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Dehydration of light crude oil using a semi-organic demulsifier derived from the aqueous extract of *Mangifera indica L.*

Deshidratación del petróleo crudo ligero utilizando un desemulsionante semiorganico derivado del extracto acuoso de hoja de *Mangifera indica L.*

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Abstract

The presence of water in water-in-oil emulsions is a significant operational problem in the oil industry due to its impact on corrosion, scale formation, and increased costs during crude oil transportation and processing. This study evaluates the efficiency of a semi-organic demulsifier obtained from *Mangifera indica L.* leaf extract for the dehydration of light crude oil as a sustainable alternative to conventional synthetic agents.

The aqueous extract was obtained using maceration and Soxhlet methods and evaluated in synthetic W/O emulsions (80:20 v/v) prepared with a light crude oil of 32.87 °API from the Campeche Sound. Dehydration tests were performed in accordance with ASTM D-4007 at a temperature of 60 ºC, using different concentrations of the demulsifier (500, 1000, and 2000 μL). Additionally, the crude oil was characterized before and after treatment by determining its density, API gravity, and SARA analysis.

The experimental results showed that the semi-organic demulsifier was most efficient at a concentration of 1000 μL, achieving a higher water recovery than that obtained with a commercial demulsifier under the same operating conditions. At higher concentrations, a decrease in efficiency was observed, attributed to interfacial supersaturation phenomena that favor emulsion stabilization. The results indicate that *Mangifera indica L.* leaf extract does not significantly alter the physicochemical properties of crude oil and performs competitively, positioning itself as a viable alternative with low environmental impact and potential for industrial application in light crude oil dehydration processes.

Keywords: Demulsification; crude oil dehydration; Mangifera indica L.; W/O emulsions.

Resumen

La presencia de agua en emulsiones agua-en-aceite constituye un problema operativo relevante en la industria petrolera, debido a su impacto en la corrosión, la formación de incrustaciones y el incremento de costos durante el transporte y procesamiento del crudo. En este trabajo se evalúa la eficiencia de un desmulsificante semi-orgánico obtenido a partir del extracto de hoja de *Mangifera indica L.* para la deshidratación de crudo ligero, como alternativa sostenible a los agentes sintéticos convencionales.

El extracto acuoso fue obtenido mediante los métodos de maceración y Soxhlet, y evaluado en emulsiones sintéticas W/O (80:20 v/v) preparadas con un crudo ligero de 32.87 °API proveniente de la Sonda de Campeche. Las pruebas de deshidratación se realizaron conforme a la norma ASTM D-4007, a una temperatura de 60 ºC, empleando diferentes concentraciones del desmulsificante (500, 1000 y 2000 μL). Adicionalmente, el crudo fue caracterizado antes y después del tratamiento mediante determinación de densidad, grados API y análisis SARA.

Los resultados experimentales mostraron que el desmulsificante semi-orgánico presentó su mayor eficiencia a una concentración de 1000 μL, alcanzando una recuperación de agua superior a la obtenida con un desmulsificante comercial bajo las mismas condiciones operativas. A concentraciones más elevadas se observó una disminución en la eficiencia, atribuida a fenómenos de sobresaturación interfacial que favorecen la estabilización de la emulsión. Los resultados indican que el extracto de hoja de *Mangifera indica L.* no altera significativamente las propiedades fisicoquímicas del crudo y presenta un desempeño competitivo, posicionándose como una alternativa viable, de bajo impacto ambiental y con potencial de aplicación industrial en procesos de deshidratación de crudos ligeros.

Palabras clave: Demulsificación; deshidratación de crudo; *Mangifera indica L.*; emulsiones W/O.

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1 Introduction

Crude oil emulsion is one of the most significant challenges in the oil industry due to the damage it causes during production, generating additional repair costs. Recently, there has been interest in the use of chemical demulsifiers to separate the aqueous phase from the crude oil emulsion. Separating the water from the emulsion is crucial before transport and refining to avoid complications from the aqueous phase. Emulsions form naturally during crude oil production, and their presence can affect this stage of crude oil and facilities during drilling, transportation, production, and processing of crude oil, as well as in many places, such as hydrocarbon reservoirs, facilities, refineries, and transportation systems (Hani & Mohammed, 2019).

Emulsions are systems consisting of two partially or totally immiscible phases, one of which is identified as the continuous phase and the other as the discrete (or dispersed) phase. Emulsions have a stability ranging from a few minutes to years, depending on the nature of the oil and the water content. Water-oil separation in crude oil is a key operational and economic challenge in the oil industry: stable emulsions increase transportation costs, increase the risk of corrosion, and can affect the quality of the final product, making efficient crude oil dehydration a critical step in the energy value chain (Faizullayev *et al.*, 2022).

It is essential to break these emulsions before transport through pipelines and prior to refining (Chuiza Rojas *et al.*, 2018). Demulsification can only occur when a chemical agent breaks the interfacial layer whose surface activity is higher than that of asphaltenes. Several factors affect the demulsification process, some of which depend on the characteristics of the continuous phase, such as viscosity, asphaltene content, resins, carboxylic acids, clays, and/or waxes; others depend on the structural modification of the demulsifier molecules (Chuiza Rojas *et al.*, 2018). In particular, asphaltenes are complex polyaromatic hydrocarbons (PAHs) found in crude oil and characterized by their high molecular weight and polar nature. They have condensed aromatic structures with alkyl chains and variable heteroatoms, such as nitrogen, sulfur, and oxygen. (Mananquil, 2024; Parlov *et al.*, 2019) They have a sufficient number of functional groups to form an interfacial layer with high mechanical strength.

Traditionally, this separation is achieved through the use of synthetic chemical demulsifiers, which can be expensive, toxic, and generate undesirable by-products (Smith & Jones, 2022). In this context, the search for more sustainable alternatives with less environmental impact has stimulated interest in natural agents that use plant extracts as potential sources of demulsifiers.

Experimental studies have demonstrated the effectiveness of extracts from coconut, orange peel, lotus leaves, and *Mangifera indica L*, as well as other plant-based raw materials, as demulsifying agents or as bases for formulated demulsifiers, achieving significant reductions in water content and comparable separation times under laboratory conditions (Pal *et al.*, 2021; Ye *et al.*, 2021). In particular, the *Mangifera indica L* leaf has been extensively studied because it has been reported to be rich in bioactive compounds, notably the polyphenols mangiferin and quercetin, which are concentrated in the leaves, bark, and fruit.

These findings position *Mangifera indica L* leaf extract as a promising raw material for The growing demand for more sustainable and less toxic methods for dehydrating light crude oil has driven research into semi-organic demulsifiers that can replace or complement traditional agents based on synthetic compounds. Among these alternatives, extracts from *Mangifera indica L.* have shown significant potential due to their richness in phenolic and bioactive compounds that interact with water-in-crude emulsions, promoting interface breakdown and facilitating phase separation. *Mangifera indica L.* is an abundant source of natural metabolites with functional properties that have been explored in various industrial applications, including food preservation and antioxidant functionality in oily matrices, suggesting their potential usefulness in improving complex industrial processes such as crude oil dehydration (Buelvas-Puello *et al*l., 2021).

These secondary (bioactive) metabolites are recognized for their antioxidant, antimicrobial, and stabilizing properties, suggesting their potential role as surfactants or capping agents in dispersed systems (Alaiya & Odeniyi, 2023). These compounds have demonstrated the potential to modify emulsion properties and could be effective in breaking water-in-oil emulsions, a critical step in light crude oil processing for water removal and improvement of the final product quality. The application of natural extracts as semi-organic demulsifiers represents a promising alternative for reducing the environmental impact associated with conventional dehydrants, aligning with global sustainability trends.

These findings position *Mangifera indica L* leaf extract as a promising raw material for developing an environmentally friendly demulsifier capable of destabilizing light crude/water emulsions through physicochemical mechanisms that are less aggressive than conventional ones. By applying this natural approach, it would be possible to reduce dependence on synthetic chemicals, lessen environmental impacts, and add value to locally available agricultural waste, in line with the principles of circular economy and sustainability (Ye *et al*., 2021).

Therefore, this research project proposes to evaluate the effectiveness of a demulsifier based on an aqueous extract from *Mangifera indica L* leaves as a demulsifying agent. Due to its high concentration of secondary metabolites, which have polar and non-polar regions, it can adsorb at the water-oil interface, displacing the asphaltenes and resins responsible for the stability of emulsions in crude oil. This interaction facilitates the coalescence of water droplets and, therefore, phase separation.

Mangifera indica L leaf extracts reduce interfacial tension and alter the elasticity and rigidity of the interfacial film. This mechanism is comparable to that of commercial demulsifiers, but with the advantage of using naturally occurring compounds. This responds to the need to reduce the environmental impact associated with the use of conventional synthetic demulsifiers, many of which are highly toxic and persistent in the environment.

Birbal *et al*., (2025) conducted studies with Ni/Fe nanoparticles on properties such as viscosity, recovery factor, sulfur content, final crude oil quality determined by SARA analysis, and water recovery. It is essential to examine how the synthesis of the extracts impacts the dehydration of light hydrocarbons, as it has the potential to dilute them, which could influence their viscosity and, consequently, affect the effectiveness of the demulsifier.

2 Methodology

The methodology consisted of four main activities: 1) synthesis of the demulsifier (Soxhlet and maceration), 2) chemical characterization of the extract, 3) dehydration of the crude oil, and 4) characterization of the properties of the crude oil. For a better understanding, Table 1 shows the classification of the different conditions under which the demulsification processes were carried out, as well as the corresponding nomenclature for describing the results in this research work.

2.1 Mangifera Indica L. *extract*

Based on the methodology proposed by Chuiza Rojas *et al*. (2018) and Tixi *et al*. (2021), Mangifera Indica L extract was obtained using the maceration method and Soxhlet method, respectively. To do this, the leaves were collected. The *Mangifera indica L.* leaves were first washed, then dried for 48 hours at 60 ºC in an oven (Isotemp Over, Fisher Scientific brand). Once the drying time was complete, the leaves were crushed to obtain a homogeneous particle size and finally stored.

2.1.1 Extraction by Maceration

For this procedure, 5 g of the previously crushed *Mangifera indica L.* leaves were weighed and placed in a 200 mL glass jar with a mixture of 70% ethanol and 30% distilled water (Fermon). It was then placed on a hot plate mixer for 10 min at 1000 rpm and 40 ºC. Finally, it was left to macerate for 10 days at room temperature, shaking it manually twice a day for 5 minutes. At the end of the 10 days, the macerate was filtered using a 0.45 μm membrane (Whatman) and finally passed through a simple distillation process (see Figure 1a) at 70 ºC. In this process, the mangifera with ethanol was recovered, which will be used as a demulsifier (Quiroz-Reyes *et al*., 2013).

2.1.2 Soxhlet extraction

Figure 1b shows the Soxhlet extraction. Five grams of crushed leaves were placed in a cellulose thimble, which was inserted into the extraction body, and 200 mL of an ethanol/H_2O mixture (70:30 v/v) was added as the extraction solvent. The thimble was positioned so that the condensed solvent continuously percolated through the thimble, allowing repeated contact of the plant material with fresh solvent in order to maximize the extraction of soluble compounds. The extraction was carried out for 4 continuous hours under reflux conditions. At the end of the established time, the extract of *Mangifera indica L.* was collected and stored in a properly labeled amber bottle for subsequent characterization and evaluation as a demulsifier.

Table 1. Classification and nomenclature of samples.

Sample	Type of oil	Synthesis	Toluene dissolution (%)	Demulsifier concentration (μL)
S: Sample	U: Untreated	S: Soxhlet	0	0
			10	500
		M: Macerated	20	1000
	E: Emulsified		40	
		C:Commercial	60	2000

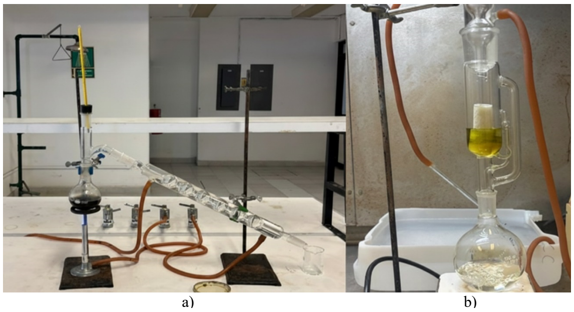
a) b)

Figure 1. Methods for obtaining the demulsifier: a) Distillation unit and b) Extraction unit.

2.2 *Chemical characterization of the extract*

Chromatographic analysis of *Mangifera indica L.* leaf extracts was performed using high-performance liquid chromatography (HPLC) with an Agilent 1260 Infinity II system (Agilent Technologies, USA) equipped with a quaternary pump, in-line degasser, autosampler, and diode array detector (DAD). Chromatographic separation was performed on a ZORBAX Eclipse Plus C18 reverse phase column (250 × 4.6 mm, 5 μm), maintained at a constant temperature of 30 ºC. The mobile phase consisted of water acidified with 0.1 % acetic acid (99.5 %, Fermont) (phase A) and HPLC-grade acetonitrile (phase B), applying an elution gradient. The flow was kept constant at 1.0 mL/min and the injection volume was 20 μL. Detection was performed using a UV-Vis detector at 280 nm. The phenolic compounds were tentatively identified based on their retention times and spectral profiles, with mangiferin standing out as the major compound.

The chemical characterization of *Mangifera indica L.* leaf extract obtained by maceration and Soxhlet extraction was performed using Fourier transform infrared spectroscopy (FTIR) to identify the functional groups present and evaluate the influence of the extraction method on the chemical functionality of the extract. The FTIR spectra were acquired using a Thermo Scientific Nicolet iS50 spectrometer (Thermo Fisher Scientific, USA), equipped with an attenuated total reflectance (ATR) accessory with diamond crystal. The samples were analyzed directly without additional pretreatment by depositing a small amount of the concentrated extract on the ATR crystal. The spectra were recorded in the range of 4000–400 cm^{-1}, with a spectral resolution of 4 cm^{-1} and an average of 32 scans per sample, in order to improve the signal-to-noise ratio.

2.3 *Synthetic W/O emulsion*

The synthetic water-in-oil (W/O) emulsion was prepared using light crude oil obtained from the Campeche well with an API gravity of 32.87 °API. The crude oil was emulsified with distilled water in a ratio of 80:20 (v/v) crude oil/water. The emulsion was obtained by manual stirring for 10 min, ensuring homogeneous dispersion of the aqueous phase in the oil phase, and was used immediately for dehydration tests.

2.4 *Crude oil dehydration process*

The oil dehydration process was carried out in accordance with ASTM D-4007-2022, using saturated toluene (MEYER, 99.5%) as the solvent. Three concentrations of the extract were evaluated as a demulsifier (500 μL, 1000 μL, and 2000 μL) in triplicate. Figure 2 shows the methodology used. In each test, equal volumes of emulsified crude oil and saturated toluene (50% v/v) were placed in the tubes. The corresponding volume of demulsifier was then added and the samples were homogenized by manual stirring for 10 s.

The samples were subjected to heat treatment in a water bath at 60 ºC for 15 min, after which they were centrifuged for 10 min at 2000 rpm. Once the process was complete, the volume of water and sediments at the bottom of the tube was recorded. The procedure was repeated until the volume of water recovered remained constant in two consecutive readings. Dehydration efficiency was calculated using the following equation, considering the total volume of water initially present in the emulsion.

$$Efficiency\ percentage = \frac{volume\ of\ separated\ water}{initial\ volume\ of\ water} \tag{1}$$

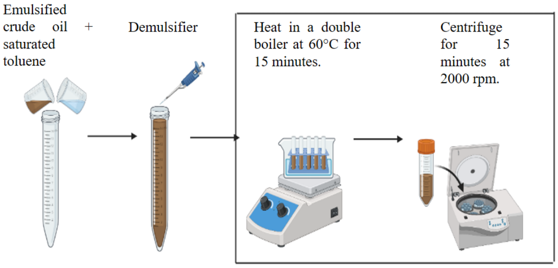

Figure 2. Crude oil dehydration process.

2.5 *Characterization of crude oil properties*

Light crude oil (API gravity of 32.87) from a Campeche Sound field was used to develop this project. According to some literature (Bila & Torsaeter, 2021; Rezaei *et al.*, 2020), the basic characterization of crude oil is essential for evaluating its behavior during the demulsification process. In this regard, the most relevant physicochemical parameters of the hydrocarbon were determined, including API gravity in accordance with ASTM D-287-2000, SARA composition (Saturated, Aromatics, Resins, Asphaltenes) in accordance with ASTM D-2007-2019, ASTM D-3279-1997, as well as the specific density of the hydrocarbon. These properties were measured before and after the demulsification process in order to evaluate whether the use of the semi-organic demulsifier induces changes in the physicochemical properties of the hydrocarbon.

2.6 *Statistical analysis*

All crude oil dehydration tests and associated characterization tests were performed in triplicate to ensure reproducibility of results. Experimental data were reported as average values. Statistical analysis was performed using OriginPro 9.1 software (OriginLab Corporation, USA). To evaluate the statistical significance of the differences observed between the different treatments and demulsifier concentrations, a one-way analysis of variance (ANOVA) was applied, considering a significance level of $p < 0.05$. This approach allowed for the objective identification of statistically significant differences between the extracts obtained by maceration, Soxhlet, and the commercial reference demulsifier. The statistical treatment was used as an additional criterion to support the trends observed in dehydration efficiency and in the physicochemical parameters evaluated.

3 Results and discussion

3.1 *Results of the chemical characterization of the extract*

Figure 3 shows a comparison of the HPLC chromatograms of the extract obtained by maceration and Soxhlet extraction, revealing significant differences in peak intensity and resolution. The extract obtained by Soxhlet presented more intense and defined signals, particularly for the peak attributed to mangiferin (~7–9 min), suggesting greater efficiency in the extraction of phenolic compounds. This is consistent with recent chromatographic studies conducted on ethanolic extracts of *Mangifera indica L.* leaves (Mehmood *et al*., 2024; Işik *et al*., 2025). Other peaks detected correspond to phenolic compounds of lower molecular weight, flavonoids and their glycosides, which contribute synergistically to the interfacial behavior of the extract.

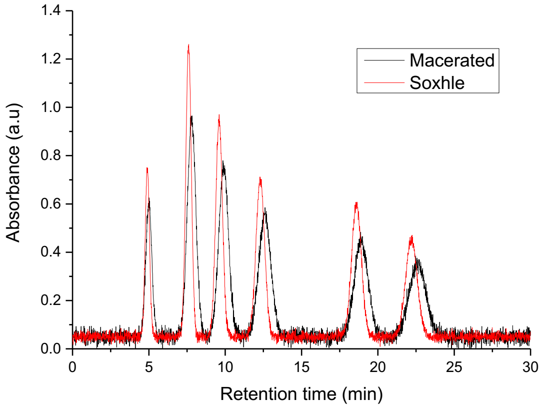

Figure 3 HPLC results of the *Mangifera indica L* extract maceration vs. Soxhlet.

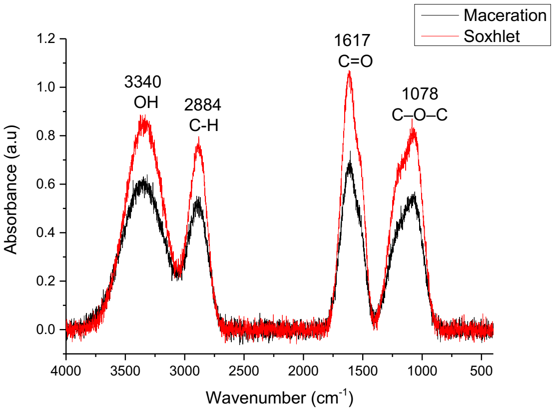

Figure 4 FTIR results of *Mangifera indica L* leaf extract maceration vs. Soxhlet.

In contrast, the maceration extract showed broader peaks of lower intensity, associated with a more gradual and less energetic extraction. The aromatic and polar structure of mangiferin and flavonoids favors their adsorption at the water-oil interface, displacing asphaltenes and resins that stabilize W/O emulsions. This mechanism reduces interfacial tension and weakens the interfacial film, promoting the coalescence of water droplets and, consequently, phase separation, which explains its performance as a semi-organic demulsifier.

These compositional differences explain the better performance of the Soxhlet extract observed in crude oil dehydration tests, as it provides greater availability of interfacially active compounds. These differences confirm that Soxhlet favors the recovery of phenolic compounds, while maceration preserves a broader but less concentrated profile. Maceration remains attractive due to lower energy consumption and a "greener" approach (in line with the contribution of natural origin).

Additionally, the diversity of metabolites observed in the chromatogram supports the synergistic effect of the extract, which explains why higher dehydration efficiencies are achieved at optimal concentrations (1000 μL). In contrast, at higher concentrations, the interfacial supersaturation of these compounds can increase the viscosity of the interface, stabilizing the emulsion again, a phenomenon that has been reported in recent studies on natural demulsifiers (Faizullayev *et al.*, 2022; Ye *et al.*, 2021).

Figure 4 shows the FTIR spectra of the *Mangifera indica L.* leaf extract obtained by maceration and Soxhlet extraction. The Soxhlet extract shows greater intensity of bands associated with phenolic groups (3340 cm^{-1}), carbonyls (1617 cm^{-1}), and aromatic structures, evidencing greater recovery of interfacially active compounds.

The broad band centered around 3340 cm^{-1}, attributed to O–H stretching vibrations, is characteristic of hydroxyl groups present in polyphenols and alcohols (Quiroz-Reyes *et al.*, 2013). The higher intensity of this band in the Soxhlet extract indicates a higher relative concentration of phenolic compounds, suggesting that this extraction method favors the recovery of species with high polarity and the ability to interact with the aqueous phase.

In the region of 2884 cm^{-1}, bands corresponding to aliphatic C–H vibrations are identified, associated with hydrocarbon chains that contribute to the affinity of the extract with the oily phase of the crude oil. The higher intensity observed in the Soxhlet extract suggests a greater presence of amphiphilic components, a favorable condition for the breakdown of water–oil emulsions.

The intense signal located at 1617 cm^{-1} is attributed to C=O and/or conjugated aromatic C=C stretching vibrations, typical of flavonoids, xanthones, and other aromatic phenolic compounds. This band is notably more intense in the Soxhlet extract, indicating a higher density of conjugated aromatic structures, which are directly related to adsorption at the water-oil interface and the displacement of asphaltenes. Finally, the band around 1078 cm^{-1}, associated with C–O–C and C–O vibrations, confirms the presence of ether and alcohol bonds in glycosylated phenolic compounds, such as mangiferin. The higher intensity of this signal in the Soxhlet extract reinforces the evidence of a more efficient extraction of these bioactive compounds.

Taken together, the differences observed in the intensity of the FTIR bands indicate that the Soxhlet method increases the density of phenolic and aromatic functional groups, which correlates with the extract's better performance as a demulsifier in crude oil dehydration tests. For its part, the extract obtained by maceration retains the same functional groups, although in a lower proportion, confirming its potential as a less energy-intensive and more sustainable alternative.

Table 2. Characterization of crude oil.

Parameter	Result
°API	32.87
Viscosity at 60 °C (cP)	5.3985
Viscosity at 25 °C (cP)	15.555
Specific density (g/cm^3) a 25° C	0.8608
Asphaltene content (% weight)	51.03
Saturated content (% weight)	15.24
Resin content (% weight)	7.62
Aromatic content (% weight)	3.51

3.2 *Results of the characterization of crude oil properties*

For the experimental part of oil dehydration, a hydrocarbon with a gravity of 32.87 °API at room temperature was used, which is classified as a light hydrocarbon. The specific density of the hydrocarbon was calculated using the data obtained from the API, substituting equation 2 to obtain the corresponding value (0.8608 g/cm^3).

$$Specific\ density = \frac{141.5}{API + 131.5} \tag{2}$$

Table 2 shows the results obtained from the characterization of the light crude oil used prior to the W/O emulsion. It can be seen that the viscosity decreases as the temperature increases. This effect is particularly important in dehydration, as the reduction in viscosity improves the dehydration process.

3.3 *Results of the chemical demulsifier*

In this research project, the demulsifiers obtained were compared with a commercial chemical demulsifier (F-46, DMO-46). This is a mixture of oil-soluble nonionic surfactants, considered a surface-active agent designed to improve the separation of water and crude oil, used in conjunction with toluene to break emulsions and separate the aqueous, oily, and solid components of crude oil. The physical-chemical properties obtained from the substance safety data sheet are shown in Table 3.

The water content in the emulsion is 20 % (W/O), which is one of the most important factors for evaluating the effectiveness and efficiency of the demulsifier. Table 4 summarizes the data obtained for demulsifier F-46. With reference to the APIs, it was observed that the reference crude oil had a value of 32.87 °API, while samples with a concentration of

Table 3. Properties of the F-46 demulsifier.

Appearance	Brown liquid
Density (kg/m^3)	1.0
Boiling point (°C)	100
Ph	12

Table 4. Parameters of the F-46 demulsifier.

Concentration (μL)	API	Water cut (%)	Efficiency (%)	Asphaltene (%)
500	31.51	12	60	48.42
1000	30.47	14	70	33.82
2000	29.41	14	70	32.17

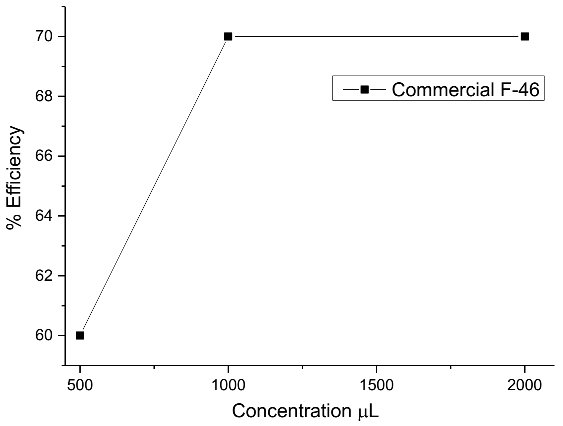

Figure 5. Percentage efficiency of commercial demulsifier F-46.

500 μL of F-46 had a value of 31.5 °API. As the concentration of the demulsifier increased, the samples reduced their value. °API, and the samples with a concentration of 500 μL of F-46 obtained a value of 31.5 °API. As the concentration of the demulsifier increased, the samples reduced their API value.

The effects of demulsifier concentration on water separation efficiency for light crude oil are shown in Figure 5, where it was observed that water separation efficiency was 60 %, 70 %, and 70 %, respectively. It is clear that demulsification efficiency increases with demulsifier concentration, increasing this efficiency. However, this efficiency remains stable at higher concentrations, as the demulsifier molecules completely cover the W/O interface, causing the asphaltenes to be carried away from the interface when the concentration is increased. As a result, the protective film around the dispersed water droplets thins, then breaks, and coalescence occurs (Hani & Mohammed 2019).

Figure 6 shows the experimental evaluation with the commercial demulsifier F-46 by centrifugation. In this experiment, it was observed that the first emulsion breakup occurred before passing through the water bath, although its interface was not yet fully defined. Once the first measurement was taken, it was observed that the water quality was cloudy, as proposed by Hani & Mohammed (2019), who describes that the turbidity of the water is due to the excess of chemical product contained in the commercial demulsifier. With regard to the separated solid residues in the samples, the volume shown is very small, as residues of the commercial demulsifier were visible at the bottom of the tubes. The final interface in all samples can be observed with the naked eye, and no runoff was observed on the walls of the tubes at any of the concentrations.

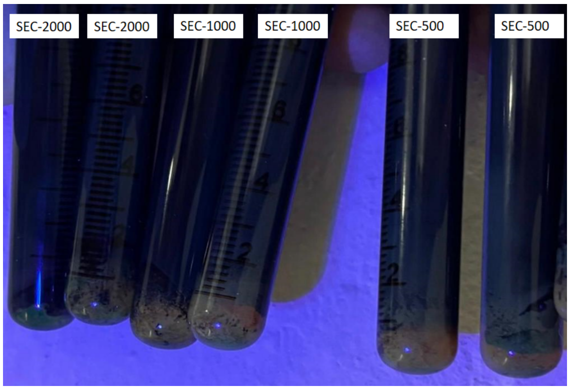

Figure 6. Results of the test with commercial demulsifier F-46.

3.4 *Results of the demulsifier by maceration*

For the experimental evaluation of 10 % saturation with toluene, no alteration of the emulsions was detected throughout the water bath. The phases identified after centrifugation were crude oil, emulsified water, and very clearly separated water. Furthermore, during the second temporary measurement in the water bath, the interface showed an unstable trend, as the water was not visible to the naked eye. During the dilution of 20 % toluene, at the end of the centrifugation process, it was observed that some samples contained a small amount of water, while the rest appeared trapped in a kind of thick, stable sludge. In addition, the interface showed an unstable trend, as the water was not visible to the naked eye when removed from the water bath. When the samples were re-centrifuged, the water quality remained intact until the third measurement, as shown in Figure 7.

For the 40 % toluene concentration, it was observed that when the demulsifier was applied, a distinct phase formed, characterized by the demulsifier's tendency to generate bubbles, which required subsequent homogenization.

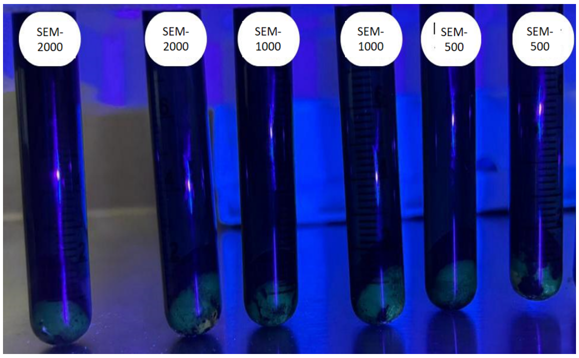

Figure 7. Results of the maceration dehydration test.

Table 5. API ° of the demulsifier by maceration.

Dilutions (%)		10			20	
Concentration (μL)	500	1000	2000	500	1000	2000
API	32.63	32.61	32.38	32.6	32.64	32.53
Dilutions (%)		40			60	
Concentration (μL)	500	1000	2000	500	1000	2000
API	32.70	32.62	32.62	32.69	32.61	32.76

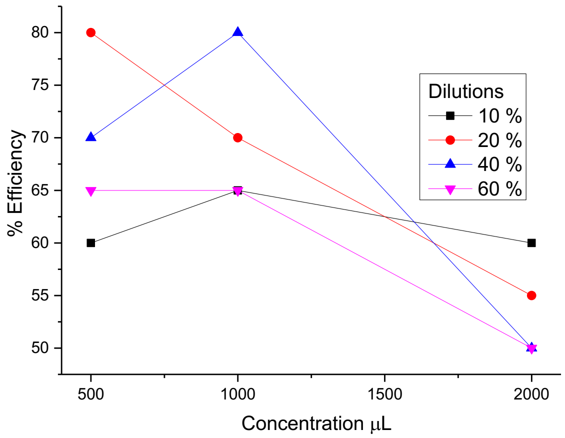

Figure 8. Percentage efficiency of the demulsifier by maceration.

The water quality in the tubes containing a concentration of 500 μL and a concentration of 1000 μL showed poor water quality but higher water recovery (14 % and 16 %, respectively); the tubes containing the samples had a discernible gray tone; in contrast, the remaining tubes showed superior water quality. At a toluene concentration of 60 %, an interface characterized by the demulsifier's propensity to generate bubbles was observed; however, this reading showed more pronounced bubble formation. According to the previous evaluations, the same differentiated phases were observed. The interface remained constant in all tubes, and the volume of separated sediments in the tubes was greater in the tubes with lower concentrations (500 μL) and in the tubes with higher concentrations (2000 μL).

These results indicate that a temperature of 60 ºC is favorable for water separation; however, increasing the dose of demulsifier did not result in better water removal. Figure 8 shows that concentrations of 1000 μL presented the best efficiency percentage for the four dilutions. The highest efficiency point occurs for the 40 % dilution at 1000 μL. This suggests that under these conditions (40 % dilution, 1000 μL volume), maceration is more effective for achieving dehydration. At very large volumes (2000 μL), efficiency is reduced for all dilutions, which could indicate saturation, mass transfer limitations, or some inhibition of Mangifera that prevents dehydration. The 60 % dilution does not exhibit a pronounced peak, suggesting that at very high concentrations (or high dilutions), maceration may not be as efficient or may be limited by other phenomena.

Maceration is a relatively simple technique and does not require high temperatures, making it suitable for thermally sensitive materials. However, its performance is affected by the diffusion of water from inside the material to the maceration medium (Durović *et al*., 2022). In more diluted solutions (10 %, 20 %), there may be sufficient concentration gradient to promote water removal, but the total volume may not be optimal for maximizing efficiency if a certain limit is exceeded.

Table 5 shows the results obtained from the API grades for the three concentrations. The demulsifiers by maceration method have grades similar to those of the base crude oil, close to 33 API, indicating that adding the semi-organic demulsifier prepared with *Mangifera Indica L.* by maceration does not affect its density.

3.5 Results of the demulsifier by Soxhlet

Figure 9 shows the results of crude oil dehydration by the Soxhlet method. During the 10 % toluene dilution, no alteration of the emulsions was observed after initial exposure in the water bath; all test tubes showed the presence of three distinct phases, including separated water at the bottom, an emulsified water phase in the middle, and finally crude oil at the top. In particular, during the first measurement cycle, the emulsions were found to break down after passing through the centrifuge tubes, and the quality of the recovered water was classified as satisfactory, as it appeared translucent and free of suspended particles. In addition, it was observed that the volume of the emulsified water phase decreased progressively with each centrifugation cycle. However, the tubes containing a concentration of 500 μL and 1000 μL showed acceptable water quality and greater recovery (16 %), as observed visually for a 20 % dilution. In contrast, tubes with concentrations of 2000 μL showed lower water recovery (12 %) and poorer water quality, which was perceived when ultraviolet light was applied, revealing the presence of suspended sediments.

Table 6. °API of the demulsifier by Soxhlet.

Dilutions (%)		10			20	
Concentration (μL)	500	1000	2000	500	1000	2000
API	32.46	32.56	32.61	32.6	32.62	32.57
Dilutions (%)		40			60	
Concentration (μL)	500	1000	2000	500	1000	2000
API	32.63	32.61	32.65	32.66	32.72	32.72

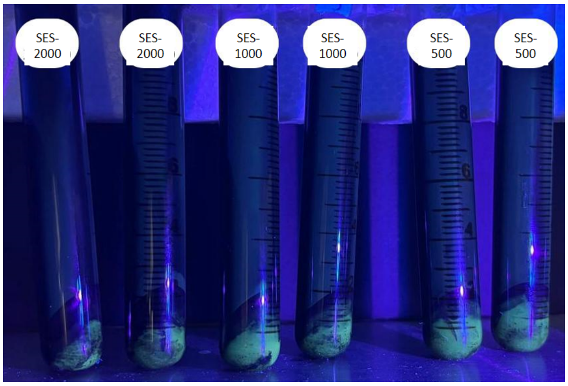

Figure 9. Results of the Soxhlet dehydration test.

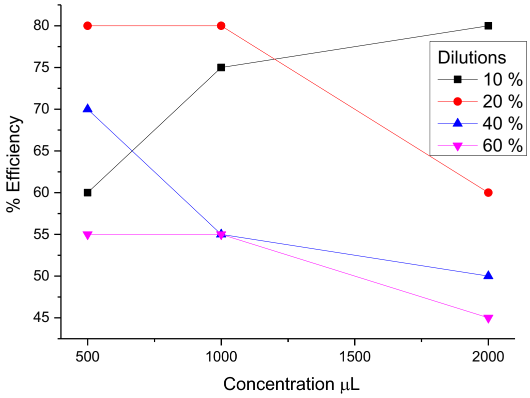

Figure 10. Percentage efficiency of the demulsifier by Soxhlet.

For the 40 % toluene dilution, no breakup of the emulsions was observed after passing them through the water bath; however, passing through the centrifugation process resulted in a noticeable separation of different phases with different shades of gray, corresponding to crude oil, emulsified water, and segregated water. In this phase of the investigation, particularly in the 60 % toluene dilution, it was initially observed that the water quality was not satisfactory, as the tubes with a concentration of 500 μL did not contain recovered water, as it still had a dark shade, indicating that not all the crude oil had been separated. In contrast, the tubes with concentrations of 1000 μL and 2000 μL showed no noticeable breakup of the emulsion.

The demulsifier using the Soxhlet method shows an efficiency ranging from 45 to 80 %, with the 20 % toluene solution showing the best efficiency, as it has two concentrations with 80 % efficiency. but we can also see that the 10 % toluene solution behaves similarly to that described by Tixi *et al.* (2021), who found that higher concentrations of demulsifier result in better efficiency. When the dilutions of 40 % and 60 % toluene are increased, the efficiency decreases from 70 % and 55 %, respectively, compared to those with lower dilutions, as shown in Figure 10. The 2000 μL dilution of the demulsifier by Soxhlet shows values lower than 60 % efficiency for the 20 %, 40 %, and 60 % toluene dilutions, suggesting that the phytochemicals in *Mangifera indica L.* are reacting directly with the carbon structure of crude oil.

Table 6 shows the API degree data for the Soxhlet process, comparing the three different concentrations (500, 1000, 2000 μL). The effect of concentration is shown in different variants, where the homogeneity of the results (32.5 API) is observed, close to the base hydrocarbon, which has an API grade of 32.87, suggesting that the semi-organic demulsifier prepared with *Mangifera Indica L* does not alter its density.

3.6 Asphaltene test results

The untreated base crude oil sample had an asphaltene content of 51.03%, which is the fraction that predominates in the composition of the crude oil evaluated. This value was used as the upper reference limit to analyze the variation in asphaltene content in the samples treated with different demulsifiers in the following samples. It was one of the parameters evaluated to determine its variation with respect to each type of demulsifier applied.

In order to evaluate the effect of the demulsifier on the asphaltene fraction, only those samples that achieved a dehydration efficiency equal to or greater than 60% were selected. Out of a total of 27 tests, 16 optimal samples were identified, all of which corresponded to demulsifiers formulated from extracts of *Mangifera indica L.* The % of asphaltenes by weight was determined for the control samples, with the upper limit being the result of untreated crude oil, which contains an asphaltene value of 51.03%, and the lower limit being the emulsified crude oil sample, with a value of 25.74%. Of the 16 samples selected, 3 corresponded to the commercial demulsifier F-46, 8 to the extract obtained by maceration, and 5 to the extract obtained by Soxhlet. In the case of the F-46 demulsifier, the results showed a decreasing trend in

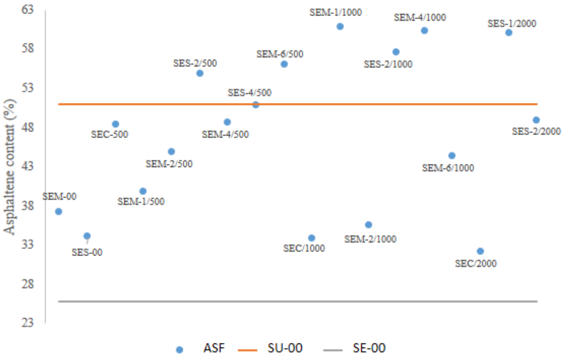

Figure 11. Percentage of the asphaltene fraction.

asphaltene content with increasing concentration, with lower percentages of asphaltenes observed at higher concentrations (500, 1000, and 2000 μL).

Figure 11 shows the extracts obtained by maceration. Three samples (MAM-1/1000, MAM-4/1000, and MAM-6/500) had asphaltene values above the reference limit of 51.03%, suggesting a significant interaction between the extract components and the asphaltene fraction of the crude oil. Similarly, in the extracts obtained by Soxhlet, samples MAS-2/500, MAS-2/1000, and MAS-1/1000 exceeded this limit, while sample MAS-4/500 remained close to the upper limit.

Asphaltenes are heavy fractions of crude oil that are highly aromatic, polar, and prone to forming aggregates or precipitating in the presence of variations in crude oil composition (dilution) and interactions with external polar compounds. Mangifera indica L leaves contain high levels of polar compounds such as flavonoids, aldehydes, and aromatics. Many of these are highly polar and aromatic, capable of interacting with carbonaceous surfaces. The high concentrations of asphaltenes are due to the fact that the aromatic molecules in Mangifera indica L leaves (quercetin, mangiferin, tannins) align with the aromatic rings of the asphaltenes, stabilizing their aggregation and dispersion.

Conclusions

The results obtained in this study demonstrate that the aqueous extract of *Mangifera indica L.* leaves can be effectively used as a semi-organic demulsifier for the dehydration of light crude oil. Under the conditions evaluated, the demulsifier developed showed comparable and even superior performance to that of a commercial agent, without causing significant alterations in the physicochemical properties of the crude oil, particularly in API grades and density.

It was observed that the efficiency of the process depends directly on the concentration of the demulsifier and the method of extraction of the plant extract. The optimal concentration was 1000 μL, which favored the rupture of the interfacial film stabilized by asphaltenes and resins, promoting the coalescence of water droplets and achieving greater volumes of recovered water. In contrast, higher concentrations led to a decrease in efficiency, attributed to interfacial supersaturation phenomena that promote emulsion stabilization.

Likewise, the Soxhlet extraction method showed operational advantages by requiring shorter processing times and generating extracts with more consistent performance compared to the maceration method. These findings confirm that the bioactive compounds present in the leaves of Mangifera indica L. interact effectively with the polar components of crude oil responsible for the stability of emulsions.

The relationship between the peak attributed to mangiferin and dehydration efficiency showed that, although mangiferin is a key component of the extract, its relative concentration determines demulsifying performance. The extract obtained by Soxhlet showed greater water separation efficiency, suggesting a synergistic effect between mangiferin and other phenolic compounds extracted more effectively by this method. These results indicate that the demulsification of light crude oil is governed by the overall composition of the extract and its interfacial interaction, rather than by the presence of a single bioactive compound.

The main original contribution of this work lies in the experimental validation of the use of an abundant plant residue as a raw material for the formulation of a functional semi-organic demulsifier, integrating principles of process engineering and sustainability. This approach not only expands knowledge about the application of plant extracts in breaking water-in-oil emulsions, but also proposes a viable technical alternative for the oil industry, aimed at reducing environmental impact and valorizing locally available natural resources.

From a development and application perspective, the Soxhlet extraction method stood out for its shorter processing time and for generating extracts with better overall performance, particularly at a 20% dissolution and concentrations of 500 μL and 1000 μL. In comparison, the commercial demulsifier evaluated presented limitations associated with a greater reduction in API grade and lower water recovery, reinforcing the technical viability of the proposed semi-organic approach. Taken together, these findings position the plant extract from Mangifera indica L. as a sustainable, competitive alternative with high potential for industrial scaling, capable of reducing dependence on conventional synthetic additives.

Overall, the use of plant extracts as demulsifiers represents a technically and environmentally viable alternative for the dehydration of light crude oils, with the potential to reduce dependence on conventional synthetic additives. Future work is recommended to evaluate the behavior of the demulsifier on a pilot scale and under actual operating conditions, as well as its effect on other rheological and physicochemical properties of crude oil.

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