ISSN:1984-2295

Revista Brasileira de Geografia Física

Homepage: https://periodicos.ufpe.br/revistas/rbgfe

Uso da *moringa oleífera* lam como desemulsificante na redução do teor de óleos e graxas e turbidez da água produzida

Luam de Oliveira Santos[1], Silvanito Alves Barbosa[2], Inajá Francisco de Sousa[3], Gabriel Francisco da Silva[4], Nídia de Sá Caetano[5], Shirley Silva Farias[6], Carlos Eduardo dos Santos[7]

[1] Universidade Federal de SergipeInstituto Federal de Sergipe, e-mail: luam.santos@ifs.edu.br ORCID: http://orcid.org/0000-0003-3200-8974, [2] Instituto Federal de Sergipe, e-mail: silvanito.barbosa@ifs.edu.br ORCID: https://orcid.org/0000-0003-0712-7533 [3] Universidade Federal de Sergipe, e-mail: inajafrancisco@academico.ufs.br ORCID: https://orcid.org/0000-0001-6732-0963 [4] Universidade Federal de Sergipe, e-mail: gabriel.silva@ufs.br ORCID: https://orcid.org/0000-0002-9622-2518 [5] Instituto Superior de Engenharia do Porto, e-mail: nsc@isep.ipp.pt ORCID: https://orcid.org/0000-0002-2185-6401, [6] Instituto Federal de Sergipe, e-mail: shirleyadm@hotmail.com ORCID: https://orcid.org/0009-0007-2493-1650
[7] Instituto Federal de Sergipe, e-mail: carloseduardodossantos255@gmail.com ORCID: https://orcid.org/0009-0008-5107-7725

Artigo recebido em 28/12/2024 e aceito em 04/04/2025

R E S U M O

Água produzida é um efluente resultante da extração do petróleo, e se apresenta como uma emulsão formada por óleo e água, que contém alta salinidade, produtos químicos, metais pesados, partículas em suspensão, cor e expressivo volume. A presença de emulsificantes naturais presentes no petróleo, contribui para a estabilidade destas emulsões, o que dificulta o rompimento natural delas. Desta forma, isso não acontece em tempo previsível e por isso são necessários processos que promovam o rompimento dessa emulsão e, consequentemente, a separação óleo/água. Desemulsificantes químicos são os produtos mais usados no tratamento da água produzida na indústria do petróleo. No entanto, o uso de desemulsificantes ambientalmente corretos apresenta-se como uma alternativa viável na separação óleo/água. O presente estudo investiga o uso da semente de Moringa oleífera LAM como agente desemulsificante natural no tratamento da água produzida. A pesquisa foca na eficiência do processo de separação de emulsões óleo/água utilizando diferentes concentrações da Moringa. Foram avaliados parâmetros como a remoção de óleo, redução de turbidez, redução de cor, e os comportamentos do pH e da condutividade durante o tratamento. Os resultados demonstraram que a MO além de eficiente como coagulante/floculante é uma alternativa promissora, sustentável e de baixo custo como desemulsificante natural em detrimento aos desemulsificantes químicos, com resultados de eficiências superiores a 65% em concentrações otimizadas.

Palavras-chave: Água produzida; *Moringa oleífera*; desemulsificante natural; emulsões óleo/água; tratamento de efluentes.

Use of *moringa oleifera* lam as deemulsifier to reduce the content of oils and greases and turbidity of the water produced

A B S T R A C T

Produced water is an effluent resulting from petroleum extraction and is characterized as an emulsion formed by oil and water. It contains high salinity, chemical products, heavy metals, suspended particles, color, and substantial volume. The presence of natural emulsifiers in petroleum contributes to the stability of these emulsions, making their natural breakdown challenging. Consequently, the natural separation of oil and water does not occur within a predictable timeframe, necessitating processes that promote the emulsion's breakdown and the subsequent oil/water separation. Chemical demulsifiers are the most commonly used products for treating produced water in the petroleum industry. However, the use of environmentally friendly demulsifiers emerges as a viable alternative for oil/water separation. This study investigates the use of Moringa oleifera Lam. seeds as a natural demulsifying agent in the treatment of produced water. The research focuses on the efficiency of the oil/water emulsion separation process using different concentrations of Moringa. Parameters such as oil removal, turbidity reduction, color reduction, and the behavior of pH and conductivity during treatment were evaluated. The results demonstrated that Moringa oleifera, in addition to being efficient as a coagulant/flocculant, is a promising, sustainable, and cost-effective alternative as a natural demulsifier, outperforming chemical demulsifiers with efficiencies exceeding 65% under optimized concentrations.

Keywords: Produced water; *Moringa oleifera*; Natural demulsifier; TOG and Turbidity.

Introduction

During petroleum production, water may originate from aquifers (formation water) or from water used in recovery processes, referred to as produced water, an effluent generated during oil extraction (Ramalho; Oliveira, 1999; Souza, 2023).

With the extensive exploitation of petroleum, concerns about the use and disposal of this effluent have grown, primarily due to its composition, as it contains high levels of total oil and grease (TOG), salinity, and high density. Thus, proper management of produced water, including its characterization, treatment, disposal, or reinjection, is of paramount importance (Souza, 2023).

This water, depending on chemical and/or physicochemical conditions, can form highly stable emulsions with petroleum. The water in these emulsions may contain salts, such as sodium, calcium, and magnesium chlorides, and metal oxides, which not only increase the viscosity of the emulsions but also affect pumping and transfer systems, potentially compromising various refinery operations (Oliveira; Carvalho, 1998). These salts may also cause pipeline oxidation and scaling, which obstruct the flow of oil through pipelines. Before oil can be sent to refineries, it must be "demulsified," i.e., dehydrated and desalted, ensuring a final water content of up to 1% v/v (BSW) and a salt content of no more than 570 mg/L. Therefore, prior to transport, crude oil must undergo a treatment process to remove water, salts, and, when necessary, gases. This process, known as primary processing, involves the use of chemical products (demulsifiers) and treating vessels, the most common of which are electrostatic dehydrators. In these vessels, emulsified water undergoes coalescence, separating and settling at the bottom, from where it is removed by decantation. The use of electro-coalescence in petroleum processing is widely adopted and is considered the most effective method for enhancing the efficiency of water-oil separation (Morigaki et al., 2010).

Various segments of the petroleum industry can cause environmental impacts. Within the exploration segment, one of the most significant pollutants is produced water. This effluent results from separation processes conducted at collection and treatment stations during petroleum production, and its increasing volume constitutes a potential environmental hazard (Barambu et al., 2021).

Produced water contains high salinity, oil (both emulsified and non-emulsified), chemical additives used during production processes (e.g., demulsifiers, anti-foam agents, anti-corrosion agents, and anti-scaling agents), heavy metals, and suspended materials. Due to the presence of these elements, the improper disposal of this effluent can lead to harmful environmental effects, negative repercussions, potential fines for environmental violations, and the need for corrective and mitigation actions (Liu et al., 2021; Al-Ghouti et al., 2019).

After treatment, produced water can be reused for reinjection into oil wells as part of secondary recovery strategies or disposed of in the sea, provided legal restrictions are met (Beyer et al., 2020). Currently, Petrobras already employs produced water for secondary oil recovery, but this has led to certain operational challenges, such as formation damage, which can be minimized and/or eliminated through the treatment system proposed in this project.

For reinjection purposes, produced water requires rigorous treatment to meet the specifications for secondary oil recovery processes. The current treatment processes include decantation, coagulation/flocculation, and flotation. This proposal aims to improve the quality of produced water by developing an efficient and cost-effective process for breaking oil-water emulsions. The typical composition of produced water is presented in Table 1, aligning the final product with the conditions stipulated by CONAMA Resolution No. 393/2007 regarding suspended and emulsified oily materials (CONAMA, 2007).

Table 1 – Characteristics of Produced Water

COMPONENTS		CONCENTRATION RANGE
Dissolved Solids (mg/L)	Sodium	13.009-60.348
	Potassium	245-1.149
	Calcium	1.318-17.808
	Magnesium	459-1.440
	Barium	10-868
	Strocium	25-846
	Iron (total)	0,2-46,2
	Chloride	17.240-86.614
	Sulfate	5-227
	Bicarbonate	88-684
	Carbonate	0
	Hydroxide	0
	Sulfide	10
	Total Dissolved Solids	-
Dissolved Gases(mg /L)	Oxygen	-
	Carbon dioxide	-
	Hydrogen sulfide	-
Physical Properties	Density at 15,6º	1,020-1,125
	pH	6,4-7,2
Suspended Material (mg/L)	Oil	2-565
	Sólids	1-1000

Source: Adapted from Gomes (2009).

Various microorganisms, such as bacteria, algae, fungi, and others, are often present in produced waters, potentially generating corrosive substances through their metabolism (e.g., hydrogen sulfide, sulfuric acid, etc.). The basic treatments that produced water may undergo include: removal of residual oil; removal of suspended solids; elimination of bacteria; and removal of inorganic constituents (iron, sulfide, barium, etc.). Therefore, the complexity of industrial processes has led technicians and researchers worldwide to develop processes that allow industries to treat their effluents in compliance with the parameters defined by current legislation (AL-GHOUTI et al., 2019; AMAKIRI et al., 2022).

According to studies by Santos et al. (2011), the natural presence of high salinity in produced water is a factor that enhances the demulsifying efficiency of Moringa oleifera LAM. Based on this premise, the continuation of these studies and the feasibility of this plant as an alternative for breaking the oil/water emulsion in real produced water are justified.

This work will further explore the treatment of produced water, particularly regarding the removal of oils and greases present in suspension or in the form of emulsions. Given the excellent effect of MO (Moringa oleifera) as a natural coagulant and clarifier in water treatment, as demonstrated by recent works by Santos et al. (2023 and 2024), we will test the hypothesis that the seed of Moringa oleifera LAM is also effective in breaking the oil/water emulsion in the development of a new product for the oil industry.

Based on this, the general and specific objectives of this work were:

General Objective:

To develop a sustainable product for breaking the oil/water emulsion for the treatment of produced water derived from petroleum exploration.

Specific Objectives:

- Characterize the produced water through physicochemical analyses;
- Study the influence of variables on emulsion formation;
- Verify whether the properties of the produced water after emulsion breakdown meet the refining requirements and the

standards defined by CONAMA Resolution 357/2005.

The target audience/market segment for this proposal encompasses the entire petroleum, gas, and biofuels industry, considering that the problem to be addressed is considered one of the major bottlenecks of this industry since the initiation of exploration and production activities of this mineral on the planet. It thus represents a business opportunity with the development of a new demulsifying product that could be useful in various types of produced water samples and has great potential for growth within the current and future realities of this industry, as well as the challenges it will face in the coming years.

The functionality of the proposed solution is based on previous studies in the literature regarding the use of chemical surfactants and polyelectrolytes as demulsifiers already used for this purpose, and the attempt to present a natural product that has already shown good results in demulsifying other mixtures and can, in this proposal, be used as an active ingredient in the development of a new product for oil/water emulsion demulsification.

Theoretical Framework

Conventional Treatments for Produced Water.

According to Amakiri et al. (2022) and Al-Ghouti et al. (2019), the amount of produced water associated with oil production varies significantly, depending on location, extraction technology, and the age of the well. As the well's age increases, oil and gas production declines, resulting in increased produced water. These values can vary from 2% to as much as 98% by the end of a well's economic life. Therefore, one of the objectives of produced water treatment is to recover part of the oil present in emulsion and prepare it for reinjection or disposal (AMAKIRI et al., 2022; AL-GHOUTI et al., 2019; THOMAS, 2001).

In addition, compliance with the requirements set by environmental regulatory agencies (CONAMA – National Environmental Council Resolutions) makes oily water generated in the petroleum industry and other industrial activities one of the major challenges in minimizing environmental impacts and meeting environmental legislation while reducing operational costs. According to CONAMA Resolution 357/2005, the maximum content of oils and greases (TOG) in produced water for disposal in receiving bodies should be 20 mg/L. Specifically, for offshore platform discharges, CONAMA Resolution 393/2007 applies, setting the monthly arithmetic mean of oils and greases at up to 29 mg/L, with a daily maximum of 42 mg/L. For reinjection in oil wells, the water must contain no more than 5 mg/L of oils and greases.

Produced water treatment can be carried out through various methods, including physical methods like filtration, adsorption, separation, and hydrocyclones, chemical methods like oxidation, coagulation, and flocculation, or even biological methods such as aerated biological filters and activated sludge (AMAKIRI et al., 2022; AL-GHOUTI et al., 2019).

These treatments can also be classified as primary, secondary, and tertiary. Primary treatments are effective for removing suspended particles larger than 5 µm, but they are not suitable for the removal of dissolved compounds and are primarily applied in physical treatments (AMAKIRI et al., 2022; JAFARINEJAD, 2016).

Secondary treatments aim to achieve higher effluent purity, removing approximately 90% of the oil and dissolved organic matter that was not removed in primary treatment. Techniques for secondary treatment include flotation, adsorption, and activated sludge (AMAKIRI et al., 2022; ARTHUR, LANGHUS, and PATEL, 2005).

Tertiary treatment is used when it is necessary to further reduce turbidity and the concentration of microparticles of oil and impurities beyond the levels achieved by secondary and primary treatments. Technologies used in this stage include electrodialysis, ion-exchange electrolysis, and advanced oxidation processes (AMAKIRI et al., 2022; LI et al., 2014).

Use of MO as a Natural Coagulant

Moringa oleífera LAM (MO) is a tropical plant belonging to the Moringaceae family. Around fourteen species have been identified, all of which possess coagulating properties to varying degrees (OLADOJA and PAN, 2015).

According to Dzuvor et al. (2021), the use of *Moringa oleifera* LAM (MO) presents a range of potential health benefits, including anticancer, antidiabetic, antioxidant, and anti-inflammatory properties. Additionally, its seeds and cakes can be utilized in the water treatment process for coagulation, flocculation, and as adsorbents due to their ability to eliminate microbes and organic matter.

MO contains active biocoagulants that can be used in water clarification, filtration, sedimentation, and flocculation, reducing the use of chemical-based coagulants (CAMACHO et al., 2017; VALVERDE et al., 2018).

In a review by Ueda et al. (2021), it was shown that MO has potential as a flocculation aid, reducing the use of chemical coagulants while achieving good removal results. It also functions as an adsorbent, with potential for removing various water contaminants. Furthermore, in a study by Santos et al. (2023), the significant potential of MO and sponge gourd as adsorbent biomass for slow filters in water treatment was verified.

Studies indicate that MO can reduce water turbidity by up to 85%, as well as remove 40% to 50% of the organic matter present in the water (CAMACHO et al., 2017). According to Nordmark et al. (2018), their research concluded that Moringa oleifera proteins irreversibly adsorb in water rinse models, suggesting that sand modified with Moringa proteins is stable for repeated water filtration, thus providing a simple, effective, and sustainable water filtration device.

In addition to these characteristics, studies like those by Viotti et al. (2019) indicate the promising, low-cost efficiency of using *Moringa oleifera* pods for adsorbing chemical compounds like diclofenac in water treatment.

There are several forms in which Moringa oleifera can be utilized, including seeds, pods, flour, cake, and even as activated charcoal. Ruelas-Leyva et al. (2017) found promising results using Moringa oleifera flour compared to the conventional coagulant chitosan, with Moringa being effective in removing lead and manganese, as well as reducing turbidity in river and agricultural residual waters. In some situations, Moringa oleifera flour even showed better results than chitosan.

Positive results in water potabilization were also found by Baptista et al. (2017) in the use of Moringa oleifera Lam in a combined Coagulation/Flocculation with Ultrafiltration process, producing high-quality water suitable for human consumption.

Characterization of Moringa oleifera LAM.

Below is Table 2, which presents the characterization of Moringa oleifera seeds.

Table 2. Nutritional values of seeds selected for study.

	Proteins	**Lipids**	**Carbohydrates**	**Ashes**	**Humidity**	**Tannins**	**References**
MO	32,16% to 32,52%	25,0% to 33,68%	23,48% to 32,43%	4,5% to 4,51%	5,53% to 6,16%		Santos *et al*. (2024a)

Materials and Methods

This project follows a hypothetical-deductive approach and can be classified as applied research, quantitative, exploratory, experimental, and case study. The methods used will include field research, laboratory research, bibliographic research, experimental research, and case study.

Characterization of the Study Object

The produced water samples for experimentation were collected at the Petrobras Exploration Unit UNSE/AL.

Physicochemical and Microbiological Analyses

In the laboratory, parameters such as pH, turbidity, conductivity, total dissolved solids, total alkalinity, total acidity, total hardness, calcium, magnesium, chlorides, sodium, potassium, and TOG were analyzed, as shown in Table 3.

Table 3 – Physical-chemical analysis methods and units.

Parâmetro	Método	Unidade	Referência
pH	Potentiometric method	dimensionless	NBR 7353
Turbidity	Nephelometric method	NTU	SM 2120
Conductivity	Conductometric method	(µS)/cm	SM 2130 B
Total Dissolved Solids	Conductometric method	ppm	SM 2510 B
Total Alkalinity	Neutralization volumetry	ppm CaCO3	SM 2540
Total acidity	Neutralization volumetry	ppm CaCO3	SM 2320 B
Total hardness	Complexation volumetry	ppm CaCO3	SM 2340 B
Calcium	Complexation volumetry	mg/L Ca++	SM 2340 B
Magnesium	Complexation volumetry	mg/L Mg++	SM 2340 B
Chlorides	Precipitation volumetry	ppm Cl-	SM 4500
Sodium	Flame photometry	ppm Na+	SM 3111
Potássio	flame photometry	ppm K+	SM 3111
OGC	Solvent extraction	mg/L	

Source: Authors, 2023.

Preparation of the Natural Demulsifier from Moringa Oleifera Seeds.

To prepare the Moringa Oleifera (MO) seed as a natural demulsifier, dehulled moringa seeds were used. The seeds were ground using a blender and then sieved through a household mesh sieve with a 2.5 mm opening until a fine powder was obtained, as shown in Figure 1.

Figure 1. Moringa seed processing process to obtain powdered coagulant.
Source: Santos, 2023.

In this stage, a treatment was proposed to break emulsions using the natural demulsifier (powdered moringa seed). The objective was to evaluate the direct action of the natural demulsifier as a demulsifying agent. A dosage of 100 mg/L of the natural demulsifier was used as a reference parameter. The dosages tested in the jar test were 75 mg/L, 150 mg/L, 300 mg/L, 400 mg/L, 600 mg/L, and 800 mg/L, as shown in Figure 2 (from left to right). During this test, each sample was subjected to rapid agitation at 300 rpm for 2 minutes, followed by slow agitation at 45 rpm for 20 minutes, with a settling period of 30 minutes. After this procedure, the turbidity and Total Oil and Grease (TOG) parameters of the supernatants from each beaker were collected and analyzed.

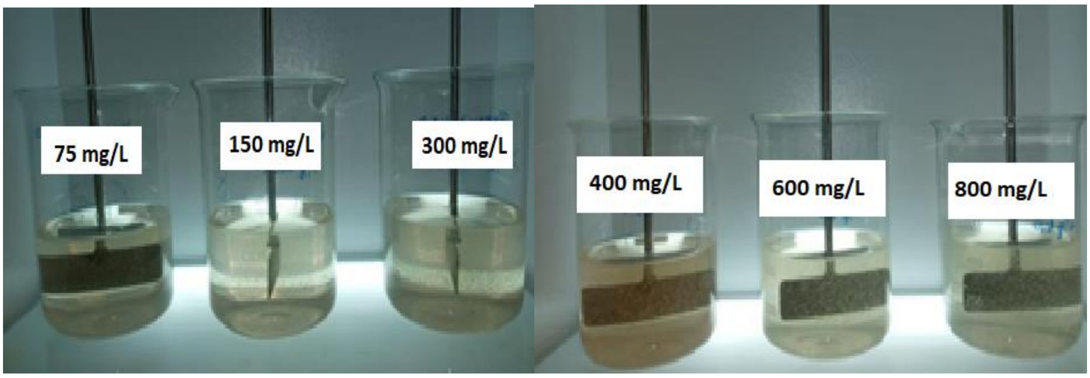

Figure 2. Agitation of the samples after adding the natural MO seed demulsifier.
Source: Authors, 2023.

Proposed Treatment

Conventional treatments include all physical-chemical processes applied to water to modify its quality, ensuring it meets the specifications required for a specific industrial application and/or for potable purposes. These treatments involve chemical clarification through pre-chlorination, sedimentation, coagulation/flocculation, and filtration. Clarification refers to the removal of finely divided and suspended matter in water. For produced water, the primary objective of treatment is to modify its quality, particularly regarding turbidity and TOG (Total Oil and Grease) parameters, as the treatment aims to either reinject the water into formations or dispose of it appropriately in compliance with regulatory requirements.

This study analyzed untreated raw produced water, comparing the analyzed parameters with results obtained after the application of a natural demulsifier. The study assessed whether the oil/water emulsion was disrupted following the use of a natural demulsifier derived from Moringa oleifera (MO).

Results and discussion

The results are presented through the physicochemical characterization of raw produced water (Table 4), followed by the mean values and standard deviations of analyses conducted on the supernatant of water samples treated with varying concentrations of the natural coagulant agent. The tested dosages were 75 mg/L, 150 mg/L, 300 mg/L, 400 mg/L, 600 mg/L, and 800 mg/L of MO seeds (Table 5). This is followed by the presentation and discussion of the turbidity, apparent color, and TOG parameters for each concentration of the natural coagulant used (Table 6, Figures 3, 4 and 5).

These three parameters were selected for discussion as they exhibited the most significant reductions due to the action of the natural demulsifier: turbidity showed a maximum reduction of 70.62%, color a maximum reduction of 59.82%, and TOG a maximum reduction of 67.31%. For other parameters, pH, conductivity, TDS (Total Dissolved Solids), total hardness, calcium, and magnesium showed an increase, while sodium and potassium showed maximum reductions of 8.22% and 20.01%, respectively. Alkalinity and total acidity remained within the recommended range established by CONAMA Resolution 357/2005 and, therefore, were not selected for further discussion.

For parameter analysis and graph construction, Prism 9 software by GraphPad was used, employing one-way ANOVA with a significance level of 5% to analyze statistical differences between parameters. Identical letters were used for samples that are not significantly different, and different letters were used for those that are statistically significantly different, as shown in figures 3, 4, and 5.

Table 4: Physical-chemical characteristics of raw produced water.

PHYSICAL AND CHEMICAL CHARACTERISTICS	VALUES FOUND AVERAGE ± SD
pH	8,52 ± 0,22
Turbidity (NTU)	86,52 ± 3,00
Color (uC)	60,56 ± 4,12
Conductivity (µS/cm)	36.960 ± 350,00
Total Dissolved Solids (mg/L)	18.237 ± 160,60
Total Alkalinity	25,75 ± 2,52
Total acidity (mg/L $CaCO_3$)	16,41 ± 4,56
Total hardness (mg/L $CaCO_3$)	12.650 ± 220,34
Calcium (mg/L Ca^{++})	3.846 ± 86,46
Magnesium (mg/L Mg^{++})	738 ± 12,45
Chlorides (mg/L Cl^-)	32.356 ± 120,42
Sodium (mg/L Na^+)	6.875 ± 62,48
Potassium (mg/L K^+)	368 ± 7,56
Oil and grease content (mg/L)	120 ± 6,42

Source: Autores, 2023.

After conducting the jar test with dosages of 75 mg/L, 150 mg/L, 300 mg/L, 400 mg/L, 600 mg/L, and 800 mg/L of Moringa oleifera (MO) seeds, the supernatants were analyzed for all proposed parameters. It was observed that, except for turbidity, apparent color, and TOG, the variations in the other parameters were considered minor. Table 5 presents the mean results for the evaluated dosages.

Table 5: Physical-chemical characteristics of the mean results of Moringa oleifera dosages (75 mg/L; 150 mg/L; 300 mg/L; 400 mg/L; 600 mg/L and 800 mg/L).

CARACTERÍSTICAS FÍSICO-QUÍMICAS	VALORES ENCONTRADOS MÉDIA ± DP
pH	8,38 ± 0,06
Turbidez (UNT)	29,86 ± 3,29
Cor (uH)	28,07 ± 2,54
Condutividade (µS/cm)	37.365 ± 254
Sólidos Totais Dissolvidos (mg/L)	19.642,44 ± 63,92
Alcalinidade Total (mg/L $CaCO_3$)	18,53 ± 7,70
Acidez Total (mg/L $CaCO_3$)	14,33 ± 3,88
Dureza Total (mg/L $CaCO_3$)	13.807,77 ± 2448,41
Cálcio (mg/L Ca^{++})	2902,50 ± 440,92
Magnésio (mg/L Mg^{++})	1593,94 ± 662,46
Cloretos (mg/L Cl^-)	33.867 ± 2392
Sódio (mg/L Na^+)	7.150 ± 165
Potássio (mg/L K^+)	390 ± 14
TOG (mg/L)	54,72 ±7,33

Source: Autores, 2024.

Therefore, we will present only the results of these three parameters, comparing them with the raw water results.

Table 6: Turbidity, pH, color and OGC analysis of raw water and after adding different concentrations of Moringa oleifera (natural demulsifier).

CONCE NTRACI ONS (mg/L)	pH	Turbidi ty (UNT)	Color (uC)	OGC (mg/L)
Água Bruta	8,52	86,52	60,56	120
75	8,49	27,40	28,32	56
150	8,45	25,42	24,33	40
300	8,37	28,78	26,84	48
400	8,35	30,65	27,61	58
600	8,33	32,75	29,38	62
800	8,29	34,14	31,93	66

Source: Autores, 2024.

Turbity

In this section, we will discuss the efficiency of Moringa oleifera (MO) in the removal of turbidity from produced water, as shown in Figure 3 below.

The results obtained in this study are lower than those reported by Desta and Bote (2021), who achieved a 99.5% reduction in turbidity and 97.7% in color for basic waters and a 98% reduction in turbidity and 90.76% in color for acidic waters. They are also lower than the findings of Santos et al. (2023), who achieved approximately 97% turbidity reduction in surface water treatment using MO, and those of Valverde et al. (2018), who obtained reductions of 70% in turbidity and 75% in apparent color using MO seeds as a coagulant agent. These variations in results can be attributed to several factors affecting the coagulating activity of MO, including the pH and initial turbidity of the raw water, the coagulant dosage, and the method of coagulant administration, all of which influence the level of interaction between particles.

In the study conducted by Santos et al. (2011) using MO for the treatment of synthetic produced water, a turbidity removal efficiency of 85.2% was achieved. In this study, using produced water collected from Petrobras UNSE/AL's Exploration Unit with characteristics previously described in Table 4, a maximum turbidity removal of 70.62% was achieved with a dosage of 150 mg/L of the natural coagulant, as shown in Figure 3 below.

The behavior of the coagulant observed in this study aligns with that reported by Santos et al. (2024), who also investigated the use of natural coagulants as an alternative for treating synthetic water.

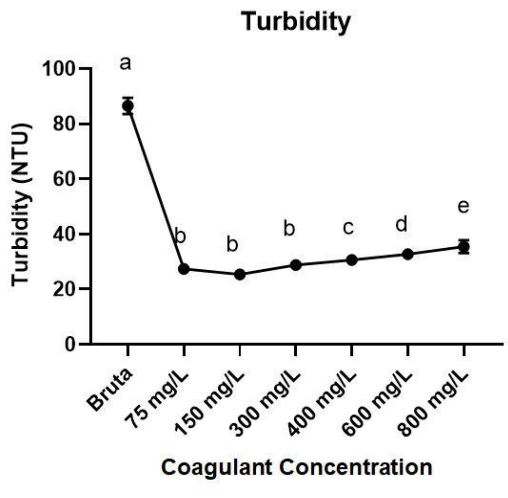

Figure 3. Turbidity results for different concentrations of MO seeds. Source: Authors, 2024.

Apparent Color

In this section, we will discuss the efficiency of Moringa oleifera (MO) in the removal of apparent color from produced water, as shown in Figure 4 below.

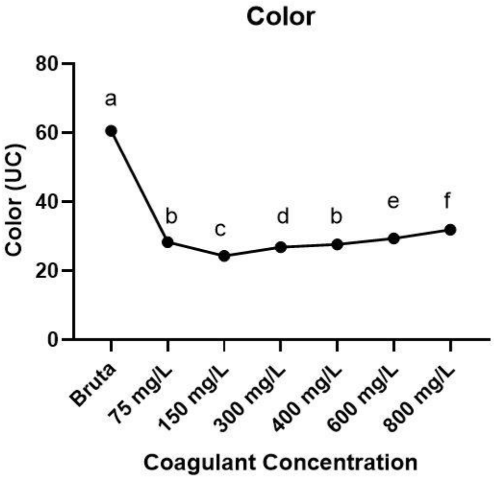

Figure 4. Apparent color results for different concentrations of MO seeds.
Source: Authors, 2024.

The results obtained regarding the reduction of apparent color are also lower than those reported by Santos et al. (2023), who achieved a 96.62% reduction in apparent color of the sample, and by Valverde et al. (2018), who obtained a 75% reduction in color. This difference is mainly due to the characteristics of the treated water, as natural clarifiers are highly affected by the initial water characteristics, as observed in studies conducted by Santos et al. (2024). Generally, water with higher initial turbidity and apparent color shows greater removal efficiency of these parameters by the natural clarifier.

In this study, the maximum reduction of apparent color achieved was 59.82% with a concentration of 150 mg/L of MO seeds.

Oil and Grease Content - TOG

In this section, we will discuss the efficiency of Moringa oleifera (MO) in reducing TOG from produced water, as shown in Figure 5 below.

In the study conducted by Santos et al. (2011) using MO for synthetic produced water treatment, a TOG reduction efficiency of 82% was achieved. In this study, using produced water collected from Petrobras UNSE/AL's Exploration Unit, with characteristics previously described in Table 4, a maximum TOG removal of 66.67% was obtained with a dosage of 150 mg/L of the natural coagulant, as shown in Figure 5 below.

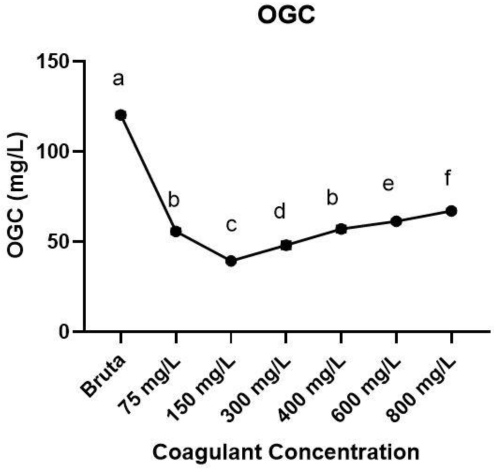

Figure 5. OGC results for different MO seed concentrations.
Source: Authors, 2024.

pH

The pH measures the acidity or alkalinity of a sample. In this experiment, it was possible to observe the variation in pH after the addition of the demulsifier at different concentrations and assess whether pH control is necessary during treatment. According to Table 6 and Figure 6, it is observed that pH decreases as MO is added, but with minimal variations, with the maximum reduction being 0.23% in pH relative to raw water at a concentration of 800 mg/L.

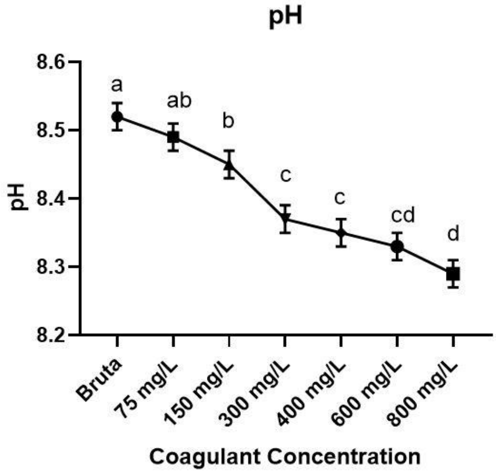

Figure 6. pH results for different MO seed concentrations.
Source: Authors, 2024.

Taynara et al. (2011) compared the pH values of samples treated with MO and found that they remained virtually constant for all concentrations used. In contrast, when using aluminum sulfate, a significant reduction in pH was observed as the concentration increased, which can be explained by the fact that aluminum sulfate is an acidic coagulant, capable of drastically lowering the pH of the solution.

Table 6 and Figure 7 present the final results of each jar with the respective concentrations of the natural demulsifier (75, 150, 300, 400, 600, and 800 mg/L, from left to right).

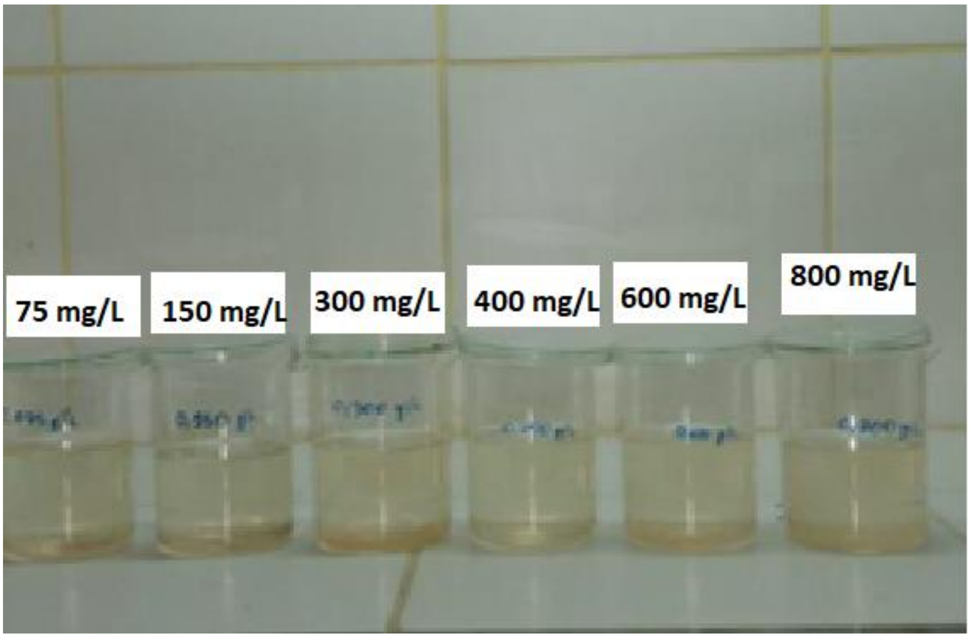

Figure 7: Result of the different dosages after the jar test with addition of the natural demulsifier (75; 150; 300; 400, 600 and 800 mg/L from left to right).
Source: Authors, 2023.

Conclusions

With all these analyses, it can be observed that after performing the jar test, varying the dosage of the natural demulsifier directly added to the raw water samples without prior treatment, the addition of 150 mg/L was considered the optimal dosage. This dosage resulted in the greatest reduction in turbidity, apparent color, and TOG compared to raw water. Turbidity was reduced by 70.62%, apparent color by 59.82%, and TOG by 66.7%. Based on these results, it can be concluded that the use of Moringa oleifera (natural demulsifier) added directly to the raw produced water proved to be highly effective in reducing the studied parameters. Although the values obtained exceed those stipulated by CONAMA Resolution No. 357/05, this reinforces the hypothesis that the use of the natural demulsifier from Moringa oleifera (MO) contributes complementarily to the treatment of produced water by breaking the oil/water emulsion and consequently reducing turbidity and TOG.

Acknowledgments

L. O. Santos thanks CAPES (Coordination for the Improvement of Higher Education Personnel) for the sandwich grant process No. 88881.690128/2022-01. Thanks to the IFS for the removal process Nº 23288.000359/2021-46 for the doctoral course and also, thanks to FAPITEC for the funding of my doctoral program from edital No. 13/2013 and for funding the project through the edital No. 15/2023.

References

Al-Ghouti, M. A., Al-Kaabi, M. A., Ashfaq, M. Y., & Da'na, D. A. (2019). Produced water characteristics, treatment and reuse: A review. *Journal of Water Process Engineering*, *28*, 222–239. https://doi.org/10.1016/j.jwpe.2019.02.001

Amakiri, K. T., Canon, A. R., Molinari, M., & Angelis-Dimakis, A. (2022). Review of oilfield produced water treatment technologies. *Chemosphere*, *298*(134064), 134064. https://doi.org/10.1016/j.chemosphere.2022.134064

Arthur, J. D., Langhus, B. G., & Patel, C. (2005). Technical summary of oil & gas produced water treatment technologies. *All Consulting, LLC, Tulsa, OK*.

Barambu, N. U., Bilad, M. R., Bustam, M. A., Kurnia, K. A., Othman, M. H. D., & Nordin, N. A. H. M. (2021). Development of membrane material for oily wastewater treatment: A review. *Ain Shams Engineering Journal*, *12*(2), 1361–1374. https://doi.org/10.1016/j.asej.2020.08.027

Beyer, J., Goksøyr, A., Hjermann, D. Ø., & Klungsøyr, J. (2020). Environmental effects of offshore produced water discharges: A review focused on the Norwegian continental shelf. *Marine Environmental Research*, *162*(105155), 105155. https://doi.org/10.1016/j.marenvres.2020.105155

BRASIL. Resolução CONAMA 357, de 17 de março de 2005. Conselho Nacional de Meio Ambiente. Disponível em: https://www.icmbio.gov.br/cepsul/images/stories/legislacao/Resolucao/2005/res_conama_357_2005_classificacao_corpos_agua_rtfcda_altrd_res_393_2007_397_2008_410_2009_430_2011.pdf

BRASIL. Resolução CONAMA 393, de 08 de agosto de 2007. Conselho Nacional de Meio Ambiente. Disponível em:https://www.cbhdoce.org.br/wp-content/uploads/2018/08/CONAMA_RES_CONS_2007_393.pdf

Camacho, F. P., Sousa, V. S., Bergamasco, R., & Ribau Teixeira, M. (2017). The use of Moringa oleifera as a natural coagulant in surface water treatment. *Chemical Engineering Journal (Lausanne, Switzerland: 1996)*, *313*, 226–237. https://doi.org/10.1016/j.cej.2016.12.031

Desta, W. M., & Bote, M. E. (2021). Wastewater treatment using a natural coagulant (Moringa oleifera seeds): optimization through response surface methodology. *Heliyon*, *7*(11), e08451. https://doi.org/10.1016/j.heliyon.2021.e08451

Dzuvor, C. K. O., Pan, S., Amanze, C., Amuzu, P., Asakiya, C., & Kubi, F. (2022). Bioactive components from *Moringa oleifera* seeds: production, functionalities and applications – a critical review. *Critical Reviews in Biotechnology*, *42*(2), 271–293. https://doi.org/10.1080/07388551.2021.1931804

Gomes, E. A., Tratamento Combindo da Água Produzida de Petróleo por Eletroflotação e Processo Fenton. Dissertação, UNIT, Aracaju, 2009, 95p. Jafarinejad, S. (2016). *Petroleum waste treatment and pollution control*. Butterworth-Heinemann.

Li, X., Cao, X., Wu, G., Temple, T., Coulon, F., & Sui, H. (2014). Ozonation of diesel–fuel contaminated sand and the implications for remediation end-points. *Chemosphere*, *109*, 71–76. https://doi.org/10.1016/j.chemosphere.2014.03.005

Liu, Y., Lu, H., Li, Y., Xu, H., Pan, Z., Dai, P., Wang, H., & Yang, Q. (2021). A review of treatment technologies for produced water in offshore oil and gas fields. *The Science of the Total Environment*, *775*(145485), 145485. https://doi.org/10.1016/j.scitotenv.2021.145485

Baptista, A. T. A., Coldebella, P. F., Cardines, P. H. F., Gomes, R. G., Vieira, M. F., Bergamasco, R., & Vieira, A. M. S. (2015). Coagulation–flocculation process with ultrafiltered saline extract of Moringa oleifera for the treatment of surface water. *Chemical Engineering Journal (Lausanne, Switzerland: 1996)*, *276*, 166–173. https://doi.org/10.1016/j.cej.2015.04.045

Morigaki, M. K., Chimin, R. Q. F., Sad, C. M. dos S., Filgueiras, P. R., Castro, E. V. R. de, & Dias, J. C. M. (2010). Salinidade em petróleo bruto: otimização de metodologia e proposta de um novo método para extração de sais em petróleo. *Quimica Nova*, *33*(3), 607–612. https://doi.org/10.1590/s0100-40422010000300023

Nordmark, B. A., Bechtel, T. M., Riley, J. K., Velegol, D., Velegol, S. B., Przybycien, T. M., & Tilton, R. D. (2018). *Moringa oleifera* seed protein adsorption to silica: Effects of water hardness, fractionation, and fatty acid extraction. *Langmuir: The ACS Journal of Surfaces and Colloids*, *34*(16), 4852–4860. https://doi.org/10.1021/acs.langmuir.8b00191

Oladoja, N. A., & Pan, G. (2015). Modification of local soil/sand with Moringa oleifera extracts for effective removal of cyanobacterial blooms. *Sustainable Chemistry and Pharmacy*, *2*, 37–43. https://doi.org/10.1016/j.scp.2015.08.003

Oliveira, R. C. G.; Carvalho, C. H. M. Influência do Tipo de Emulsão Sobre o Escoamento e o Processo de Deposição Orgânica de Petróleos. Boletim Técnico

Petrobras, Rio de Janeiro, RJ, 41 (3/4): pp. 153-159, jul./dez. 1998.

Ramalho, J. B. V. S.; Oliveira, M. C. K. Metodologia para Determinação da Distribuição de Gotas em Emulsões e Petróleo do Tipo Água-Óleo por Difração a Laser. Boletim Técnico Petrobras, Rio de Janeiro, RJ, 42(1/4): pp. 72-76, jan./dez. 1999.

Ruelas-Leyva, J. P., Contreras-Andrade, I., Sarmiento-Sánchez, J. I., Licea-Claveríe, A., Jiménez-Lam, S. A., Cristerna-Madrigal, Y. G., & Picos-Corrales, L. A. (2017). The effectiveness of *Moringa oleifera* seed flour and chitosan as coagulant-flocculants for water treatment. *Clean: Soil, Air, Water*, *45*(8). https://doi.org/10.1002/clen.201600339

Santos, Oliveira, L. de, Sousa, I. F. de, Silva, G. F. da, Barbosa, S. A., & Caetano, N. de S. (2024a). Analysis of the efficiency of different Oleaginous seeds and shells for use as natural coagulants. *Revista Brasileira de Geografia Física*, *17*(3), 1833–1847. https://doi.org/10.26848/rbgf.v17.3.p1833-1847.

Santos, L. de O., Sousa, I. F. de, Silva, G. F. da, & Barbosa, S. A. (2023). Tecnologia social de tratamento de água utilizando FiME com biomassa de moringa oleífera e bucha vegetal. *Revista Brasileira de Geografia Física*, *16*(4), 1923–1937. https://doi.org/10.26848/rbgf.v16.4.p1923-1937

Santos, T. M., Pereira, D. F., Santana, C. R., & Silva, G. F. da. (2011). Estudo do tratamento físico químico da água produzida utilizando Moringa oleifera Lam em comparação ao sulfato de alumínio. *Exacta*, *9*(3), 317–322. https://doi.org/10.5585/exacta.v9i3.3073

Souza, Jôsy Suyane de Brito. S. (2023). *Tratamento de água produzida utilizando microemulsão formulada a partir de tensoativos de origem vegetal* [UFBA]. https://repositorio.ufba.br/handle/ri/37955

Thomas, J. E. Fundamentos de Engenharia do Petróleo. 2. ed. Rio de Janeiro: Interciência. RJ, 2001.

Valverde, Karina Cardoso et al. Combined water treatment with extract of natural *Moringa oleifera* Lam and synthetic coagulant. Revista Ambiente & Água [online]. 2018, v. 13, n. 3, e 2135.

Viotti, P. V., Moreira, W. M., Santos, O. A. A. dos, Bergamasco, R., Vieira, A. M. S., & Vieira, M. F. (2019). Diclofenac removal from water by adsorption on Moringa oleifera pods and activated carbon: Mechanism, kinetic and equilibrium study. *Journal of Cleaner Production*, *219*, 809–817. https://doi.org/10.1016/j.jclepro.2019.02.129

Ueda Yamaguchi, N., Cusioli, L. F., Quesada, H. B., Camargo Ferreira, M. E., Fagundes-Klen, M. R., Salcedo Vieira, A. M., Gomes, R. G., Vieira, M. F., & Bergamasco, R. (2021). A review of Moringa oleifera seeds in water treatment: Trends and future challenges. *Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers, Part B*, *147*, 405–420. https://doi.org/10.1016/j.psep.2020.09.044.