can ideally disrupt the complex particles and liberate the oil content for the enhancement of oil recovery yield.

The one-factor-at-a-time (OFAT) method employed in classical optimization studies is often time-consuming and does not demonstrate the interaction effect between several factors. To address this constraint, response surface methodology (RSM), a combination of statistical and mathematical approaches that incorporate the interaction effect between numerous elements, is utilized (Myers & Montgomery 1996). Rather than investigating all conceivable combinations, the aggregate mix proportion can be determined with a minimum number of experiments. To the best of our knowledge, there has been no published study addressing the optimal ultrasonic pre-treatment conditions for enhancing oil recovery from POME using RSM. Furthermore, feasibility studies for ultrasound enhancement are also rarely reported. This study aims to fill this gap by focusing on optimizing the ultrasonic pre-treatment conditions using RSM and evaluating the cost–benefit analysis of ultrasound enhancement. Additionally, this study also explores the use of non-edible recovered oil from POME as an alternative feedstock for biodiesel production.

2. METHODS

2.1. Wastewater – POME

A raw POME sample before undergoing any biological treatment process was obtained from a palm oil mill in the district of Batang Padang, Perak, Malaysia, with a fresh fruit bunches (FFB) process throughput level of 80 metric ton/hour (MT/h) expandable to 120 MT/h. The characteristics of the POME sample were conducted in triplicate in compliance with the American Public Health Association (APHA) on Standard Methods for the Examination of Water and Wastewater (Eaton *et al.* 1995).

2.2. Optimization of ultrasound pre-treatment conditions for the oil enhancement process using RSM

An attempt to enhance the oil recovery was carried out by introducing ultrasonic pre-treatment on raw POME. An ultrasonic processor model Q500 from Qsonica (Newton, CT, USA), which was equipped with a threaded-end type probe and a replaceable titanium alloy tip of 1.3 cm diameter, was utilized in this study for the pre-treatment of 200 mL POME. This equipment operates at a frequency of 20 kHz and features configurable ultrasonication amplitude and time. An ultrasonication chamber used for the batch ultrasonication was a 250 mL borosilicate glass beaker with dimensions of 9.5 cm in height and 7.5 cm in diameter, respectively. The probe position in the reaction chamber was controlled using an adjustable support laboratory jack.

A three-factor face-centered central composite design (FCCD) was applied using Design-Expert version 12.0 software (Stat-Ease, Inc. Minneapolis, MN, USA) to assess the combined impacts of three independent components and optimize the ultrasound pre-treatment conditions. The design comprises 2^n factorial runs with $2n$ axial runs and $2n$ replication of the center point, where n is the number of factors being investigated (for this case, $n = 3$). Overall, a total of 20 designated experimental runs were generated.

The range of independent variables for the optimization study was selected based on the preliminary study's results by Tang *et al.* (2021) and is summarized in Table 1. The improvement of oil recovery yield, as computed by Equation (1), was selected as the dependent variable, which is the response of the experiment. $O\&G_i$ is the non-ultrasonicated sample's O&G concentration, whereas $O\&G_f$ is the ultrasonicated sample's O&G concentration. The samples utilized throughout the study are

Table 1 | Range of independent variables for the optimization of ultrasonication conditions

		Range of independent variables		
Codified value	**Variables**	**− 1 (low)**	**0 (medium)**	**+ 1 (high)**
A	Ultrasonication amplitude (%)	20	30	40
B	Ultrasonication duration (min)	0.167	2.0835	4
C	Probe immersion depth (cm)	2	3	4

consistent; hence, the initial O&G concentration was the same (1,550 mg/L):

$$\text{Improvement of oil yield (\%)} = \left(\frac{\text{O\&G}_f - \text{O\&G}_i}{\text{O\&G}_i}\right) \times 100\% \quad (1)$$

The model's adequacy was assessed by the fit summary statistics test where four sequential models are involved: linear, two-factor interactions (2FI), quadratic, and cubic. The coefficient of determination (R^2) serves as a quality indicator for the fitted polynomial model, and the Fisher's test (*F*-test) was utilized to validate the statistical significance. Analysis of variance (ANOVA) was used to determine the significance of individual, quadratic, and interaction terms. The significance of the model terms was evaluated using probability (*p*-value) with a 95% confidence level. Design-Expert software is also capable of generating three-dimensional (3D) response surfaces and contour plots, which display a more precise relationship between the variables and the response.

2.3. Economic analysis on ultrasound enhancement

The focus of the current economic analysis is to explore the viability of utilizing ultrasound pre-treatment as a means of enhancing the oil recovery yield from POME. Specifically, this study will assess the economic feasibility of this process by taking into account of the revenue generated from the sale of the recovered oil, alongside the associated operating cost. A key focus of the operating cost is placed on the electricity consumption required for the process, as this is considered a crucial factor. The operating cost analysis of the enhanced oil recovery process was evaluated at its optimum condition.

2.4. Biodiesel synthesis from POME-recovered oil

POME with ultrasound pre-treatment was subjected to oil recovery in accordance with APHA 5220B. The recovered oil from POME was found to possess a high concentration of free fatty acid content (8.95%), rendering it incompatible with the conventional biodiesel production method. Thus, an acid esterification is required as a pre-treatment prior to alkaline transesterification to produce biodiesel using POME-recovered oil (Hayyan *et al.* 2011). The qualities of the produced biodiesel, including density, ester content, oxidation stability, total acid value, and viscosity, were analyzed according to the prescribed methods of the American Society for Testing and Materials (ASTM) and European Standards (EN) and compared against international (EN 14214 and ASTM D6751) and local (MS 2008:2008) standard specifications.

3. RESULTS AND DISCUSSION

3.1. POME attributes and qualities

Table 2 illustrates the characteristics of POME from a local palm oil mill in the state of Perak, Malaysia, along with the regulatory discharge standards. The results were shown non-compliance to the POME-discharged limits. The properties of POME vary considerably depending on the fruit batches, palm oil processing mechanisms, and weather conditions. Owing to the high levels of BOD, COD, and solid contents, indiscriminate discharge of the untreated POME would negatively impact the ecosystem. Despite the enhanced extraction process in the palm oil mills, significant amounts of O&G were discovered in the effluent as oil losses, limiting the efficacy of the subsequent biological treatment process. Oil losses in POME highlighted the potential of oil recovery for higher value-added products.

Table 2 | Characteristics of POME along with the regulatory discharge standards

Parameters	Mean value	Discharge limit[a]
pH	4.27 ± 0.01	5–9
Biochemical oxygen demand, BOD_5 (mg/L)	$21{,}200 \pm 819$	100
Chemical oxygen demand, COD (mg/L)	$62{,}333 \pm 2{,}082$	–
Total solids, TS (mg/L)	$37{,}500 \pm 2{,}500$	–
Suspended solids, SS (mg/L)	$11{,}100 \pm 2{,}000$	400
Total volatile solids, TVS (mg/L)	$15{,}967 \pm 2{,}779$	–
Oil and grease, O&G (mg/L)	$1{,}550 \pm 36$	50

[a]Environmental Quality (Prescribed Premises) (Crude Palm Oil) (Amendment) Regulations 1982.

3.2. Optimization study of ultrasound conditions for the maximum improvement of oil yield using RSM

The oil content in POME cannot be fully recovered by the stand-alone method since it is emulsified and entrapped in suspended solids. Alternatively, ultrasound pre-treatment on POME is believed to lead to a slightly higher fraction of easily extractable oil. The impact of ultrasound on enhancing oil recovery could be explained by the breakdown of cell membranes and the subsequent release of oil from suspended particles that have not been disrupted.

Twenty proposed experiments by central composite design (CCD), including six replications of central points (Runs 1, 2, 10, 13, 15, and 20), were conducted randomly to limit the effect of inexplicable variables in the observed response. The experimental results are tabulated in Table 3. The negative value in the table implies no improvement in oil yield over POME without ultrasonication pre-treatment but a decrease in oil concentration.

The software proposes a quadratic model to reflect the improvement of oil recovery yield, and this option is supported by the reports as presented in Tables 4 and 5. According to the fit summary in Table 4, the quadratic model is significant since it matches the circumstances where the sequential *p*-values are less than 0.05. Similarly, the probability of lack of fit is greater than 0.05, indicating that it is insignificant and implying that the observed results are well aligned with the suggested model. The R^2 for this model was calculated to be 0.9561, suggesting that the model does not explain only 4.39% of the total variation. Values greater than 0.80 show that the quadratic model and the experimental data are in satisfactory agreement. The value-adjusted coefficient of determination (R^2_{adj}) is 0.9166, which is close to one, indicating a good degree of linear fit between the experimental and projected values.

Based on Table 5, the model had a high *F*-value of 24.19 and a low *p*-value ($p < 0.0001$), implying that this model was very significant. Model terms with *p*-values less than 0.05 are considered significant. According to the ANOVA analysis, the independent variable (B); two-level interactions (AB and BC); and the quadratic factor (A^2) are the significant model terms. The experimental findings revealed an adequate precision (AP) value of 18.391, which is larger than 4, indicating a satisfactory signal-to-noise ratio.

Table 3 | CCD: experimental parameters and responses

Run	Variables *A*: Ultrasonication amplitude (%)	*B*: Ultrasonication duration (min)	*C*: Probe immersion depth (cm)	Response Improvement of oil yield (%)
1	30	2.0835	3	10.97
2	30	2.0835	3	15.48
3	20	0.167	2	29.05
4	30	4	3	−7.10
5	40	2.0835	3	3.50
6	30	2.0835	4	19.55
7	40	0.67	2	27.37
8	40	4	4	−29.05
9	30	2.0835	2	12.85
10	30	2.0835	3	16.77
11	40	4	2	−31.60
12	30	0.167	3	40.22
13	30	2.0835	3	5.16
14	20	4	4	−12.29
15	30	2.0835	3	15.48
16	20	0.167	4	7.74
17	20	2.0835	3	−0.58
18	20	4	2	−12.88
19	40	0.167	4	16.77
20	30	2.0835	3	17.42

Table 4 | Fit summary

Source	Linear	2FI	Quadratic	Cubic
Sequential *p*-value	<0.0001	0.3303	**0.0009**	0.2795
Lack of fit *p*-value	0.0220	0.0213	**0.3110**	0.3251
Lack of fit *F*-value	6.97	7.29	**1.59**	1.19
R^2	0.7232	0.7854	**0.9561**	0.9790
Adjusted R^2	0.6713	0.6863	**0.9166**	0.9336
Predicted R^2	0.4902	−0.2514	**0.7602**	−3.9742

Bold values in Table 4 indicate that the "*Quadratic*" model is significant. Consistent with the desired emphasis for the information presented in Section 3.2 Paragraph 3.

Table 5 | Coefficient of variables in the regression models and their significance

Sources	Sum of squares	df	Mean square	*F*-value	*p*-value
Model	6,199.64	9	688.85	24.19	<0.0001
A – amplitude	57.89	1	57.89	2.03	0.1844
B – duration	4,583.02	1	4,583.02	160.92	<0.0001
C – depth	48.66	1	48.66	1.71	0.2204
AB	229.41	1	229.41	8.06	0.0176
AC	20.10	1	2010	0.7057	0.4205
BC	153.65	1	153.65	5.40	0.0426
A^2	610.60	1	610.60	21.44	0.0009
B^2	0.1090	1	0.1090	0.0038	0.9519
C^2	0.0712	1	0.0712	0.0025	0.961

Figure 1 shows the Design-Expert plots, which aid in judging the model satisfactoriness by assessing the pattern of all data points. As illustrated in Figure 1(a), the observed results are distributed reasonably close to the 45° regression line, showing a modest deviation between actual and anticipated values. Figure 1(b) shows the residuals versus runs for the improvement of

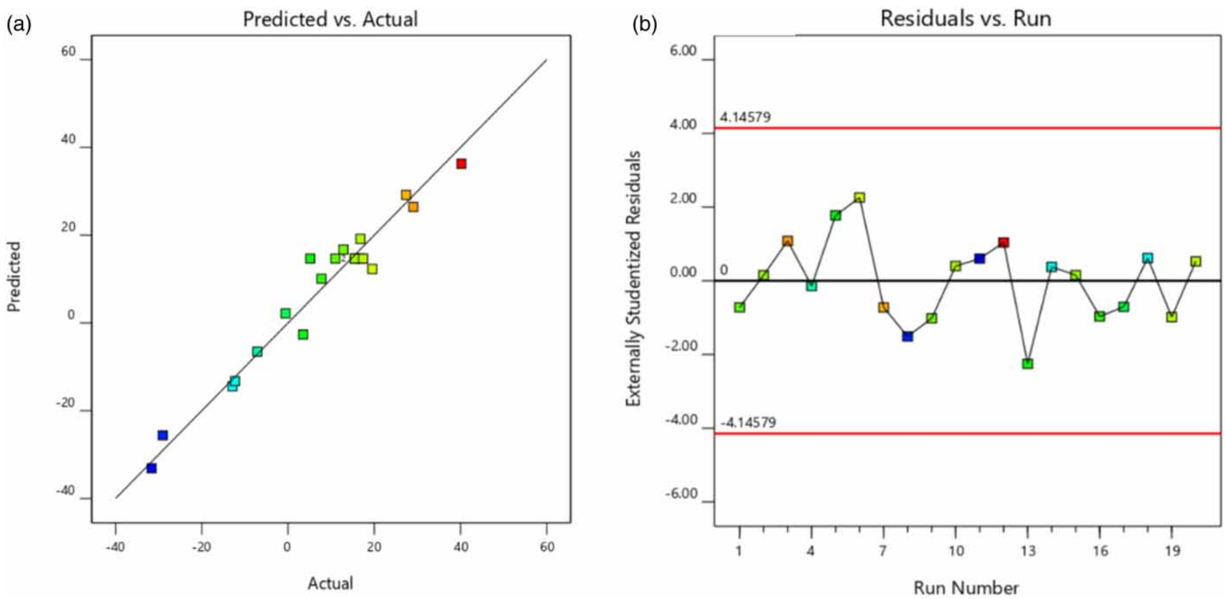


Figure 1 | Design-Expert plot: (a) predicted versus actual and (b) residual versus run. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2023.264.

oil yield. Although the highlighted run differs, there is no cause for concern as it is within the red control boundaries. Both plots are satisfactory, implying that the empirical model adequately describes the enhancement of oil recovery using ultrasound pre-treatment. In other words, the existing model was precise enough; hence, no further model modification was necessary.

The 3D response surface and contour plots displayed in Figure 2 were generated to visualize the combined impact of two independent variables on the dependent ones. Compared to the other interactions (*AC* and *BC*), the interaction between the ultrasonication amplitude and ultrasonication duration (*AB*) demonstrated the greatest effect on the response variable, provided by the high *F*-value of 8.06.

Figure 2(a) shows the improvement of residual oil recovery in terms of ultrasonication amplitude and ultrasonication duration (*AB*) at a fixed probe immersion depth. The ultrasonication amplitude and duration varied from 20 to 40% and 0.167 to 4 min, respectively. It was discovered that with the increment of ultrasonication amplitude to 30% and ultrasonication duration of 10 s, the percentage of improved oil recovery reached the maximum at 40.22%. Hashemi *et al.* (2016) reported this observation in their research of ultrasound-assisted solvent extraction of *Pistacia khinjuk* hull oil, where a rise in the sonication amplitude resulted in an increase in oil output. These findings can be explained by the fact that higher ultrasonication amplitude induces a more rapid form of cavitations, which aided in the shattering of biological membranes by high-speed fluid microjets and expedited the diffusion of oil yield (Fan *et al.* 2014; Nora & Borges 2017). Increases in ultrasonication amplitude beyond the optimum value, on the other hand, may not necessarily generate favorable effects, as seen in Figure 2(a), where the improvement of oil yield declined as the ultrasonication amplitude increased from 30 to 40%. Jadhav *et al.* (2016) discovered a similar scenario in oil extraction from waste date seeds assisted by ultrasound, where no further increment in oil extraction yield was detected when sonication amplitude raised over 30%. This could be attributed to the formation of larger and longer-lived bubbles around the probe, which act as a barrier to acoustic energy transmission.

Figure 2(b) depicts a surface plot of oil recovery as a function of ultrasonication amplitude and probe immersion depth (*AC*) at a constant ultrasonication duration of 10 s. There is no discernible difference in the improvement of oil yield regardless of amplitude or depth. The plot reveals that the interaction has a negligible effect on improving oil recovery from POME, as evidenced by the low *F*-value (0.7057) and the high *p*-value (0.4205).

Figure 2(c) illustrates the combined effect of ultrasonication duration and probe immersion depth (*BC*) on oil recovery improvement at a constant ultrasonication amplitude of 30%. The interaction between ultrasonication duration and probe immersion depth (*BC*) also demonstrated a significant effect on the response variable, provided by the high *F*-value of 5.40. As the time of ultrasonication increased from 10 s to 4 min, the improvement in oil recovery yield decreased. Prolonged ultrasonication induced the formation of highly reactive hydroxyl radicals and increased localized temperature, which could cause the decomposition of oil, and, as a result, a decrease in oil yield. This finding is consistent with that of Suksaroj *et al.* (2020), who also discovered that pre-treatment of POME with ultrasonication for an extended period resulted in lower O&G content. Another possible explanation is that oil components reabsorb into oil-bearing ruptured particles due to their comparatively huge surface area, thus decreasing the oil yield (Buddin *et al.* 2018). In other words, the amount of residual oil recovered was more remarkable at a shorter ultrasonication period and this may result in greater cost-savings in terms of electricity consumption.

A particle size distribution analysis has been conducted in this experiment to provide empirical credence to the explanation. Figure 3 illustrates the particle size distribution of POME, which ranges in size from 0.030 to 954.993 μm, with an asymmetric behavior curve. The mean particle size of the POME sample reduced as soon as ultrasonication was incorporated. The drop in particle size demonstrated that the particles were broken up and entrapped oil was released, contributing to improved oil recovery. However, a further increase in ultrasonication dosage only has little contribution to the particle size reduction. Still, it results in coarsening of agglomerates due to the increased release of intracellular polymers, which is advantageous for particle re-flocculation and entrapment of oil, thus decreasing the oil yield. These results reflect those of Wong *et al.* (2016) who also observed comparable changes in the particle size profile of POME after ultrasonic treatment. Hence, ultrasonication pre-treatment to enhance the oil recovery yield was more remarkable at lower ultrasonication dosage.

The perturbation plot in Figure 4 displays the effects of all independent variables on the improvement of oil recovery yield. A steep slope observed in the ultrasonication duration (*B*) indicates that the response was very sensitive to the variable. The curvature of ultrasonication amplitude (*A*) similarly exhibits response sensitivity, albeit in different patterns. In contrast, the

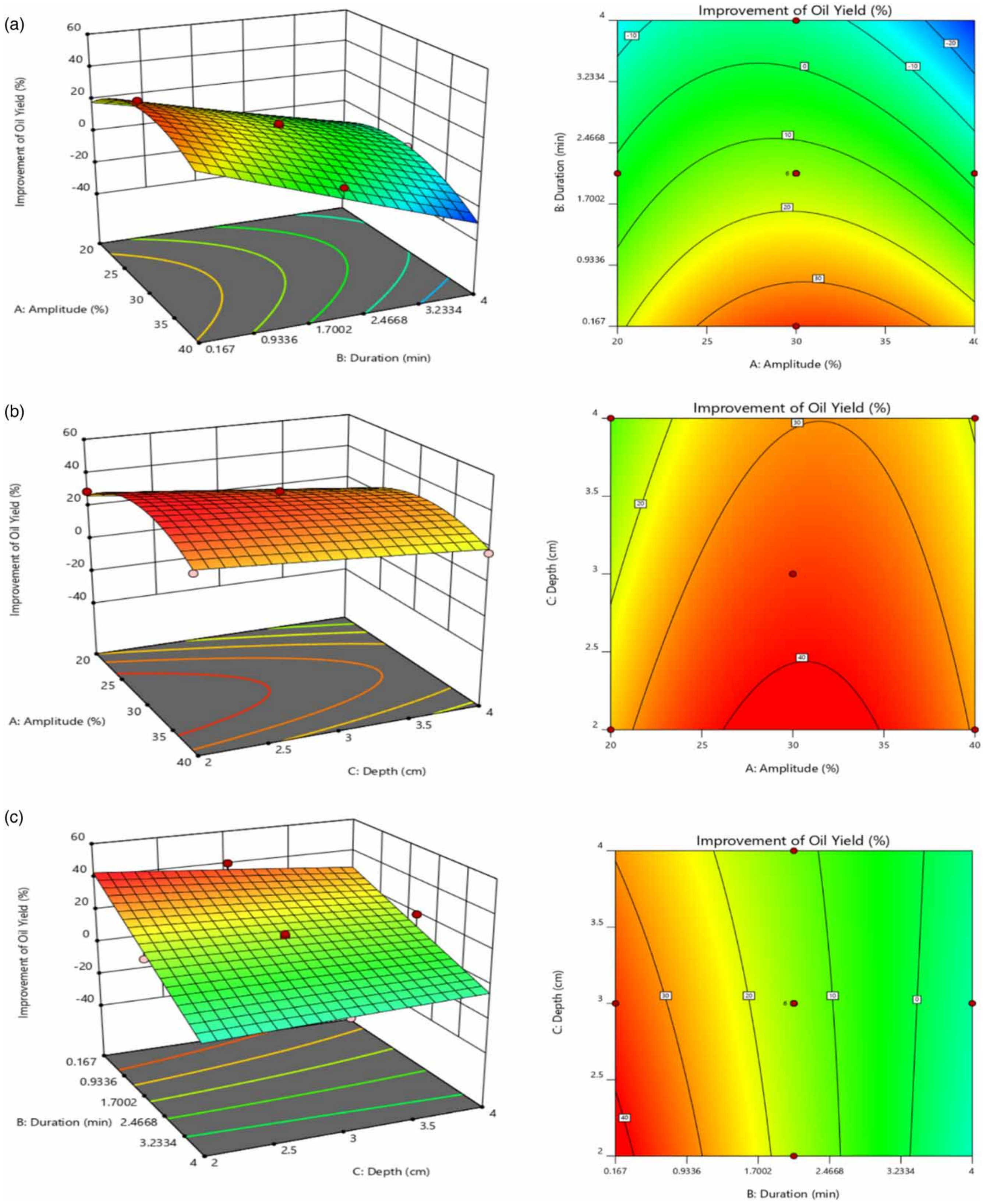


Figure 2 | 3D response surface and contour plots: (a) interaction between *AB*, (b) interaction between *AC*, and (c) interaction between *BC*.

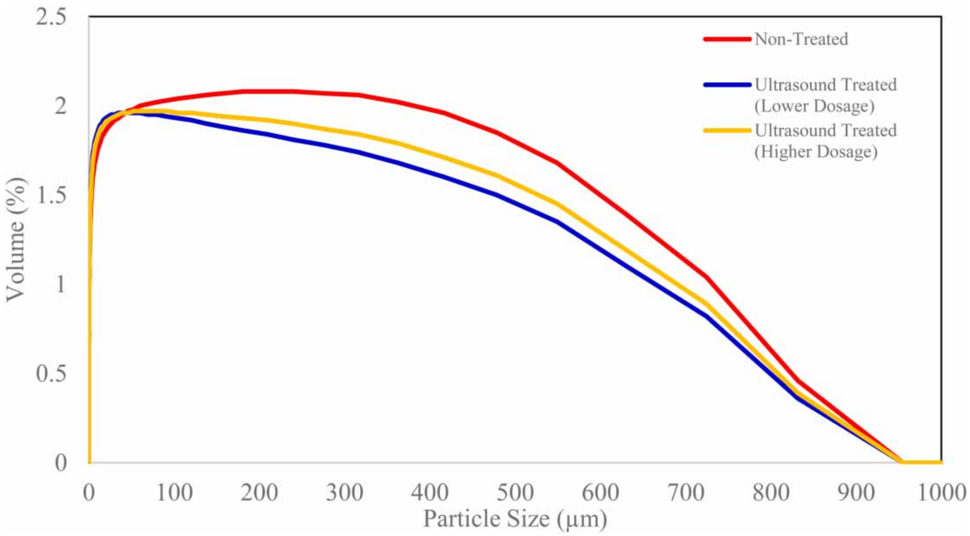


Figure 3 | Particle size distribution of non-treated and ultrasound-treated POME.

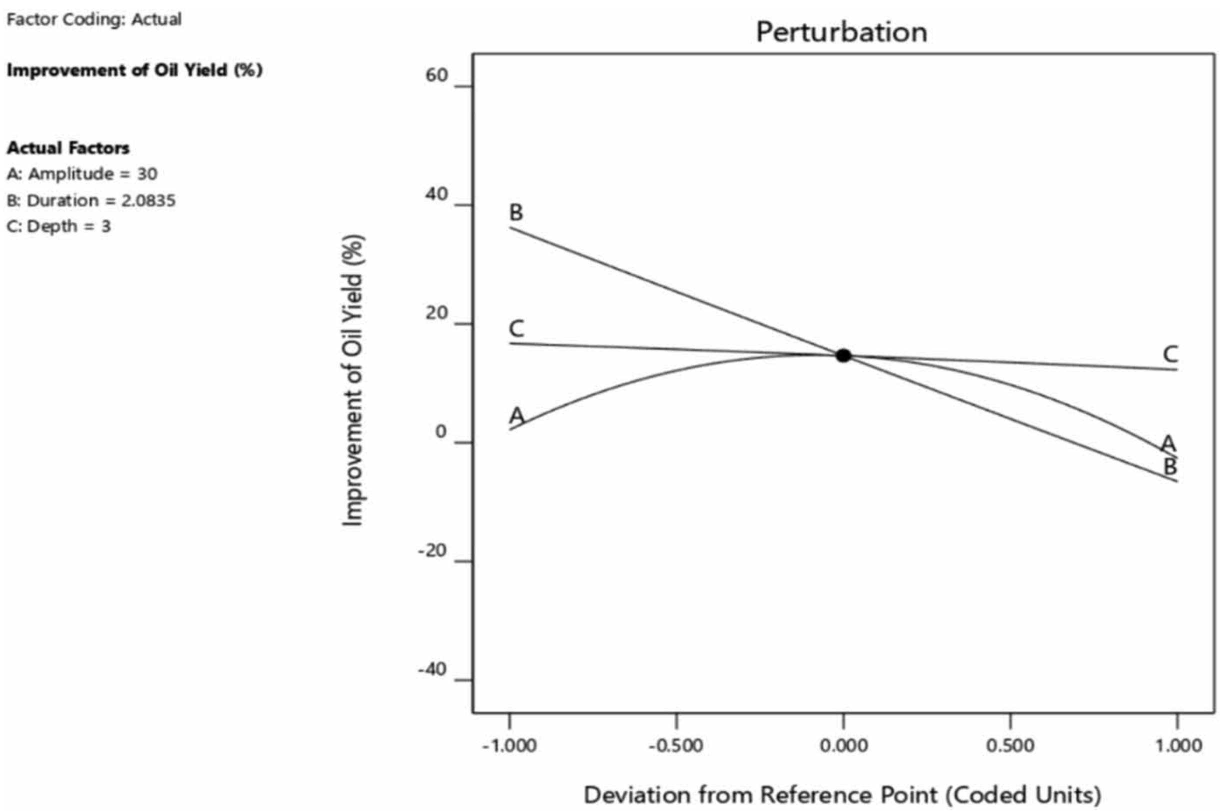


Figure 4 | Perturbation plot for the improvement of oil yield.

comparatively flat line of probe immersion depth (*C*) shows insensitivity to change in that factor on response. Overall, ultrasonication duration (*B*) exhibited the greatest effect, followed by ultrasonication amplitude (*A*) and finally the probe immersion depth (*C*).

Equation (2) shows the final empirical model for the improvement of residual oil recovery (Y, %). The model equation was utilized to forecast the optimum ultrasonication performance. The equation's sign indicates whether the corresponding factors positively or negatively affect the responses:

$$Y = 14.67 - 2.41A - 21.41B - 2.21C - 5.35AB + 1.58AC + 4.38BC - 14.90A^2 + 0.1991B^2 - 0.1609C^2 \quad (2)$$

The optimal ultrasonication conditions for the response were determined via numerical optimization. The factors were set to be in the range, whereas the response was aimed to be maximized. Three RSM-proposed conditions with high desirability, ranging from 83.7 to 85.2%, were chosen to check the accuracy of the models. The experiments were conducted in accordance with the proposed operating conditions, and the experimental results were compared with the predicted results. As illustrated in Table 6, there is only a minor difference between the predicted and observed values, which are less than 5% of the error rate, implying that the model was satisfactory for forecasting performance. In short, the optimum conditions of 30.074% ultrasonication amplitude, 0.167 min ultrasonication duration, and 2 cm probe immersion depth resulted in an additional 42.5% improvement in oil yield.

3.3. Economic analysis

A preliminary economic cost–benefit analysis was conducted to assess the feasibility of utilizing ultrasonication as a pre-treatment to enhance oil recovery from POME in a local palm oil milling plant, which typically processes 80–120 MT of FFB per hour. In an average 100 MT/h FFB processing plant, 60 MT of POME was generated hourly. The milling plant operates on an intermittent basis, depending on the demand and pricing. With 16 h of operation per day and 320 working days per year assumed, the annualized rate of FFB processing was 512,000 MT/year, with 307,200 MT of POME generated annually per mill. Considering 0.155% as the current oil loss in POME, ultrasound pre-treatment improves the oil recovery by 42.5%, corresponding to 0.221% of oil. Given that the market price per ton of CPO fluctuates between Ringgit Malaysia (RM) 5,345.50 to RM 6,873.00 from January to June 2022 (Malaysian Palm Oil Board 2022), the average CPO price is around RM 6,301.50/ton. With the assumption of the residual oil recovered from POME can be sold for 50% of the typical CPO price, the selling price is approximately RM 3,150.75/ton.

Since the enhancement of oil recovery using ultrasonication does not involve the use of chemicals, electricity consumption would be the most concerning factor. In this scenario, ultrasonication dosage in Equation (3), defined as the amount of energy supplied per unit of sludge volume, remains an important metric. An ultrasonication dosage of 7.5 kWs/L is required to achieve the maximal improvement of oil recovery under the optimized condition. According to the low-voltage industrial electricity tariff provided by Tenaga National Berhad (2022), electricity is charged at RM 0.38/kWh. To treat 60 MT of POME per hour, 125 kWh of electricity is required for the ultrasonication process. The estimated hourly electrical cost for the process is RM 47.50, totaling RM 243,200 in annual utility bills. Table 7 presents the economic analysis of the enhancement of oil recovery from POME using ultrasonication:

$$\text{Ultrasonication dosage} = \frac{\text{Power (kW)} \times \text{Time(s)}}{\text{Volume (L)}} \quad (3)$$

The enhancement of oil recovery using ultrasound pre-treatment will bring in the additional revenue of RM 638,815 per mill per year, depending on the mill's oil loss. Even with the consideration of the electricity consumption of ultrasound pre-treatment, this pre-treatment can still generate a profit of RM 395,615, making ultrasound pre-treatment a viable process.

Table 6 | Verification of forecasted responses for ultrasonication treatment on POME

Ultrasound condition						
Amplitude (%)	**Duration (min)**	**Depth (cm)**	**Desirability**	**Predicted improvement (%)**	**Experimental improvement (%)**	**Error rate (%)**
30.454	0.167	2.000	0.852	42.738	40.50	5
30.074	0.67	2.000	0.851	42.716	42.50	1
31.397	0.210	2.000	0.837	42.008	41.32	2

Table 7 | Economic analysis on the residual oil enhancement using ultrasonication

FFB processed (MT/year)	512,000	
POME generated (MT/year)	307,200	
Method	**Non-ultrasonicated**	**Ultrasonicated**
Oil (%)	0.155	0.221
Oil (MT/year)	476.16	678.91
Revenue (RM/year)	RM 1,500,261	RM 2,139,076
Differences	RM 638,815	
Electricity cost (RM/year)	RM 243,200	
Earnings after accounting for electricity (RM/year)	RM 395,615	

Table 8 | Properties of biodiesel produced from POME-recovered oil

Properties	This study	Standards[a]	Malaysian CPO methyl ester
Density at 15 °C (kg/m^3)	861	860–890	870–880
Ester content (%)	92.9	Min 96.5	>98.5
Iodine value	51.5	Max 110	52
Oxidation stability at 110 °C (h)	29.3	Min 8	>6
Total acid value (mg KOH/g oil)	0.07	Max 0.5	<0.5
Viscosity at 40 °C (mm^2/s)	4.55	1.9–6.0	4.4

[a]Compilation of European Standard (EN 14214), American Standard (ASTM D6751), and Malaysian Standard (MS 2008:2008).

Ultrasound pre-treatment not only reveals a new economic opportunity for palm oil millers, but it can also appreciably reduce the treatment operation footprint and subsequently save treatment costs. Hence, it seems plausible to integrate ultrasonication in the existing POME treatment facility.

3.4. Characterization of biodiesel produced from POME-recovered oil

A series of fuel properties indices was carried out to evaluate the quality of biodiesel produced. Table 8 summarizes the properties of biodiesel produced from POME-recovered oil through a two-step esterification and transesterification process. The results were compared to both standard specifications and the properties of conventional palm-based biodiesel produced in Malaysia. In general, except for the ester content, all these results satisfy most of the international as well as local standards. The low ester content in biodiesel can be attributable to the presence of impurities in oil or an incomplete reaction. These pollutants, however, can be eliminated using a distillation of the filtration procedure. Furthermore, the attributes of POME methyl ester are comparable to those of palm-based biodiesel produced in Malaysia, demonstrating that the residual oil from POME is a viable feedstock for biodiesel synthesis, with the biggest advantage of its non-interference with the food supply chain.

4. CONCLUSIONS

The study provides valuable insight into optimizing ultrasonication conditions for enhanced oil recovery from POME and demonstrates the potential of POME-recovered oil as a sustainable feedstock for biodiesel production. The optimum conditions of 30.074% ultrasonication amplitude, 0.167 min ultrasonication duration, and 2 cm probe immersion depth resulted in an additional 42.5% improvement in oil recovery yield, which was close to the anticipated value (42.74%). This indicates that the model was deemed satisfactory for forecasting the ultrasonication performance in maximizing resource recovery from waste, driving the palm oil industry toward more sustainable development. In addition, the economic study showed that ultrasound pre-treatment is a feasible process for enhancing oil recovery from POME. The biodiesel produced from POME-recovered oil complies with most of the international standard limits for physicochemical properties, as mandated by ASTM and EN standards, thereby progressing toward industrial symbiosis and circular economy.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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