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Moringa oleifera Seed Powder as a Natural Coagulant for Produced Water Treatment: Performance Optimization and Evaluation under Dynamic Oil Field Conditions

Polvo de semillas de *Moringa oleifera* como coagulante natural para el tratamiento de agua de producción: optimización del rendimiento y evaluación bajo condiciones dinámicas de campo petrolero

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ABSTRACT

Managing produced water generated from crude oil and natural gas extraction is crucial in mitigating pollution, environmental, and operational risks. Traditional coagulants like aluminum sulfate and iron sulfate effectively treat produced water but pose environmental and health concerns. This study presents a comprehensive evaluation of *Moringa oleifera* seed coagulation using real produced water from an operating oil field, addressing critical gaps in previous research that relied solely on synthetic water mixtures. The produced water samples were collected from an on-shore oil field in Colombia and treated with a *Moringa oleifera* coagulant solution, using jar test experiments to evaluate removal efficiency regarding total suspended solids (TSS), oil and greases, and turbidity. The results indicate that the *Moringa oleifera* coagulant effectively reduces oil and greases, achieving a 81.3% removal efficiency at a concentration of 4.0 g/L. The removal efficiency values for TSS and turbidity were moderate: 33.8 and 40.8%, respectively. The optimal coagulant concentration was 4.0 g/L, beyond which the removal efficiency decreased. A water chemistry analysis showed minimal cation and anion variations, maintaining injection compatibility for enhanced oil recovery applications. Variations in well conditions were also assessed, showing that the coagulant's performance was better under stable conditions but faced reduced efficiency in the face of increased contaminant levels. Specifically, TSS removal improved slightly under high-load conditions, while the oil and greases removal efficiency decreased significantly under dynamic field conditions. This study concludes that *Moringa oleifera* is a promising sustainable alternative to conventional coagulants for produced water treatment from oil reservoirs, offering environmental benefits and a potential for large-scale industrial applications, although further assessment is required to confirm economic feasibility.

Keywords: produced water, coagulation-flocculation, Moringa oleifera, enhanced oil recovery, water chemistry, sustainable treatment

RESUMEN

La gestión del agua de producción generada durante la extracción de petróleo crudo y gas natural es fundamental para mitigar la contaminación y los riesgos ambientales y operativos. Los coagulantes tradicionales, como el sulfato de aluminio y el sulfato de hierro, tratan eficazmente el agua de producción, pero representan preocupaciones ambientales y de salud. Este estudio presenta una evaluación integral de la coagulación con semillas de *Moringa oleifera* utilizando agua de producción real de un campo petrolero en operación, abordando vacíos críticos en investigaciones previas, las cuales se basaban únicamente en mezclas sintéticas de agua. Las muestras de agua de producción fueron recolectadas de un campo petrolero terrestre en Colombia, y fueron tratadas con una solución coagulante de *Moringa oleifera*, empleando pruebas de jarras para evaluar la eficiencia de remoción de sólidos suspendidos totales (TSS), aceites y grasas, y turbidez. Los resultados indican que el coagulante de *Moringa oleifera* reduce eficazmente los aceites y grasas, logrando una eficiencia de remoción del 81.3 % a una concentración de 4.0 g/L. Los valores de eficiencia de remoción para TSS y turbidez fueron moderados: 33.8 y 40.8 % respectivamente. La concentración óptima del coagulante fue de 4.0 g/L, por encima de la cual la eficiencia de remoción disminuyó. Un análisis de la química del agua indicó variaciones mínimas en cationes y aniones, manteniendo la compatibilidad para inyección en aplicaciones de recobro mejorado de petróleo. También se evaluaron variaciones en las condiciones del pozo, mostrando que el desempeño del coagulante fue mejor bajo condiciones estables, pero presentó una eficiencia reducida frente a incrementos en los niveles de contaminantes. En particular, la remoción de TSS mejoró ligeramente bajo condiciones de alta carga, mientras que la eficiencia de remoción de aceites y grasas disminuyó significativamente en condiciones de campo dinámicas. Este estudio concluye que *Moringa oleifera* es una alternativa sostenible y prometedora a los coagulantes convencionales para el tratamiento de agua de producción proveniente de yacimientos petroleros, ya que ofrece beneficios ambientales y un potencial para aplicaciones industriales a gran escala, aunque se requiere una evaluación adicional para confirmar su viabilidad económica.

Palabras clave: agua de producción, coagulación-floculación, Moringa oleifera, extracción mejorada de petróleo, química del agua, tratamiento sostenible

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Introduction

Water is an essential resource for the energy sector, which, in 2021, consumed around 54.1 billion cubic meters of water around the world [1]. Approximately 34.7% of this water was allocated to the production of primary energy from fossil fuels, positioning the oil and gas industry as a significant consumer of water within the energy sector. Water management occurs at various stages in the oil and gas value chain, which includes exploration, drilling, oil and gas production, transportation, refining and chemical production, and terminal and retail operations [2]. Water is utilized in several ways during oil and gas production, from boiler feed to enhanced oil recovery. However, during the extraction of crude oil and natural gas, a certain amount of water is also brought to the surface. If managed properly, this water, termed *produced water*, can offer significant economic, social, and environmental advantages, especially in locations where water is scarce [3]. There is potential for produced water to be utilized in oilfield operations for well stimulation, which includes activities like hydraulic fracturing, water flooding, and enhanced oil recovery [4]. Nevertheless, the treatment of produced water, which is a diverse mixture of organic and inorganic compounds with varying salinity (2.6-360.0 g/L) , is necessary to remove dissolved salts, sediments, and other unwanted constituents. The organic fraction includes dissolved compounds such as formic acid, propionic acid, aliphatic hydrocarbons, phenols, carboxylic acids, and low-molecular-weight aromatic compounds [5]. The inorganic fraction consists of cations such as sodium, potassium, calcium, magnesium, barium, strontium, and iron, along with anions such as chloride, sulfate, carbonate, and bicarbonate. Heavy metals, including copper, cadmium, chromium, lead, mercury, nickel, silver, and zinc, are also frequently reported [5], [6]. Several methods can be used for the treatment of produced water, *viz.* physical treatment (gravity separation, filtration, flotation, and coalescing), chemical treatment (coagulation and flocculation, pH adjustment, chemical oxidation, scale inhibitors and corrosion inhibitors), biological treatment (activated sludge, constructed wetlands, and bioreactors), thermal treatment (evaporation, distillation, and thermal desorption), membrane treatment (reverse osmosis, nanofiltration, and ultrafiltration), advanced oxidation processes (ozonation, Fenton's reagent, and photocatalysis), and electrochemical treatment (electrocoagulation and electrooxidation) [6], [7], [8]. The treatment method depends on the composition and intended use, reducing potential pollution risks during discharge [9]. Other methods address the specific contaminants present, regulatory requirements, and economic considerations. Regulatory requirements for produced water discharge or reinjection vary by region and are influenced by national and international guidelines. These typically address the maximum allowable limits for oil and grease, heavy metals, salinity, and toxic organics. Examples of institutions issuing said guidelines include the US Environmental Protection Agency (EPA), the European Union Water Framework Directive, and the World Health Organization (WHO).

Coagulation, a chemical pretreatment method, involves adding chemicals (coagulants) to neutralize charges and promote the aggregation of fine particles into larger flocs, which can then be removed by sedimentation or flotation. It plays a vital role in treating produced water, and numerous studies have explored the use of various coagulants for wastewater treatment [5]. Aluminum sulfate, aluminum polychloride, and iron sulfate are commonly utilized as coagulants in produced water treatment due to their effectiveness in removing contaminants like colloidal particles and dissolved organics [10]. The efficiency of these coagulants depends on factors such as pH and dosage, with prehydrolyzed forms often exhibiting superior performance [10], [11]. Specifically, one study identified prehydrolyzed aluminum chloride (PAC) and electrochemically derived PAC (E-PAC) as effective coagulants for treating water [12]. However, there are concerns regarding the utilization of aluminum-based coagulants, mainly because of the large amount of sludge produced and the potential health problems associated with high aluminum levels in treated water [13]. Because of this, there is a growing interest in using plant-based coagulants as sustainable alternatives to aluminum and iron-based salts [14]. Some plant-derived coagulants include *Moringa oleifera* Lam., *Strychnos potatorum* Linn., *Plantago ovata, Trigonella foenum-graecum, Opuntia ficus-indica*, and tannin-based coagulants [14], [15]. Among these, coagulants derived from *Moringa oleifera* Lam. have shown promise in water and wastewater treatment, given their cost-effectiveness, biodegradability, and renewable nature [14], [15], [16]. Additionally, *Moringa oleifera* is superior to other plant-based coagulants due to its unique cationic proteins, which provide simultaneous coagulation and antimicrobial action through multiple mechanisms (charge neutralization, polymeric bridging, and adsorption), achieving higher removal efficiencies while producing significantly less sludge than other natural alternatives that typically rely only on polysaccharides with limited mechanisms [16], [17]. These coagulants function through mechanisms such as adsorption, charge neutralization, and polymeric bridging, and they have been found to be effective in mitigating turbidity, chemical oxygen demand (COD), and total suspended solids from water [18].

A study explored coagulation-flocculation and sedimentation processes using a 5% (wt./v) crude water extract from dry *Moringa oleifera* seeds as a primary coagulant in municipal and industrial wastewater treatment [19]. The results indicated a sludge volume production four to six times lower compared to alum-based coagulants, alongside the effective removal of suspended solids, microorganisms, and certain metals, while showing lesser success in COD and nutrient removal. Another study investigating wastewater and groundwater treatment highlighted the potential of *Moringa oleifera* seeds as a natural coagulant alternative to PAC. This study reported the significant efficacy of *Moringa oleifera* coagulants, which reduced the wastewater turbidity by 98.6% and reported good reductions in conductivity (10.8%) and the biochemical oxygen demand (11.7%), as well as the successful removal of metal contents [20]. Additionally, a study investigated the application of *Moringa oleifera* seeds as a natural coagulant for textile wastewater, with 95% degradation in treated samples at a 16 mg/L concentration. The authors reported a coagulation mechanism, which included neutralization and adsorption [21], that provided a cost-effective, environmentally friendly water treatment with reduced sludge creation (21-31% less than alum). Another investigation focusing on rural water treatment applications demonstrated that *Moringa oleifera* seed powder achieved maximum removal efficiencies of 99.5% for turbidity and 97.7% for color at an optimal dosage of 0.8 g/L, with performance being pH-dependent and most effective in the 7-9 range [22]. Furthermore, research on river water treatment using Moringa oleifera seeds demonstrated exceptional heavy metal removal capabilities, achieving the complete elimination of iron and a copper and cadmium removal of up to 98% at a mere 1% seed cake concentration, while simultaneously reducing turbidity by 85-94% and improving dissolved oxygen levels [23]. According to these findings, *Moringa oleifera* seed powder could be a promising coagulant for produced water treatment, which invites further investigation.

Interestingly, one study investigated the use of *Moringa oleifera* Lam. as a coagulant for the treatment of produced water [24]. This study reported that the most effective concentration of *Moringa oleifera* was 0.1 g/L in non-saline solutions and 2.0 g/L in their saline counterparts. At these concentrations, the removal of oil from the water was reported as 83 and 85%, respectively. However, this study used synthetic produced water by mixing oil, sodium chloride (NaCl), and water to create an emulsion rather than actual samples from an oil reservoir. Furthermore, the study did not assess the influence of *Moringa oleifera* coagulants on important parameters such as total suspended solids, turbidity, alkalinity, water hardness, cations, and anions. These parameters are crucial when evaluating the potential reuse of treated produced water for water flooding in an oil reservoir. This limitation exemplifies the broader knowledge gaps in the field, where synthetic water studies fail to capture the complex multi-ionic chemistry of real produced water and do not address specific compatibility requirements for enhanced oil recovery applications. To the best of the authors' knowledge, no prior work has investigated the utilization of *Moringa oleifera*-based coagulants for treating produced water derived from a real oil reservoir. Addressing this issue is, therefore, the main objective of this work. In addition, this study will evaluate the application of *Moringa oleifera* coagulants to the treatment of produced water in terms of the removal of oil and greases, total suspended solids, and turbidity.

Materials and methods

Preparing the Moringa oleifera coagulant

The coagulant preparation involved harvesting seeds from fully mature fruits of the *Moringa oleifera* Lam. tree. The fruits were deshelled by hand, exposing seeds that had a white and yellowish hue. The extracted seeds were then pulverized in a blender to create a powder, which was passed through a 250 μm sieve to achieve a very fine powder, aiming for the good solubilization of active ingredients in the seed as well as for a better coagulation performance [25]. To standardize the coagulant's preparation, the sieved powder was dried in an oven at 55 °C for 6 h. The temperature threshold of 55 °C was chosen for the drying process, considering the degradation of proteins in *Moringa oleifera* at higher temperatures [26]. Additionally, the drying period of 6 h was selected because the final weight of the powder remained relatively constant after this point. The moisture content in the seed powder was determined using Eq. (1) [27].

$$M.C = \frac{\text{Initial weight of seed powder} - \text{Final weight of seed powder}}{\text{Initial weight of seed powder}} \times 100 \quad (1)$$

where *M.C* stands for the moisture content in % w.b.

The coagulant treatment solution was prepared by creating a mixture of *Moringa oleifera* seed powder and distilled water. For example, to create a treatment solution with a concentration of 4 g/L, 2 g of Moringa powder were mixed with 500 mL of distilled water. The mass of the powdered Moringa seed was adjusted for varying treatment concentrations (2 to 8 g/L), while the 500 mL volume of distilled water was kept constant. The suspension was subsequently stirred in a 1 L beaker, using a magnetic stirrer at a speed of 40 rpm for 30 min. This process facilitated the extraction of the active coagulant components from the Moringa powder into the treatment solution [28]. The suspension was further filtered using Whatman No. 1 filter paper. The treatment solutions were freshly prepared to treat the produced water samples and were stored in a refrigerated environment to prevent any degradation over time.

Produced water treatment using jar test

The produced water samples were collected from an onshore oil field operating in southern Colombia. Water sampling was carried out at the discharge of the injection pumps, which is employed in the facility to forcefully inject produced water into the reservoir (waterflooding) for enhanced oil recovery. To ensure reliability and comprehensiveness during coagulant treatment, multiple samples of produced water (500 mL) were collected from the facility. Samples were also collected on different days from the facility to capture the variability in the produced water, as well as to assess how the coagulant treatment performed under the dynamic conditions of the oil field.

The coagulant treatment for the produced water samples was conducted in jar testing equipment (Phipps and Bird 1 L jar tester, Richmond, USA) with six rotating axis and impellers. The samples were homogenized (stirred at 140 rpm for 1 min) using the jar tester before applying the treatment solution. After applying the treatment solution, the stirring revolutions were reduced to 40 rpm for a duration of 15 min. Subsequently, the electric homogenizer was deactivated, allowing for a 20 min waiting period to facilitate the precipitation of impurities through the flocculation and coagulation processes. Afterwards, 400 mL of treated water sample (for each test) were extracted from the surface for physicochemical characterization.

The removal efficiency of the coagulant treatment was estimated using Eq. (2), as it was important to establish the amount of pollutants that were removed before and after the treatment.

$$E = \frac{S_0 - S}{S_0} \times 100 \quad (2)$$

where E is the removal efficiency regarding the physicochemical parameters (turbidity, TSS, iron or oil and greases), S_0 is the initial pollutant load in ppm, and S is the final pollutant load in ppm.

Physicochemical characterization

The turbidity (a measure of the relative clarity of the liquid) of the samples was determined according to EN ISO 7027, using a Hach DR 2800 spectrophotometer (Hach, Iowa, US). The oil and grease contents (n-Hexane extractable material from the sample) were determined according to USEPA's Method 1664 [29]. The total suspended solids (TSS) in the samples were measured at a wavelength of 810 nm using the Hach DR 2800 spectrophotometer. The alkalinity and bicarbonate level of the samples were estimated using a sulfuric acid titration procedure as described, in the APHA's 2320 standard for water and wastewater analysis [30]. The APHA 2340 standard was followed to estimate the total hardness using ethylenediamine tetra acetic acid (EDTA) titration. The calcium hardness was determined as per HACH Method 8204 [31], and magnesium hardness was obtained as the difference between total hardness and the calcium hardness [32]. The barium level in the water sample was determined via the turbidimetric method, as described in HACH Method 8014. Similarly, the levels of sulfates, iron, calcium, potassium, and sodium in the water samples were measured according to the methods described in the HACH water analysis handbook [33].

Results and discussion

Characterization results

The moisture content in the Moringa seed powder, estimated using Eq. (1), was determined to be 1.5%. This low value is advantageous since it helps to better preserve the cationic proteins found in the Moringa seed powder, thereby enhancing the efficiency of the coagulant [34], [35]. Table I presents the characterization results of the produced water samples from the oil field, along with those obtained after treating 500 mL of the produced water sample with 25 mL of Moringa coagulant (a dosage of 50 mL/L) at a concentration of 4.0 g/L (the optimum concentration found in this study, as explained earlier). The constituents found in the produced water from the oil field fall within the range of values documented in the literature [36]. When the produced water was treated with the Moringa coagulant, there was a notable reduction in oil and greases, with a removal efficiency of 81.3%. The attained removal efficiency for these pollutants is comparable to the 85% reported in the literature for synthetic produced water treated with a concentration of 2.0 g/L of Moringa coagulant [24]. Furthermore, there was a substantial decrease in TSS (33.8%) and turbidity (40.8%) in the treated water. However, this falls short of the high turbidity removal efficiency (80-97%) typically reported for *Moringa oleifera* coagulants [37], [38], [39]. The variation can be attributed to the composition of the water undergoing treatment, including factors like its hardness as well as elevated levels of cations and anions, all of which can impact coagulation and flocculation processes [40].

Interestingly, the post-treatment variations in the concentrations of cations, anions, as well as in calcium and magnesium hardness (Table I), were generally minor, with the exception of Iron (Fe^{2+}). This is somewhat advantageous, as the fluid-fluid compatibility with the formation water will be maintained by similar cationic and anionic concentrations and hardness levels in the treated produced water when used as an injection source for enhanced oil recovery [41].

Table I. Physicochemical characteristics of produced water and water treated with Moringa coagulant

Parameters	**Produced water**	**Treated water[a]**
Calcium hardness (mg/L)	820	830
Magnesium hardness[b] (mg/L)	30	20
Oil and greases (mg/L)	17.7	3.3
Total alkalinity (mg/L)	780	740
Total hardness (mg/L)	850	850
Total suspended solids (mg/L)	10.1	6.7
Turbidity (NTU)	90.8	53.7
CATIONS		
Barium (mg/L)	22	25
Calcium (mg/L)	328	332
Iron (mg/L)	1.4	0.8
Magnesium (mg/L)	199.3	201.7
Potassium(mg/L)	641.2	649.1
Sodium (mg/L)	377.2	381.8
Strontium (mg/L)	718.3	727.1
ANIONS		
Bicarbonate (mg/L)	951.6	950.6
Chloride (mg/L)	5200	5300
Sulphate (mg/L)	0	0

[a]Produced water treated with a Moringa solution concentration of 4 g/L, at a dosage of 25 mL per 500 mL of produced water.
[b]Obtained as the difference between total hardness and the calcium hardness

Source: Authors

Effect of concentration on removal efficiency

Figure 1 shows the removal efficiency of the coagulant as its concentration increased from 2.0 to 6.0 g/L. The dosage was kept constant at 25 mL of coagulant per 500 mL of produced water.

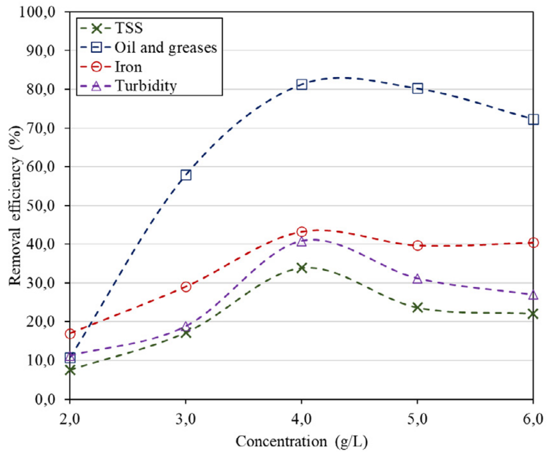

Figure 1. Removal efficiency of Moringa coagulant for total suspended solids, oil and greases, iron, and turbidity from produced water
Source: Authors

For TSS, the removal efficiency of the coagulant increased from 7.6% at 2.0 g/L to 33.8% at 4.0 g/L, and then slightly decreased to 22.1% at 6.0 g/L. In this study, the maximum removal efficiency of the *Moringa oleifera* coagulant for TSS was found to be 33,8%. Other research works have shown that Moringa coagulants can remove TSS from municipal and dairy wastewater samples by 69% [42], and that a mix of Moringa and alum-based coagulant can remove TSS from pharmaceutical wastewater samples by 99% [43]. Variations in the initial wastewater characteristics, the coagulant dosage, and the treatment conditions may be responsible for these differences. For instance, municipal, dairy, and pharmaceutical wastewaters typically contain organic matter, biological solids, and small particles that are easier to aggregate and settle, making them more amenable to treatment methods like coagulation and flocculation. In contrast, produced water, a byproduct of oil and gas extraction, contains fine particles, oil droplets, and inorganic materials that are smaller, more hydrophobic, and harder to remove. The chemical composition of produced water, which includes high levels of salts and hydrocarbons, can also interfere with TSS removal processes, making them less effective. These factors could collectively contribute to the lower TSS removal efficiency observed in produced water. At higher dosages, Moringa itself may contribute to increases in TSS due to residual organic matter, which explains the drop in removal efficiency beyond the optimum dose. There was a substantial increase in the removal efficiency for oil and greases, from 10.7% at a treatment concentration of 2.0 g/L to 81.3% at 4.0 g/L. After 4.0 g/L, the removal efficiency for these components decreased, reaching around 72.4% at 6.0 g/L. The results suggest an optimal coagulant concentration of .,0 g/L for maximum oil and grease removal efficiency. The decrease beyond 4.0 g/L could be due to the overdosing of the *Moringa oleifera* coagulant, which imparts an excess positive charge to the particles. This can cause charge reversal and restabilization, reducing aggregation and floc formation and lowering the effectiveness of the coagulation process [44]. However, the specific mechanisms behind this decrease, particularly in the context of produced water treatment, are not fully understood and would benefit from further detailed investigation. The optimum concentration determined in this study differs from the one reported in the literature, where a concentration of 2.0 g/L of *Moringa oleifera* coagulant was used for synthetic produced water [24]. The aforementioned study used synthetic produced water made by mixing distilled water with oil and NaCl. In practical applications, however, various other cations and anions will be present in the water, potentially influencing the coagulation and flocculation process—as was our case.

The removal efficiency of iron increased from 17.0% at 2.0 g/L to 43.3% at 4.0 g/L, and it remained relatively constant at approximately 40% until 6.0 g/L were reached. A previous study also reported a removal efficiency of 41% for iron when using Moringa coagulant at a concentration of 5.0 g/L to treat potable water, which is consistent with our findings. Furthermore, the removal efficiency regarding turbidity exhibited a trend comparable to those of TSS and oil and greases with increasing concentrations. It reached its highest level (40.8%) at a 4.0 g/L coagulant concentration and then decreased. The overall trend indicates that the Moringa coagulant is most effective at this concentration, especially for the removal of oil and greases. For TSS, iron, and turbidity, the removal efficiencies are moderate but show a peak around 4.0 g/L. This indicates that, while *Moringa oleifera* is highly effective for oil and grease removal in produced water, its moderate performance for TSS, turbidity, and iron represents a limitation in wastewater treatment.

Coagulant performance under dynamic well conditions

The estimated values for TSS and oil and greases present in the produced water samples over three consecutive weeks are presented in Figure 2.

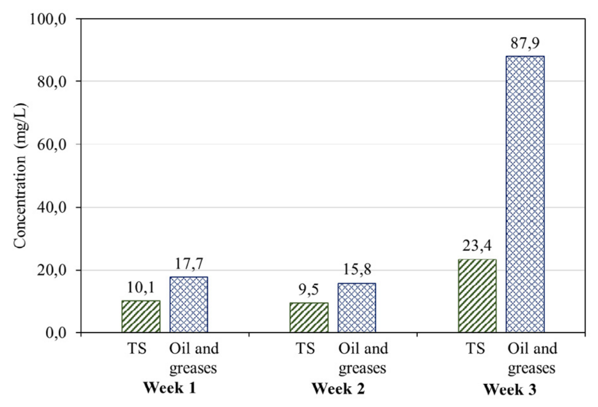

Figure 2. Quantity of total suspended solids and oil and greases in the produced water samples collected over three consecutive weeks from the oil reservoir
Source: Authors

As shown in Figure 2, during the first two weeks, both TSS and oil and greases display stable values, albeit with a slight decrease, indicating stable well operating conditions and a consistent treatment suitability for the produced water. However, in week 3, there is a noticeable increase in both TSS and oil and greases, suggesting a possible disturbance in the operating conditions of the oil field. This disturbance could be due to operational adjustments, changes in well dynamics, or environmental factors. To evaluate the suitability of the coagulant under these conditions, 500 mL of produced water samples from weeks 1 and 3 were treated with 25 mL of *Moringa oleifera* coagulant at a concentration of 4.0 g/L. The resulting removal efficiency for TSS and oil and greases are shown in Figure 3

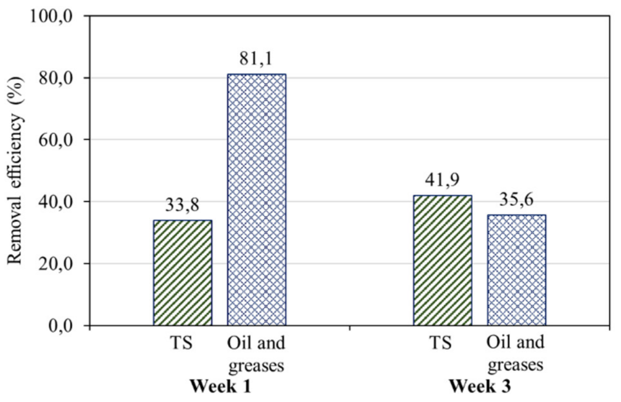

Figure 3. Efficiency of *Moringa oleifera* coagulant in removing total suspended solids and oil and greases from produced water samples collected during weeks 1 and 3
Source: Authors

The removal efficiency for TSS in the produced water samples from week 3 slightly improved to 41.9%, as illustrated in Figure 3. This suggests that the efficiency of the coagulant in removing solids increased under the modified conditions. Nevertheless, the removal efficiency for oil and greases decreased significantly to 35.6%. This decrease implies that the capacity of the coagulant to perform effectively may have been impeded because of the elevated levels of oil and greases in week 3. The concentration of oil and greases in the treated produced water from week 3 (56.6 mg/L) significantly exceeds the maximum daily limit of 42 mg/L recommended by the EPA [45]. While this limit can vary across different jurisdictions, the week 3 value still surpasses the thresholds set by most regulatory agencies [46]. Notably, all other tests in this study had oil and greases levels within acceptable limits. While the Moringa coagulant shows promise when used at an optimal dosage under stable conditions, its performance becomes limited when there is a change in pollutant load, indicating the need for adaptive treatment strategies. Such strategies include implementing sensors to continuously measure pollutant levels and adjust the Moringa dosage accordingly; introducing pretreatment processes, such as sedimentation or filtration, to stabilize pollutant loads before Moringa application; and/or exploring the combination of Moringa with other coagulants or chemicals to enhance coagulation under different conditions.

Conclusion

This study represents a significant advancement in produced water treatment research by providing a comprehensive evaluation of *Moringa oleifera* coagulant using real oilfield produced water, moving beyond the synthetic water limitations of previous studies. The results indicate that our Moringa coagulant is highly successful in reducing oil and greases in produced water, achieving significant removal efficiencies at an optimal concentration of 4.0 g/L. The removal efficiency for TSS and turbidity was moderate, but it was found to be optimum at 4.0 g/L. Specifically, the removal efficiency for oil and greases reached 81.3%, while those for TSS and turbidity were 33.8% and 40.8%, respectively. The treatment resulted in only minor variations in cation, anion, and hardness levels, which is advantageous as it aids in maintaining the fluid-fluid compatibility with the formation water, making the treated water suitable for use as injection water in enhanced oil recovery.

The performance of the coagulant was evaluated under dynamic well conditions, investigating its applicability to varying pollutant loads. The effectiveness of the treatment was consistent during stable well operations but showed a decline in efficiency for oil and greases when faced with increased pollutant loads due to changes in operational conditions. This indicates that, while *Moringa oleifera* coagulants are promising for stable conditions, their performance can be impacted by fluctuations in pollutant load. Additionally, the moderate performance regarding TSS, turbidity, and iron highlights a limitation of *Moringa oleifera* in fully treating produced water. Future studies should be conducted to develop adaptive treatment procedures that can accommodate the dynamic operating conditions in an oil well. The findings of this study underscore the potential of *Moringa oleifera* as a sustainable and biodegradable alternative to conventional aluminum and iron-based coagulants.

CRediT author statement

Juan Camilo Tovar Casanova: conceptualization, data curation, formal analysis, investigation, methodology, writing (original draft). *Omex Mohan*: data curation, formal analysis, validation, visualization, writing (original draft). *Olugbenga Abiola Fakayode*: formal analysis, validation, writing (review and editing).

Access to research data

The datasets generated and/or analyzed during this study are available from the authors upon reasonable request.

Conflicts of interest

The authors declare that they have no conflict of interest.

Statement on artificial intelligent

The authors did not use IAG. The authors take full responsibility for the contents of this publication.

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