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Stabilization of oil/water emulsions using soybean lecithin as a biobased surfactant for enhanced oil recovery

Jalliah Sharelle U. Tabaniag¹, Mary Quincy D. Abad¹, Christian Jules R. Morcelos¹, Gene Vincent B. Geraldino¹, Jon Larsen M. Alvarado¹ and Edgar Clyde R. Lopez^{2,3*}

*Correspondence:
edgarclayedlopez09@gmail.com

¹ Chemical Engineering
Department, Adamson
University, San Marcelino St.,
Ermita, 1000 Manila, Philippines

² Department of Chemical
Engineering, University of Santo
Tomas, España Blvd., Manila,
Sampaloc 1015, Philippines

³ Nanotechnology Research
Laboratory, Department
of Chemical Engineering,
University of the Philippines
Diliman, 1100 Quezon City,
Philippines

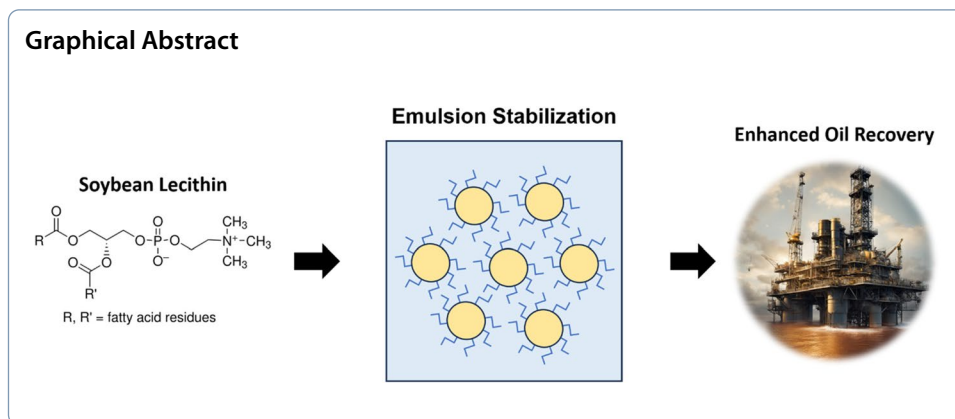
Abstract

Enhanced oil recovery (EOR) relies on the use of surfactant to flood the wellbore and thus extract the oil from the rocks. However, current surfactants used for EOR are non-biodegradable and are made from toxic chemicals. Here, we report the potential of soybean lecithin as a biobased surfactant for enhancing oil recovery by stabilizing oil-in-water (O/W) emulsions. Our findings show that pH has a significant impact on stability, with lower pH levels leading to improved stability. Salinity affects stability, but soybean lecithin shows minimal sensitivity to salt concentration. Surfactant loading also plays a crucial role, with higher concentrations causing instability. The optimized operating parameters for soybean lecithin are determined to be at pH = 4, salinity = 84,171.08 ppm, and surfactant loading = 4.48 wt.%. Comparative evaluation reveals that soybean lecithin performs competitively, outperforming certain commercial surfactants in terms of emulsion stability in oil phase. The solubilization ratio of oil (SR_o) values are lecithin = 3.2219, CAPB = 0.7028, CTAC = 11.1044, NP10EO = 11.1570, and SLES = 11.7067. Utilizing soybean lecithin as a biobased surfactant in enhanced oil recovery offers a sustainable and environmentally friendly alternative with potential economic advantages. Further research can focus on optimizing formulation and exploring synergies with other additives.

Highlights

- Soybean lecithin was used as a biobased surfactant to stabilize oil/water emulsions for EOR applications.
- The operating parameters were optimized to maximize emulsion stability.
- Soybean lecithin has comparable performance with commercial surfactants in stabilizing oil/water emulsions.

Keywords: Enhanced oil recovery, Biobased surfactant, Soybean lecithin, Emulsion stability



Introduction

Enhanced oil recovery (EOR) aims to modify the qualities of the oil rock in order to get more oil production; enhanced oil recovery techniques can generate more than 50% ranging up to 80% of the oil in place [29]. However, several negative environmental effects of EOR have been identified, including contamination of land and surface waters by oil, brine, or other chemicals, loss of biota; excessive erosion and sedimentation, primarily in hilly/terrain areas; groundwater contamination; and excessive air emissions from thermal operations [28]. Given these problems, it is becoming increasingly vital to identify and execute ground-breaking methods for reducing oil and petroleum derivative contamination.

Surfactant flooding, a method for enhancing the production of oil, improves oil production by reducing the tension at the interface between layers, increasing oil mobility, and allowing injected water to displace oil [10]. The application of surfactant EOR increases the wettability of porous rocks, which enables water to move more quickly through them and displace more oil than would be possible without the treatment [23]. Despite its extensive application, surface flooding continues to encounter issues such as instability in harsh (or typical) reservoir conditions and excessive adsorption, among others [18].

When a surface-active agent or an emulsifier is present, an oil–water emulsion significantly lowers the interfacial tension between the displaced fluid and the residual oil [7]. In addition, an oil–water emulsion stops the interface from becoming coalesced. The fluid is forced to flow through the unswept areas of the displacing sections, which improves the sweep and displacement efficiency and the oil recovery. This is because the dispersed phase drops of the emulsions effectively obstruct the more permeable routes [17]. Among the challenges faced in EOR, the stabilization of oil/water emulsions stands out as a crucial factor influencing the overall success of recovery operations.

Traditional surfactants, while effective, often raise environmental concerns due to their non-biodegradable nature and potential ecological impact. To address these challenges, biosurfactants made from renewable sources have recently gained the interest of various researchers. The intrinsic qualities of biodegradability, low toxicity, and higher usefulness in hard conditions account for the majority of this range of applicability compared to synthetic alternatives [12]. Biosurfactants contain amphipathic molecules that have hydrophobic and hydrophilic parts, allowing access to hydrophobic substrates, reducing surface tension, increasing the contact area for insoluble compounds (such as

hydrocarbons), and improving mobility, bioavailability, and biodegradability [30]. They can be categorized broadly into two types: elevated molecular weight polymers that are more successful at stabilizing emulsions and low molecular weight molecules that effectively reduce interfacial and surface tensions. Phospholipids, glycolipids, and lipopeptides are the most important low-mass surfactants. On the other hand, polymeric and particulate surfactants are the most important high-mass surfactants [25].

Emulsions are colloidal systems composed of two immiscible liquids—in this case, oil and water—stabilized by surfactants. In the context of EOR, the formation and stabilization of oil/water emulsions are both desired and challenging. Emulsions can improve the displacement efficiency of oil, aiding in its mobilization within the reservoir and subsequent recovery. However, the stability of these emulsions is essential, as their destabilization can lead to phase separation, hindering the extraction process. Achieving the delicate balance between emulsion stability and susceptibility to demulsification is a complex task, requiring tailored surfactants with optimal properties [2, 31]. Several mechanisms have been proposed for the spontaneous emulsification of oil-in-water emulsions including interfacial turbulence from Marangoni flow, development of transient negative values of interfacial tensions (IFT), and vigorous diffusion of surfactants across the interface due to local supersaturation in some region [15].

Lecithin is a generic term for a mixture of phospholipids, triglycerides, fatty acids, glycolipids, and sterols [13]. Soy lecithin ($C_{35}H_{66}NO_7P$) is a surfactant made from soybean oil. It has a hydrophilic head and a lipophilic tail. Phospholipids make up around 65–75% of soy lecithin, with triglycerides accounting for the remaining 34%. Colors, carbohydrates, sterol glycosides, and sterols are all present in trace levels [20]. Lecithin is known for its amphiphilic nature, making it an ideal surfactant for stabilizing oil/water emulsions. This ability to modify interfacial properties is crucial for stabilizing emulsions, as it impacts the formation and persistence of the oil/water interface. Moreover, its biocompatibility and biodegradability make soybean lecithin an attractive alternative to traditional surfactants, aligning with the growing global emphasis on sustainable practices in the oil and gas industry. This aligns with the industry's evolving commitment to environmentally responsible practices and provides an avenue for reducing the carbon footprint of oil recovery operations. Beyond the immediate goal of enhancing oil recovery efficiency, the adoption of soybean lecithin as a surfactant may contribute to a paradigm shift in the way we approach EOR. The integration of biobased surfactants into standard EOR practices can pave the way for a more sustainable and environmentally conscious oil and gas industry.

Several studies have already been done to use biosurfactants for enhanced oil recovery. However, most studies focused on the use of microbe-derived biosurfactants [5, 19, 22], rhamnolipids [9], and other biosurfactants [21] for EOR. Moreover, only very few reported the impact of environmental conditions such as pH on the resulting solubilization of oil [26]. Even rarer are studies that used design of experiments to elucidate the effect of these factors. Understanding of the effect of these parameters on the oil solubilization of surfactants is essential to optimize the process.

In this study, we aim to investigate the performance of soybean lecithin as a biosurfactant in enhancing the stability of oil/water emulsions. In particular, the effect of lecithin concentration, pH, and salinity on the oil solubilization ratio of lecithin

was investigated. To further investigate the effectiveness of soybean lecithin as a bio-based surfactant, it was compared to various classes of surfactants that are customarily employed in enhanced oil recovery. This research represents a pioneering effort in exploring the potential of soybean lecithin, a natural and sustainable material, as a surfactant in EOR. The use of natural or bio-based surfactants like soybean lecithin introduces a more environmentally friendly and sustainable option compared to some traditional synthetic surfactants. Ultimately, this research helps in finding greener and more sustainable alternatives to chemical surfactants for enhanced oil recovery.

Methods

Materials

Soybean lecithin biosurfactant (L- α -phosphatidylcholine) was purchased from Sigma-Aldrich. Cetyl trimethylammonium chloride (CTAC, cationic), sodium lauryl ether sulfate (SLES, anionic), nonylphenol ethoxylate (NP10EO, nonionic), and cocamidopropyl betaine (CAPB, amphoteric) were purchased from Dalkem Corporation. Sodium chloride (NaCl), which was used for adjusting the salinity of water, hydrochloric acid (HCl), and sodium hydroxide (NaOH) which are used for pH adjustments were obtained from Ajax Finechem Ltd. Diesel, which served as the oil phase for this study, was purchased from Petron Corporation.

Determination of critical micelle concentration

The critical micelle concentration of the surfactants was determined using conductivity method. Here, the concentration of the surfactants was varied from 0.1 to 6 wt. % in deionized water. Then, the conductivity of the resulting solutions was determined using a conductivity meter. The results were plotted against the surfactant concentration to calculate the CMC.

Effect of operating parameters on emulsion stability

Here, the effect of pH, salinity, and surfactant concentration on the stability of O/W emulsions was investigated. Design Expert v.13 (Stat-Ease, USA) was used to generate a face-centered central composite design of experiments. The pH values varied within the range of pH 4 to pH 11 [4], salinity levels ranged from 40,000 to 110,000 parts per million (ppm) [24], and the surfactant concentration varied from 2 to 6 wt.%. pH (X_1), salinity (X_2), and surfactant concentration (X_3) were coded at three levels, - 1, 0, and 1, which correspond to the low, middle, and high levels of the variables, respectively. All of the 20 experimental runs were performed in triplicate (Table 1).

Table 1 Levels of the parameters using face-centered central composite design (FC-CCD)

Independent Variables	Unit	Symbol	Levels		
			- 1	0	+ 1
pH	-	X_1	4.0	7.5	11.0
Salinity	mg/L	X_2	40,000	75,000	110,000
Surfactant concentration	wt.%	X_3	2	4	6

Emulsion stability experiments

The O/W emulsion was prepared based on the procedure in the study of Al-Sakkaf and Onaizi [3] with some modifications. In a typical experiment, a 1:1 v/v oil-in-water mixture was prepared by adding appropriate amounts of diesel into the water solution and mixing them on a magnetic stirrer at 500 rpm for 10 min at room temperature. The pH was adjusted using HCl and NaOH. The concentration of NaCl and lecithin, as well as the final pH of the solution, were based on the CCD. Homogenization of the emulsion was done by subjecting it to a 15-min sonication using an ultrasonic sonicator bath. The emulsion container was immersed in a cold-water bath to prevent excessive emulsion heating during the sonication process. The above procedure was done for all the experimental runs.

Measurement of solubilization ratio

The prepared emulsions were stored in covered glass vials at room temperature for 24 h to allow the emulsion to break into individual phases [14]. The amount of oil and brine solubilized in the emulsion phase was determined (in volume) by Eq. 1:

$$V_{os} = V_{oi} - V_{of} \quad (1)$$

where V_{os} = volume of oil solubilizes in the emulsion phase, V_{oi} = initial volume of oil in the solution, and V_{of} = final volume of oil in the upper phase. Then, the solubilization ratio is calculated for each sample by Healy et al. using Eq. 2 [11]:

$$SR_o = \frac{V_{os}}{V_s} \quad (2)$$

where SR_o = solubilization of oil and V_s = volume of surfactant in the emulsion. The solubilization ratio obtained from emulsion stability tests was used as the response in the CCD.

Statistical treatment

After completion of the experimental data, the solubilization ratio was fitted into a model suggested by Design Expert and the model coefficients were estimated by regression. Then, analysis of variance (ANOVA) was done to identify the significant terms in the model. Insignificant terms were not included in the final working model. Furthermore, residual analysis was done to check for data outliers. For the residual analysis, the natural plot of residuals, residual vs. predicted, residual vs. run, and predicted vs. actual plots were generated. Moreover, influence plots were checked to see if there are influential data points that could skew the model. Contour plots were generated to further investigate the effect of the said parameters on the solubilization ratio. All of these were performed in Design Expert v.13 (Stat-Ease, USA).

Optimization of parameters

To maximize the solubilization ratio, the process parameters were optimized in Design Expert v.13 (Stat-Ease, USA). All other parameters are held within the range

of the investigated design space. A validation experiment was then conducted to compare the actual solubilization ratio from the experiment against the model-predicted values. This was done by performing an emulsion stability study at the optimum value of the process parameters.

Comparison with other surfactants

To evaluate the potential of soybean lecithin as an emulsifier for EOR, the solubilization ratio of soybean lecithin at optimum conditions were compared to surfactants commonly used in EOR. The emulsification of oil-in-water mixtures were investigated using cetyl trimethylammonium chloride (CTAC, cationic), sodium lauryl ether sulfate (SLES, anionic), nonylphenol ethoxylate (NP10EO, nonionic), and cocamidopropyl betaine (CAPB, amphoteric). These surfactants were tested for emulsion stability using the optimal pH, salinity, and surfactant concentration.

Results and discussion

Evaluation of the critical micelle concentration

The critical micelle concentration (CMC) of soybean lecithin in an aqueous solution was examined via conductivity method (Fig. 1). A conductivity meter was used to evaluate the conductivity of solutions of soybean lecithin ranging in concentration from 0.1 to 6 wt.%. Using this method, we found that the CMC of soybean lecithin is 1.9990 wt.%. At low concentrations, surfactant molecules are mainly present as individual monomers in the solution. As the concentration increases, the surfactant molecules reach a critical concentration where they start to aggregate and form micelles. This aggregation leads to an increase in the electrical conductivity of the solution. The steep rise in electrical conductivity at low concentrations is indicative of the transition from individual surfactant molecules to the formation of micelles. The CMC is associated with the abrupt change

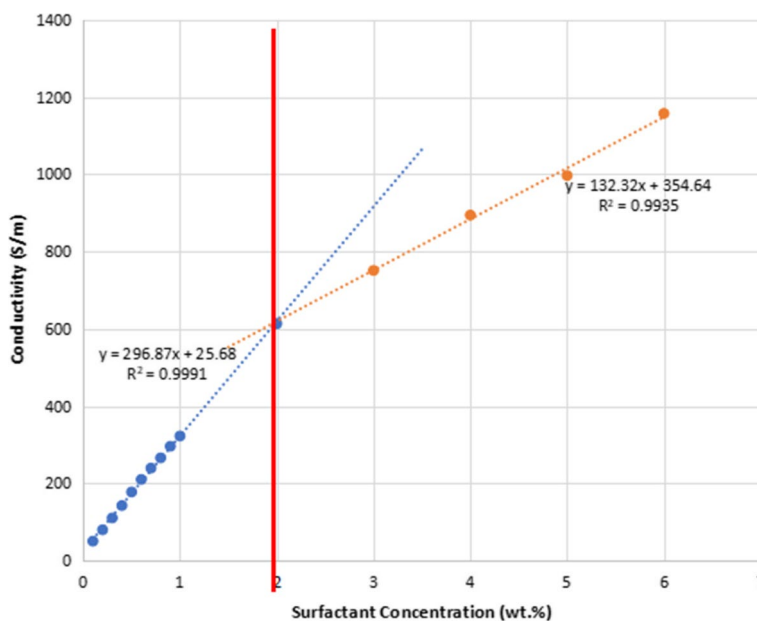
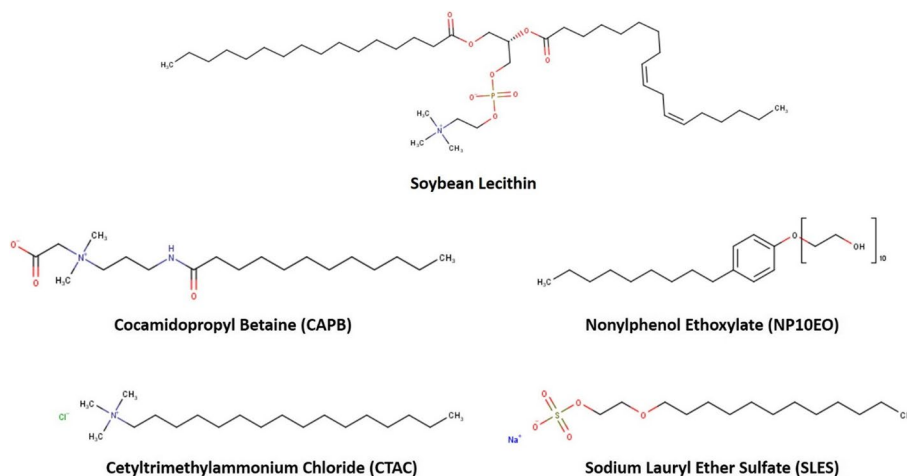


Fig. 1 CMC of soybean lecithin from conductivity measurements

Table 2 Summary of CMC of various surfactants

Surfactant	Nature of surfactant	CMC value (wt.%)
CAPB	Amphoteric	0.8640
CTAC	Cationic	1.3862
Lecithin	Amphoteric	1.9990
NP10EO	Nonionic	2.5188
SLES	Anionic	2.9403

**Fig. 2** Chemical structures of the surfactants used in the study

in the slope of the electrical conductivity curve. Beyond the CMC, there is only a gradual increase in the electrical conductivity. This can be attributed to factors such as increased ionization of surfactant molecules or the presence of excess surfactant monomers in solution.

CMC of other surfactants

We also investigated the CMC of the four commercially available surfactants, which are sodium lauryl ether sulfate (SLES), cetyl trimethylammonium chloride (CTAC), nonylphenol ethoxylate (NP10EO), and cocamidopropyl betaine (CAPB). A conductivity meter was used to evaluate the conductivity of solutions of the four commercially available surfactants with concentrations ranging from 0.1 to 6 wt.%. Table 2 summarizes the CMCs of various surfactants measured using electrical conductivity method. In general, a lower CMC is favorable to ensure that only a small amount of surfactant is needed to stabilize the emulsion during EOR. It was shown that the CMC of lecithin falls within the range of the CMC values of commercial surfactants used in EOR. While there are other surfactants with lower CMC, the use of soybean lecithin offers a competitive advantage because it is biodegradable and is derived from green raw materials.

The CMC is influenced by the size, shape, and polarity of the surfactant molecules, as well as the nature of the solvent and temperature. The CMC values of each surfactant differ due to their distinct chemical properties. The hydrophilic–lipophilic balance

(HLB) of the surfactant is critical. Figure 2 shows the chemical structures of the surfactants used in this study. The hydrophilic head group's size and type have an impact on the CMC value. Surfactants with higher hydrophilic portions relative to their lipophilic portions have higher CMC values. The CMC value tends to increase with larger and more polar head groups because they prevent micelle formation. Additionally, by providing electrostatic attraction or repulsion between surfactant molecules, charged head groups like sulfonate or quaternary ammonium groups can have a considerable impact on the CMC. SLES has a relatively high hydrophilicity due to its ethoxylation and sulfate groups, resulting in a highest CMC among the investigated surfactants.

The length of the hydrocarbon chain is also important. Longer hydrocarbon chains promote micelle formation at higher concentrations, resulting in surfactants with higher CMC values. In general, the CMC value decreases as the hydrophobic chain lengthens. Stronger intermolecular hydrophobic interactions are facilitated by longer hydrophobic chains, which improve micelle formation at lower concentrations. NP10EO has a higher CMC than other surfactants in this study due to its longer alkyl chain.

Furthermore, the presence of specific functional groups, such as quaternary ammonium in CTAC and amine oxide in CAPB, can affect the CMC. These groups influence the self-assembly behavior of surfactants and contribute to their amphiphilicity. As such, CTAC and CAPB has the lowest observed CMC among the investigated surfactants.

The CMC value can be impacted by branching or substituents on the hydrophobic chain. The steric hindrance is increased by branching, which makes it more difficult for surfactant molecules to pack and form micelles and raises the CMC. The packing of surfactant molecules can also be disrupted by the addition of bulky or polar substituents, increasing the CMC value. The CMC value of surfactant molecules may be impacted by unsaturated hydrocarbon chains. Double bonds cause the hydrophobic chain to kink, which prevents micelle production and tight packing. When compared to saturated surfactants with equal chain lengths, this frequently results in greater CMC values. As such, lecithin has an intermediate CMC among the surfactants.

Finally, the differences in CMC values between surfactants and lecithin are due to differences in their chemical structures, HLB, hydrocarbon chain length, presence of functional groups, and presence of unsaturation. At specific concentrations, these factors affect the surfactant's ability to self-assemble into micelles.

Effect of parameters on the solubilization ratio

We evaluated the effects of pH, salinity, and surfactant concentration on oil-in-water emulsion stability using soybean lecithin. We generated emulsions and then analyzed their solubilization ratios after 24 h. According to our results, each of the three parameters had an effect on the emulsion stability. The run at pH 4, salinity of 75,000 mg/L, and surfactant concentration of 4.0 wt.% achieved the highest solubilization ratio of 3.0633. Meanwhile, the run at pH 11, salinity of 110,000 mg/L, and surfactant concentration of 6.0 wt.% achieved the lowest solubilization ratio of 0.5146.

Effect of pH

Figure 3 shows the effect of pH on the oil solubilization ratio of lecithin. As shown in the figure, the highest oil solubilization ratio can be found at pH 4.00. The solubilization

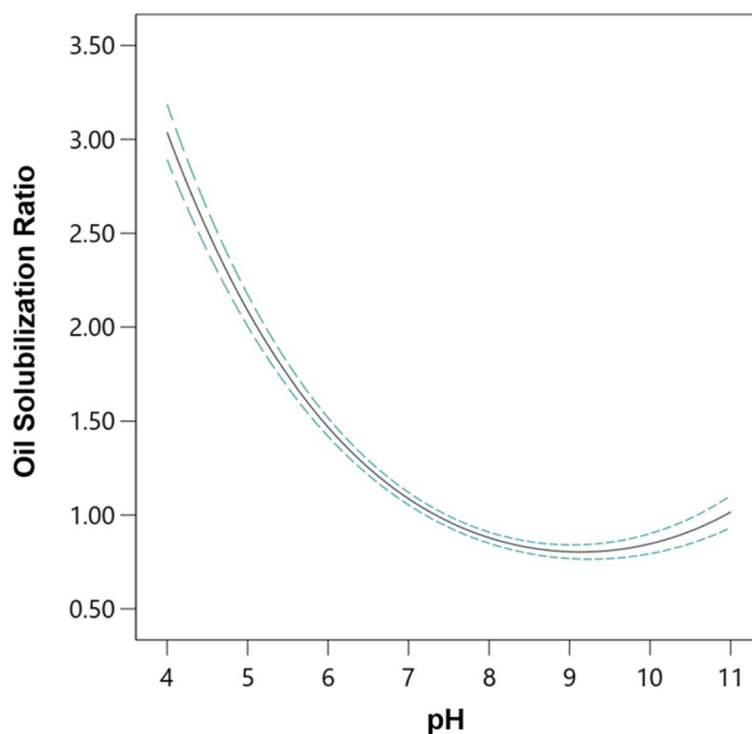


Fig. 3 Effect of pH on the oil solubilization ratio of soybean lecithin

ratio decreases from pH 4.00 until reaching a minimum value at pH 9.00. Finally, the solubilization ratio increases slightly from pH 9.00 to pH 11.0. Using analysis of variance, it was determined that the $p = 1.8077 \times 10^{-27}$ for the pH value (X_1). As the p -value is less than 0.05, the pH has a significant effect on the solubilization ratio at 95% confidence level. pH is the most influential factor in emulsion stability. Additionally, we found that the pH of the mixture had a substantial effect on emulsion stability. At higher pH levels, emulsions were unstable, whereas at lower pH levels they were more stable.

When the pH of the solution is 4, soybean lecithin is protonated, which implies that it has a positive charge. Emulsion stability is improved because of the positive charge, which increases electrostatic repulsion between the emulsifying agents and decreases the phospholipids' propensity to aggregate or coalesce. Additionally, a pH of 4 decreases the surface tension of the water phase, which makes it simpler for the oil droplets to remain suspended and be dispersed throughout the solution. This reduces the probability of coalescence, which can result in separation of phases and reduces the emulsion stability. From our study, we found that soybean lecithin has the highest levels of stability and emulsifying properties at a pH level of 4. Because positively charged surfactant molecules adsorb at the oil–water interface, the repulsion forces between the oil droplets are increased at lower pH. This improved droplet dispersion and decreased droplet coalescence, resulting in more stable emulsions.

Soybean lecithin is relatively near its isoelectric point (IEP) at pH 7, where the surface of the emulsifying agent has no net charge. When emulsifying agents are at the IEP, the electrostatic repulsion between them is substantially reduced, making it simpler for the emulsifying agents to coalesce or agglomerate and so reducing emulsion

stability. This decreased electrostatic repulsion may additionally result in the formation of larger oil particles that are more probable to coalesce and form a distinct oil layer.

At a pH of 11, soybean lecithin is significantly deprotonated, indicating that it possesses a negative charge. Since oppositely charged particles tend to attract each other, the electrostatic repulsion between the emulsifying agents may decrease, allowing for the formation of aggregates and a loss of emulsion stability. When exposed to a high pH, soybean lecithin is at risk of becoming denatured, which results in a reduction in its capacity to emulsify. Additionally, the surface tension of the water phase is greater at pH 7 and pH 11, making it harder for oil droplets to remain suspended and dispersed. Correspondingly, larger oil droplets may form, which are more probable to coalesce into a distinct oil layer, ultimately reducing emulsion stability.

The above discussion is supported by zeta-potential measurements in a previous study [32]. According to their results, at low pH, lecithin is protonated. Meanwhile, at high pH, lecithin is deprotonated. The electric potential differential between the surface of a particle or droplet and the surrounding solution is referred to as zeta potential. Zeta potential is an important factor in emulsions because it affects how stable oil-in-water emulsions are. It shows the strength of the electrostatic attraction between the scattered oil droplets, which influences their propensity to group together or coalesce. Interestingly, the zeta potential trend matches the trend observed in the solubilization ratio of lecithin. This implies that the effect of pH can be explained by the zeta potential of the system.

The ionization of soybean lecithin's functional groups is what causes it to behave differently depending on the pH when used as a surfactant. The charge on the emulsion droplets and the surfactant molecules can change depending on the ionization state of the functional groups in soybean lecithin at various pH levels. The zeta potential is impacted by this charge shift, which also has an effect on the stability of the emulsion. The degree of electrostatic repulsion between the droplets, which inhibits their coalescence, is determined by the size and sign of the zeta potential. Zeta potential of emulsions stabilized by soybean lecithin may be managed by adjusting the pH of the system. The zeta potential can be enhanced or kept within a suitable range for emulsion stability by modifying the pH of the aqueous phase to generate that environment.

Here, we found that the pH of the system has a significant impact on the effectiveness of soybean lecithin as a biobased surfactant for stabilizing oil-in-water emulsions in improved oil recovery. Based on the structure of soybean lecithin (Fig. 1), it consists of long chain hydrocarbons and ionizable tetraamino and phosphate groups. The protonated form exists at low pH while the deprotonated form exists at high pH. pH levels below the surfactant's isoelectric point were found to be advantageous, resulting in better emulsion stability, lower interfacial tension, and enhanced surfactant solubility and dispersibility. The ideal pH range for maximum emulsion stability was found to be around pH 4. These findings are important for the design and optimization of emulsion systems in improved oil recovery applications that use soybean lecithin as a biobased surfactant. It is desirable to have stable emulsions that can effectively move and displace the trapped oil in order to improve oil recovery.

Effect of salinity

Figure 4 shows the effect of salinity on the oil solubilization ratio of lecithin. As shown in the figure, the highest oil solubilization ratio can be found at around 75,000 mg/L of salinity. The solubilization ratio increases from 40,000 mg/L salinity until reaching a maximum at 75,000 mg/L. Finally, the solubilization ratio decreases from 75,000 mg/L to 110,000 mg/L. Using analysis of variance, it was determined that the $p=0.9573$ for the salinity value (X_2). As the p -value is less than 0.05, the salinity has no significant effect on the solubilization ratio at 95% confidence level. In soybean lecithin, the salt concentration has minimal effect on the emulsion-stabilizing properties.

Typically, the stability of the emulsion was affected by the salt concentration in the system, having higher salt concentrations resulting in larger droplet sizes and a reduced level of stability. The stability of emulsions formed with soybean lecithin as a surfactant can be influenced by the ionic strength of the surrounding medium. In general, an increase in ionic strength can disrupt the stability of emulsions by affecting the electrostatic interactions between the droplets. Higher ionic strength solutions contain more ions, which can shield the charges on the surfactant molecules and reduce the electrostatic repulsion between the droplets. This reduction in electrostatic repulsion can lead to droplet coalescence and phase separation, resulting in the destabilization of the emulsion.

According to Chow et al. [6], due to the increased electrostatic repulsion between the emulsifying agents at low salt concentrations, the oil droplets are more likely to remain

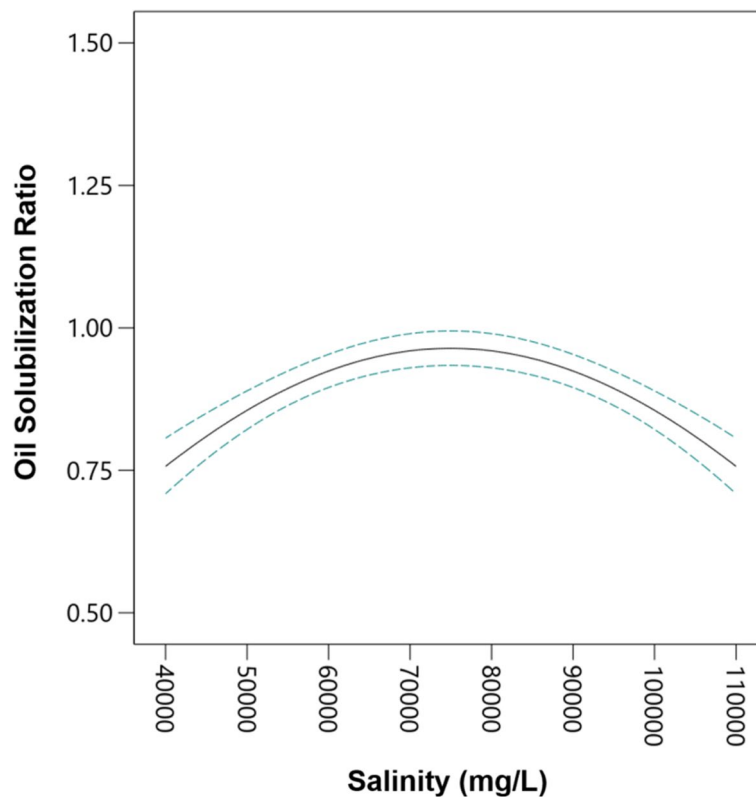


Fig. 4 Effect of salinity on the oil solubilization ratio of soybean lecithin

suspended and disperse throughout the emulsion which will result in increased emulsion stabilization. However, if the solution has high salinity, the salt ions will interact with the emulsifying agents, which will destabilize the emulsion and cause the droplets to coalesce. This will result in a reduction in the emulsion's stability.

The addition of salt to an O/W emulsion of soybean lecithin caused the lecithin molecules to become less hydrated. This led to a decrease in the stability of the emulsion, as the lecithin molecules were less able to form a protective film around the oil droplets. Our study also found that the effect of salt concentration on the stability of the emulsion was more pronounced at higher salt concentrations.

In addition to the effects of salt concentration on the hydration and solvation of lecithin molecules, salt can also affect the surface charge of the lecithin molecules. This can also affect the stability of the emulsion, as the surface charge of the lecithin molecules can influence the interaction between the lecithin molecules and the oil droplets. It has been shown that at salt concentrations of 40,000 ppm and 110,000 ppm, emulsifying agents lose their solvation shell and become destabilized in soybean lecithin emulsions because the ions of salt compete with the emulsifying agents for water molecules. Consequently, the emulsifying agents can form aggregates and coalesce, reducing emulsion stability.

There is an optimum salt concentration of 75,000 ppm that provides the best emulsion stabilization for soybean lecithin. The stability of the emulsion is enhanced by the presence of salt ions at this concentration because they increase the electrostatic repulsion between the emulsifying agents and so make it easy for the oil droplets to remain suspended and dispersed. This occurs because the charged emulsifying agents and electrostatic repulsion is effectively screened by the salt ions, minimizing their contact and keeping them in a stable dispersed form.

The ionic strength of the solution is impacted by the presence of salts in the aqueous phase, which may have an impact on the electrical double layer surrounding the dispersed oil droplets and surfactant molecules. Surfactant molecules and droplets are surrounded by charged species in the electrical double layer, including counterions and adsorbed ions. In the electrical double layer, increasing salinity tends to screen the charges, lowering the repulsive forces, and perhaps causing droplet aggregation or coalescence. The emulsion may become unstable as a result of this.

In conclusion, the quantity of salt utilized affects the stability of soybean lecithin emulsions. Salt has the ability to increase the emulsion's stability when it is present in low concentrations; yet, when it is present in excessive concentrations, it can cause the emulsion to coalesce and become less stable. To optimize the stability of emulsions with soybean lecithin, it is important to consider the ionic strength of the system and choose appropriate conditions that balance the electrostatic forces and other factors that contribute to stability. Here, we found that a salt concentration of around 75,000 ppm is optimal for stabilizing an emulsion for soybean lecithin.

Effect of surfactant loading

Figure 5 shows the effect of surfactant loading on the oil solubilization ratio of lecithin. As shown in the figure, the highest oil solubilization ratio can be found at around 2.5 wt.% lecithin loading. The solubilization ratio decreases from 2.0 wt.% lecithin until

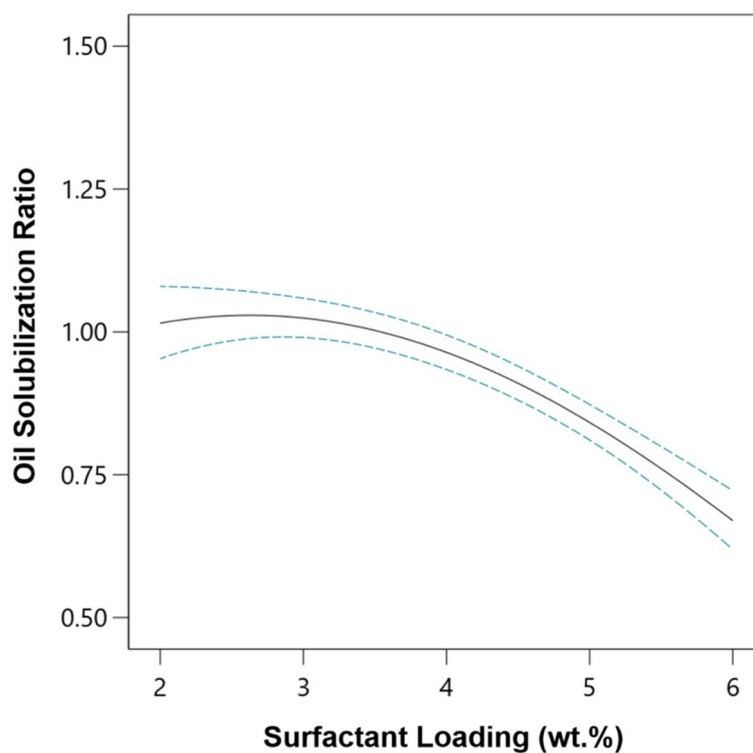


Fig. 5 Effect of surfactant loading on the oil solubilization ratio of soybean lecithin

reaching a minimum at 6.0 wt.% lecithin loading. Using analysis of variance, it was determined that the $p = 1.0718 \times 10^{-17}$ for the surfactant loading (X_3). As the p -value is less than 0.05, the surfactant loading has a significant effect on the solubilization ratio at 95% confidence level. The emulsions became unstable and coalesced fast at increased surfactant concentrations. However, when the concentration of the surfactant was decreased, the emulsions became more stable, exhibiting smaller droplet sizes as well as lower surface tensions. We found a non-linear relationship between surfactant content and emulsion stability, which suggests that there may be an ideal concentration range for soybean lecithin.

Both electrostatic interactions and van der Waals interactions are important in stabilizing oil-in-water emulsions utilizing surfactants such soybean lecithin for increased oil recovery. These interactions are impacted by the surfactant content, which in turn impacts how stable the emulsion is. Soybean lecithin is one example of a surfactant molecule with charged areas on its structure. These charged regions draw opposing ions from the aqueous phase when they are introduced to the oil-water interface, creating an electrical double layer around the droplets. The charged droplets repel one another, preventing coalescence and assisting in the stabilization of the emulsion. Attractive van der Waals forces develop as a result of temporary variations in the distribution of electrons within molecules. All atoms and molecules, including the molecules of surfactants and oil droplets, are subject to these forces. The cohesive forces that promote the aggregation or coalescence of oil droplets are caused by van der Waals interactions. By creating a barrier of surfactant molecules at

the oil–water interface, a surfactant like soybean lecithin decreases the van der Waals forces between the oil droplets. To avoid direct contact and droplet coalescence, the surfactant molecules produce a steric barrier.

At low surfactant concentrations, just above the soybean lecithin's CMC, the stability is primarily influenced by electrostatic repulsion and van der Waals interactions. In this case, the surfactant molecules adsorb at the oil–water interface, forming a protective layer around the dispersed droplets. The charged head groups of soybean lecithin can create an electrostatic double layer around the droplets, resulting in electrostatic repulsion between them. This repulsion helps to prevent the droplets from coming into close proximity and coalescing, thus maintaining the stability of the emulsion. Simultaneously, van der Waals interactions, which are attractive forces between molecules, are also present. Van der Waals forces act between the oil droplets and can contribute to their attraction. However, at low surfactant concentrations, the electrostatic repulsion predominates over the van der Waals forces, preventing droplet coalescence and ensuring emulsion stability. There may be enough surfactant molecules present at a concentration between 2.0 and 3.0 wt.% to establish a stable interface between the oil and water phases. At this region, increasing the surfactant concentration slightly increases the oil solubilization ratio, as expected. Surfactant molecules at this concentration are less likely to compete for space, allowing them to stabilize the interface and suppress the dispersion of the droplets and coalescence.

At high soybean lecithin surfactant concentrations, there are more surfactant molecules available than required to form micelles. Micelles are aggregates of surfactant molecules that form in solution when the concentration of surfactant molecules is high enough. Micelles are spherical in shape and have the hydrophobic regions of the surfactant molecules oriented towards the center of the micelle, while the hydrophilic regions of the surfactant molecules are oriented towards the outside of the micelle. In this region, the stability of emulsions can be compromised due to changes in the interplay between electrostatic repulsion and van der Waals interactions. When the surfactant concentration increases further, the excess surfactant molecules form a denser layer at the droplet interface. This denser layer intensifies the attractive forces between the droplets, thus decreasing emulsion stability. In addition, micelles can act as nuclei for the growth of new droplets. This is because the hydrophobic regions of the surfactant molecules in the micelle can attract the oil molecules in the emulsion, while the hydrophilic regions of the surfactant molecules in the micelle can attract the water molecules in the emulsion. This can lead to the formation of larger droplets, which can eventually coalesce and form a separate phase. As a result of these two factors, emulsions become unstable at high soybean lecithin surfactant concentrations.

According to Sun et al. [27], at a very high surfactant concentration, there is an excess of surfactant molecules present, which can lead to overcrowding at the interface of oil–water. This can result in the surfactant molecules competing with each other for space, which in turn can cause the emulsion to become unstable. It is also possible for the bulk phase of surfactant molecules to start forming micelles, which reduce the number of surfactant molecules available to stabilize the interface and further decreases the emulsion's stability. Also, at very high surfactant concentrations, the excess surfactant molecules may undergo self-association or aggregation, leading

to changes in the charge distribution or arrangement of the surfactant layer. This alteration can weaken the effectiveness of electrostatic repulsion and reduce its ability to counteract droplet coalescence.

The combined effect of changes in electrostatic repulsion and van der Waals interactions at high surfactant concentrations can lead to the destabilization of the emulsion. If the excess surfactant molecules form aggregates or clusters, it can result in an uneven distribution of surfactant coverage at the droplet interface. This uneven coverage creates regions with reduced electrostatic repulsion or weakened steric hindrance, allowing the droplets to approach each other closely and facilitating coalescence. Moreover, if the surfactant layer becomes overly thick or dense, it may become less effective in stabilizing the emulsion, leading to phase separation and loss of stability [16].

The effect of surfactant concentration on the emulsion stability is a complex phenomenon, as demonstrated in the work of Dongqi et al. [8] and shown in Fig. 6. Accordingly, increasing the surfactant concentration triggers a Winsor Type I III II transition of the microemulsion system by weakening the charge repulsion among surfactant molecules. At zero surfactant loading, no emulsion is formed. As the surfactant concentration increases, micelles are formed, thus solubilizing the oil phase (Winsor Type I). However, as the concentration is further increased, the droplets agglomerate, and thus the emulsion becomes unstable. The formed O/W microemulsion transforms to W/O/W or O/W/O microemulsion (Winsor Type III). This is similar to what have been observed in our study. If the surfactant concentration is further increased, it will lead to a W/O microemulsion (Winsor Type II).

Interaction of pH and salinity

Across all salinity levels, increasing the pH resulted in a decrease in oil solubilization ratio (Fig. 7). Moreover, it was observed that increasing the salinity does not have a huge effect on the oil solubilization ratio across all pH levels. Using analysis of variance, it was determined that the $p = 5.2515 \times 10^{-14}$ for the interaction between pH and salinity (X_1X_2). As the p -value is less than 0.05, the interaction has a significant effect on the solubilization ratio at 95% confidence level.

According to the findings of Abdolmaleki et al. [1], the salinity of the solution and the pH of the solution both had an effect on the emulsion stability. Their results

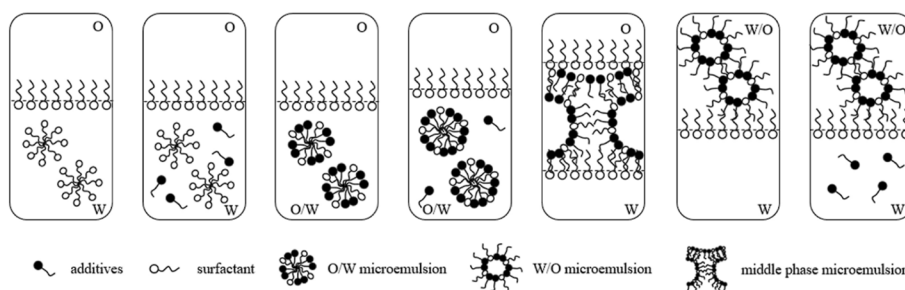


Fig. 6 Phase transformation mechanism of microemulsion with increasing surfactant concentration. Reproduced with permission from Dongqi et al. [8]. Copyright 2022, Springer

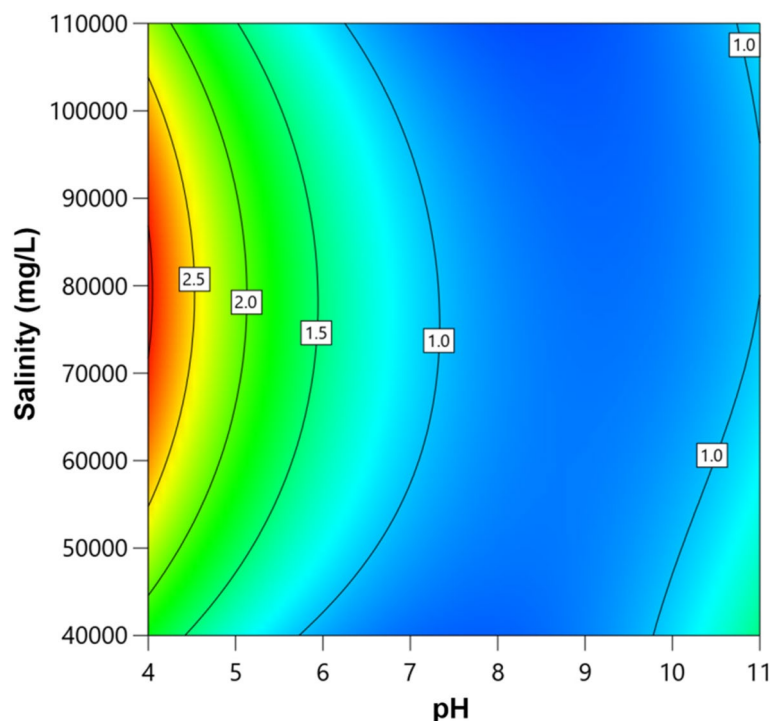


Fig. 7 Interaction effect of pH and salinity on the oil solubilization ratio of soybean lecithin

highlight the importance of considering the interplay between salinity and pH when developing and optimizing oil–water systems for a wide range of applications.

The ionization and charge of the surfactant molecules are affected by the pH of the solution. Lecithin is an amphiphilic molecule possessing both hydrophilic and hydrophobic sections. The ionization of lecithin can change at different pH levels, affecting its surface activity and emulsification capability. Meanwhile, salts can alter emulsion stability by influencing electrostatic interactions and charge screening on surfactant molecules. In the case of soybean lecithin, salts can change the structure and organization of the surfactant layers at the oil–water interface, affecting emulsion stability.

The emulsion's stability is aided by the electrostatic repulsion between the oil droplets, which is assisted by the adsorption of negatively charged soybean lecithin molecules. The net charge of the surfactant molecules can be affected by pH and salinity, which affects the repulsion or attraction between the surfactant-coated droplets. The interplay between pH and salinity can affect emulsion stability by changing the electrostatic forces acting on the droplets. Furthermore, surfactant molecules can aggregate form micelles under varying pH and salinity conditions. Micelles can aid to solubilize oil and stabilize emulsions. The pH and salinity can alter the creation and characteristics of these micelles, affecting the overall stability of the emulsion. The interaction between pH and salinity can modify the interface to stabilize the emulsion.

Interaction of surfactant loading and pH

Figure 8 shows the effect of surfactant loading on the oil solubilization ratio of lecithin. As shown in the figure, the highest oil solubilization ratio can be found at

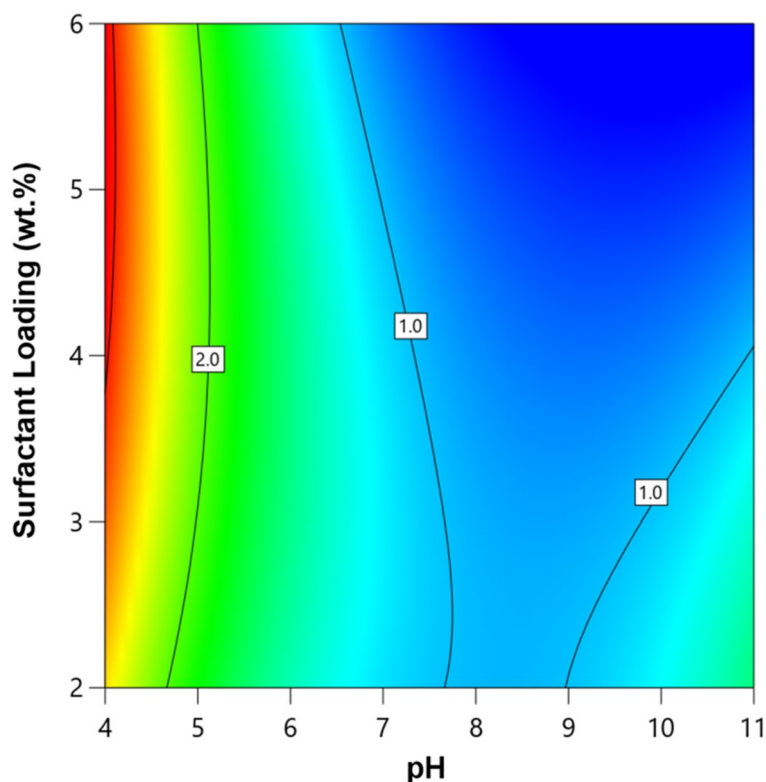


Fig. 8 Interaction effect of surfactant loading and pH on the oil solubilization ratio of soybean lecithin

around 2.5 wt.% lecithin loading. The solubilization ratio decreases from 2.0 wt.% lecithin until reaching a minimum at 6.0 wt.% lecithin loading. Using analysis of variance, it was determined that the $p = 1.6076 \times 10^{-27}$ for the interaction between pH and surfactant loading (X_1X_3). As the p -value is less than 0.05, the interaction has a significant effect on the solubilization ratio at 95% confidence level.

pH and surfactant concentration had a significant effect on the nanoemulsion's ability to remain stable, and the optimal conditions for maintaining the nanoemulsion's stability depended on the particular surfactant system employed. The emulsions displayed poor stability across all low surfactant loading and near-neutral pH levels, with considerable phase separation and droplet coalescence. Regardless of surfactant dosage, emulsion stability was shown to be usually higher in low pH circumstances compared to near-neutral pH values. This is due to changes in the surface characteristics of the soybean lecithin molecules at low pH levels, which affects their capacity to properly maintain the emulsion.

Based on the experimental results, an ideal combination of surfactant loading and pH was discovered for the performance of soybean lecithin as a biobased surfactant in stabilizing oil-in-water emulsions for improved oil recovery. The maximum emulsion stability was achieved with higher surfactant loadings paired with low pH conditions. A substantial quantity of soybean lecithin was present in this combination to adequately stabilize the emulsion, resulting in decreased droplet coalescence and

enhanced oil recovery efficiency. Moreover, the lecithin is effectively protonated at low pH, enabling good electrostatic interaction with the oil/water interface.

pH and surfactant loading can influence the charge density of the surfactant molecules present at the oil–water interface. pH affects the ionization of the surfactant, while surfactant loading determines the concentration of surfactant molecules. The combination of pH and surfactant loading can affect the overall charge density, which influences the electrostatic repulsion or attraction between droplets, thereby affecting emulsion stability. Moreover, pH and surfactant loading can impact the formation of micelles. Micelles are formed when surfactant molecules aggregate in the solution above a certain concentration (critical micelle concentration, CMC). pH and surfactant loading can influence the CMC, micelle size, and distribution. These factors can affect the surfactant's ability to stabilize the oil-in-water emulsion and impact the droplet size distribution. Lastly, pH and surfactant loading can influence the interfacial tension between the oil and water phases. pH and surfactant loading affect the packing and orientation of surfactant molecules at the interface, which influences the interfacial tension and subsequently impacts emulsion stability.

Interaction of surfactant loading and salinity

Figure 9 shows the effect of surfactant loading and salinity on the oil solubilization ratio of lecithin. Using analysis of variance, it was determined that the $p = 6.2176 \times 10^{-9}$ for the interaction between salinity and surfactant loading (X_2X_3). As the p -value is less than 0.05, the interaction has a significant effect on the solubilization ratio at 95% confidence level.

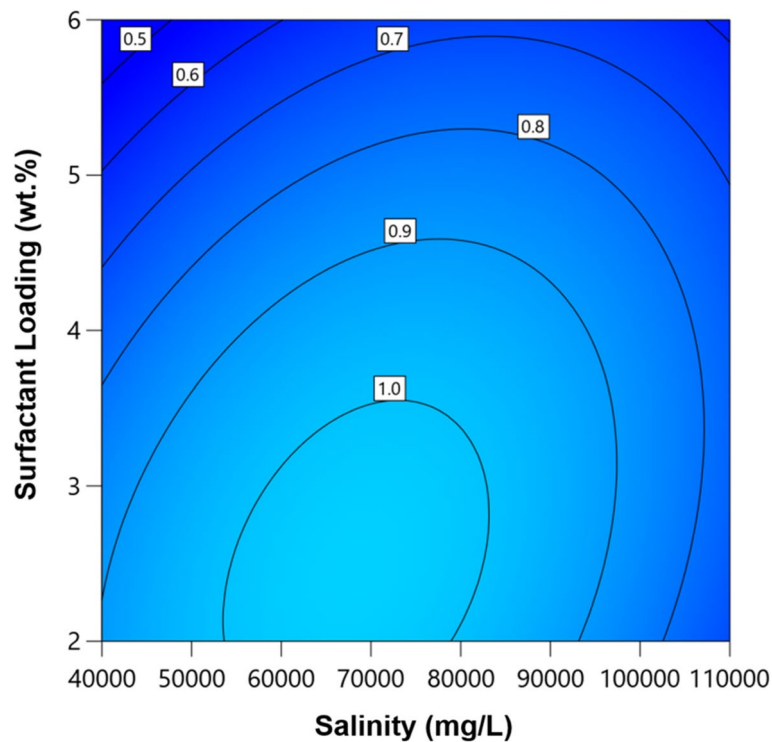


Fig. 9 Interaction effect of surfactant loading and salinity on the oil solubilization ratio of soybean lecithin

Here, salinity and surfactant concentration influence emulsion stability. We found that the optimal conditions for emulsion stability varied based on the surfactant system employed. Moreover, the optimal conditions for emulsion stability were moderate salinity and surfactant concentration.

The stability of the emulsion and the surfactant’s capacity to maintain the oil–water interface depend critically on the loading of the surfactant. By lowering the interfacial tension between the oil and water phases and creating a protective surfactant layer around the oil droplets, higher surfactant loading often improves emulsion stability. By influencing electrostatic interactions and charge screening on surfactant molecules, salts may alter the stability of an emulsion. At the oil–water interface, the structure and organization of the surfactant layers may change if salts are present in soybean lecithin. High salt concentrations can have a salting-out effect, which lowers the surfactant’s solubility or efficiency. This effect can diminish the emulsion stability and require higher surfactant loading to overcome the salting-out effect and maintain stability.

Optimization of parameters

Analysis of variance (ANOVA) was performed to determine the significance of each parameter in relation to the solubilization ratio (Table 3). It is preferable to have high *F*-values and low *p*-values, and terms or parameters with *p* > 0.05 are deemed insignificant. According to the table, there are a number of significant terms in this context, including A, C, AB, AC, BC, A², B², C², ABC, and AB². All insignificant parameters were removed from the final equation.

The *F*-value of a model depicts the average degree to which the model fits the data. It indicates the degree to which the model matches the data. The *F*-value in this instance, 273.32, is an extremely high value. The fact that there is only a 0.01% chance that this value is due to noise indicates that the model is highly significant and the results are unlikely to be the result of random chance. As a result, we can conclude that the model

Table 3 ANOVA for the reduced cubic model

Source	Sum of squares	df	Mean square	F-value	p-value
Block	0.0005	2	0.0002		
Model	4.08	10	0.4082	273.32	< 0.0001
A-pH	0.8111	1	0.8111	543.17	< 0.0001
C-surfactant	0.2691	1	0.2691	180.2	< 0.0001
AB	0.1667	1	0.1667	111.65	< 0.0001
AC	0.8155	1	0.8155	546.12	< 0.0001
BC	0.0748	1	0.0748	50.1	< 0.0001
A ²	1.28	1	1.28	856.31	< 0.0001
B ²	0.1034	1	0.1034	69.26	< 0.0001
C ²	0.0392	1	0.0392	26.28	< 0.0001
ABC	0.0309	1	0.0309	20.66	< 0.0001
AB ²	0.2482	1	0.2482	166.23	< 0.0001
Residual	0.0702	47	0.0015		
Lack of Fit	0.0049	32	0.0002	0.0353	1
Pure Error	0.0653	15	0.0044		
Cor Total	4.15	59			

provides an adequate explanation for the data. Moreover, the lack-of-fit F -value is quite low, indicating that the model fits the data quite well and that any lack-of-fit is negligible compared to the overall error. As a result, we can conclude that the model accurately represents both the variables' underlying relationship and the data.

An R^2 value of 0.9831 indicates that the model can account for 98.31% of the variations in the experimental data. A high adequate precision value of 57.6892 indicates that there is a sufficient signal-to-noise ratio, implying that the model is capable of predicting the relationship among the variables.

The magnitude and the signs of the coefficients in the coded equation (Eq. 3) show how each parameter influences the response. Here, the pH is the most influential term. Terms having negative values indicating antagonistic effects to the transformed response while those with positive values indicate synergistic effects to the response.

$$\begin{aligned} SR_o^{0.5} = & 0.9812 - 0.3677(A) - 0.0947(C) - 0.0833(AB) - 0.1843(AC) + 0.0558(BC) \\ & + 0.3930(A^2) - 0.1121(B^2) - 0.0690(C^2) - 0.0359(ABC) + 0.2274(AB^2) \end{aligned} \quad (3)$$

There is a strong curvature of the response surface as a direct consequence of the quadratic and cubic model terms in the equation. Because of such curvature, there exists an optimum point that leads to a maximum oil solubilization ratio. As such, we determined the optimum conditions by maximizing the oil solubilization ratio numerically. The value of pH 4.00, the salinity of 84,171.08 ppm, and the surfactant of 4.48 wt.% were determined as the optimal values with a model-predicted oil solubilization ratio of 3.11. Validation experiments under optimal conditions revealed that the actual oil solubilization ratio is 3.22. This is 3.54% higher than the model-predicted value. Statistical analysis has shown that at a 95% confidence level, the predicted and actual values are not statistically different from each other, indicating that the model can really predict the solubilization ratios of the oil-in-water emulsions using lecithin as a biosurfactant.

Comparison of soybean lecithin to different types of surfactants

We compared the performance of soybean lecithin with other commercially-available surfactants under optimum conditions (pH 4.00, salinity of 84,171.08 ppm, and surfactant loading of 4.48 wt.%) and the results are shown in Fig. 10. Soybean lecithin has an oil solubilization value of 3.2219, which is intermediate compared to the synthetic surfactants CTAC ($SR_o = 11.1044$), SLES ($SR_o = 11.7067$), and NP10EO ($SR_o = 11.1579$), but higher than CAPB ($SR_o = 0.7028$).

Soybean lecithin has a lower solubilization ratio compared to other surfactants. However, there are some advantages of using soybean lecithin as a surfactant over synthetic surfactants. Soybean lecithin is a natural and renewable resource, and it is non-toxic and biodegradable. It also has a lower environmental impact compared to synthetic surfactants. In contrast, some synthetic surfactants may have potential health and environmental concerns, which make them less desirable for certain applications. On an economic standpoint, since soybean lecithin is derived from natural raw materials, it is cheaper compared to chemically manufactured surfactants.

In the succeeding paragraphs, we attempt to rationalize why we obtained the different values of solubilization ratios using various surfactants. The chemical formula for

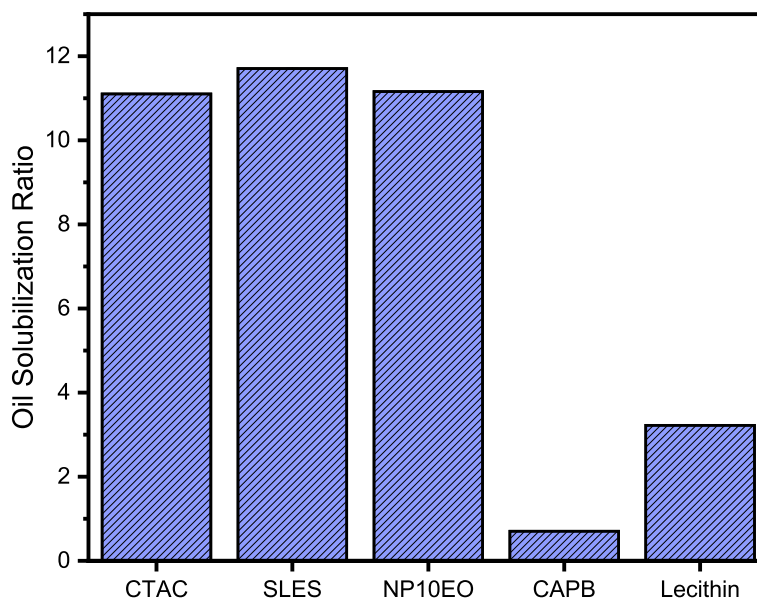


Fig. 10 Comparison of soybean lecithin to commercially-available surfactants. The experiment is conducted at optimum conditions: pH 4.00, salinity of 84,171.08 ppm, and surfactant loading of 4.48 wt.%

the amphoteric surfactant soybean lecithin is $C_{35}H_{66}NO_7P$. In terms of structure, it has a hydrophilic head and a lipophilic tail. Lecithin is a polar zwitterionic headgroup molecule with two nonpolar hydrocarbon chains. The phosphate and nitrogen groups of the headgroup give lecithin a negative and positive charge, respectively. Raw lecithin is an emulsifier with an HLB value of 3–5, being typical for water-in-oil emulsifiers.

A number of parameters influence the solubilization ratio of soybean lecithin in oil, including pH, salinity, and oil type. To prevent oil droplets from coalescing and to improve their dispersion in the water phase of an emulsion, soybean lecithin forms a protective coating around them. Because it lowers interfacial tension and provides steric hindrance against droplet aggregation, soybean lecithin is useful at stabilizing emulsions and boosting oil recovery. The hydrophobic chain's branching or substitutes may have an impact on the oil solubilization ratio. Branching or bulky substituents can make a surfactant more sterically hindered and less able to interact with and solubilize oil. Contrarily, the characteristics of hydrophobic linear and unbranched chains to be soluble in oil are often superior. This explains why lecithin has lower solubilization ratio compared to other surfactants.

The chemical formula for the cationic surfactant cetyltrimethylammonium chloride (CTAC) is $C_{16}H_{33}N(CH_3)_3Cl$. It is a hydrophilic quaternary ammonium compound with a hydrophobic tail. The hydrophobic tail has 16 carbon atoms, and the hydrophilic head has one nitrogen atom and three methyl groups. CTAC is a highly effective emulsifier, with a solubilization ratio of 11.1044, which means it can help to form stable oil-and-water emulsions. This is because CTAC's hydrophobic tail can interact with oil, whereas its hydrophilic head can interact with water. The positively charged head group on CTAC, a cationic surfactant, makes it soluble in water. Its interaction with oil or other hydrophobic substances is caused by the hydrophobic tail.

$CH_3(CH_2)_{10}CH_2(OCH_2CH_2)_nOSO_3Na$ is the chemical formula for SLES. As a surfactant, sodium lauryl ethers sulfate (SLES) possesses both hydrophilic and hydrophobic

properties. The sodium ion is responsible for the hydrophilic nature of SLES, while the lauryl ether sulfate group is responsible for its hydrophobic nature. The lauryl ether sulfate group consists of a very long chain of carbon atoms that are all attached to ethoxy groups at various points along the chain. The presence of ethoxy groups makes the lauryl ether sulfate group water-soluble, and the presence of a long carbon chain makes it oil-soluble. Typically, SLES has an HLB value in the range of 10–12. When SLES is added to water, sodium ions are attracted to water molecules while lauryl ether sulfate groups are attracted to oil molecules. This process leads to the formation of a micelles which enclose and suspend oil droplets, improving their dispersion and reducing coalescence.

$C_{15}H_{24}O$ is the chemical formula for NP10EO. NP10EO is characterized by having a hydrophobic alkyl chain and a hydrophilic ethoxylation chain. The hydrophobic alkyl chain provides the surfactant's lipophilic properties, while the hydrophilic ethoxylation chain makes it water-soluble. When NP10EO is added to a water–oil mixture, the molecules arrange themselves so that the hydrophilic heads contact the water and the hydrophobic tails contact the oil. This results in a stable emulsion with uniformly blended water and oil. The HLB value of NP10EO is approximately 13–14. The solubilization ratio of NP10EO was found to be 11.1579. Since NP10EO is a nonionic surfactant, it has no net charge and is unaffected by pH variations. It is frequently employed in a variety of processes, such as emulsification, wetting, and dispersion. Through the provision of steric hindrance and the reduction of interfacial tension, it can aid in stabilizing oil-in-water emulsions.

$C_{19}H_{38}N_2O_3$ is the formula for CAPB, an ammonium quaternary compound. CAPB has a long hydrophobic tail (the carbon chain) and a polar head (the nitrogen and oxygen atoms). As a result, it is an amphoteric surfactant that can function as both anionic and cationic surfactant. CAPB is an effective surfactant for forming emulsions due to its hydrophobic tail and polar head. The hydrophobic tail can interact with oil droplets, whereas the polar head can interact with water droplets. As a result, CAPB can form micelles around both droplet types, stabilizing the emulsion. The isoelectric point (pI) of CAPB is typically around pH 5–6. Depending on the pH of the solution, CAPB's distinctive zwitterionic structure enables it to function as both a cationic and an anionic surfactant. While the amine group may be protonated to provide a net positive charge at alkaline pH, the carboxylate group can be deprotonated to produce a net negative charge at acidic pH. It is frequently employed in formulations as a co-surfactant or foam booster, improving the overall performance of the product. Due to its amphiphilic nature, CAPB can aid in emulsifying and dispersing oils in water, but in comparison to specialized solubilizers, it has a limited capability for solubilizing oils or other hydrophobic compounds.

Mechanism underlying emulsion stability

Different chemical processes control how stable emulsions, such as water-in-oil or oil-in-water emulsions, are. Both the surfactant molecules present at the oil–water interface and the interactions between the dispersed phase (oil) and the continuous phase (water) are a part of these processes. Figure 11 shows the mechanism of emulsion stabilization using soybean lecithin as surfactant. Surfactant molecules move to the oil–water interface when they are introduced to the system, lowering the interfacial tension between the two phases. By limiting the coalescence and separation of the dispersed droplets, this decrease in interfacial tension contributes to the stabilization of the emulsion.

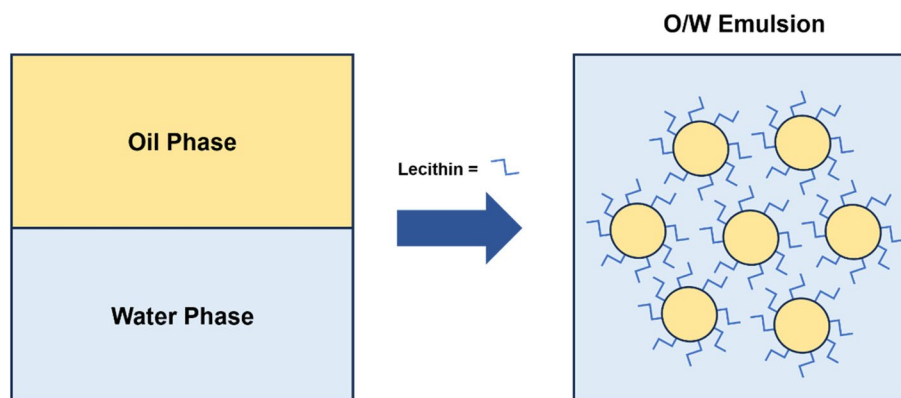


Fig. 11 Mechanism of emulsion stabilization using soybean lecithin as surfactant

At the oil–water interface, surfactant molecules preferentially adsorb, coating the droplets with a layer or film. This layer of adsorbed surfactant functions as a physical barrier to stop the droplets from coming into contact with each other and coalescing. The emulsion stability is influenced by the strength of the adsorption and the surfactant’s capacity to create a stable interfacial coating. Electrostatic repulsion between the droplets can occasionally be induced by charged surfactant molecules or additional electrolytes, preventing the droplets from aggregating. When the droplets or surfactant molecules have a net charge, electrostatic forces of repulsion between them cause the electrostatic stabilization to happen. The presence of big, surfactant molecules at the interface is necessary for steric stability. These molecules surround the droplets in a shield, forming a steric barrier that prevents droplet coalescence. The steric hindrance enhances the stability of the emulsion by preventing the close approach and fusing of the droplets.

It is critical to remember that the stability of an emulsion depends on a complex interaction of several variables, including surfactant type, concentration, pH, temperature, electrolyte concentration, and shear forces. Depending on the system, the particular surfactants, and the environmental factors at play, several processes may be present and may contribute differently to emulsion stability. Future studies may focus on the detailed characterization of the diesel oil–water–soybean lecithin emulsion system to accurately elucidate the mechanism behind the stabilization of oil/water emulsions.

Conclusions

The study found that soybean lecithin demonstrated excellent emulsifying and stabilizing properties, with the ability to decrease interfacial tension and increase emulsion stability. Utilization of soy lecithin as a biobased surfactant for enhanced oil recovery is an innovative and sustainable approach that has the potential to reduce the environmental impact of traditional oil recovery methods. Soybean lecithin has an intermediate CMC value compared to commercially available surfactants. The solution pH has the most significant effect on emulsion stability. At higher pH levels, emulsions were unstable, whereas at lower pH levels, they were more stable. Higher salt concentrations led to decreased emulsion stability. The salt concentration has minimal impact on soybean lecithin’s emulsion-stabilizing properties. At higher concentrations of surfactant, emulsions

became unstable and coalesced rapidly. When the concentration of the surfactant was decreased, the emulsions became more stable. The optimal values were determined to be pH 4.00, salinity 84,171.08 ppm, and surfactant 4.48 wt.%, with a model-predicted oil solubilization ratio of 3.11. Validation experiments showed a 3.22 oil solubilization ratio under optimal conditions, 3.54% more than the model predicted value. Soybean lecithin has an oil solubilization value of 3.2219, which is intermediate when compared to the synthetic surfactants. Soybean lecithin is a potent surfactant with solubilization capabilities equivalent to both synthetic and natural surfactants. Future research ought to focus on formulating lecithin-optimized systems and investigating interactions with other surfactants or additives. Moreover, the performance of soybean lecithin under actual well conditions should be assessed. Overall, the study's findings provide valuable insights into the potential of soybean lecithin as a biobased surfactant for enhanced oil recovery and highlight the importance of exploring sustainable alternatives to traditional oil recovery methods.

Abbreviations

ANOVA	Analysis of variance
CAPB	Cocamidopropyl betaine
CMC	Critical micelle concentration
CTAC	Cetyltrimethylammonium chloride
HLB	Hydrophilic-lipophilic balance
NP10EO	Nonylphenol ethoxylate
O/W	Oil-in-water
SLES	Sodium lauryl ether sulfate
SR _o	Solubilization ratio of oil

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by JJDU, JMB, ED, KMD, and KR. The first draft of the manuscript was written by ECRL, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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