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Utilization of Whey Protein Isolate as CO_2 Foam Stabilizer for Enhanced Oil Recovery

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Abstract. Understanding the fundamental aspects of foaming properties will influence its generation and stabilization at different concentrations of the critical aggregation concentration (CAC), foam volume stability, foam height, salinity influences, and crude oil CO_2-foam stability. Carbon-Dioxide based enhanced oil recovery techniques are widely employed to extract additional oil from the reservoir. The adsorption of protein at the interfaces produces extremely viscoelastic layers with high viscosity. This research aims to investigate whether whey protein isolate (WPI) is a foaming agent that can be used to improve oil recovery. WPI lowers the interfaces' surface tension, which also has a propensity to disclose and stabilize the interface by forming a viscoelastic network and directing to high surface moduli. Comparatively, the surface tension is lowered by sodium dodecyl sulfate (SDS) surfactants than the WPI, but they do not produce a high modulus interface. WPI is demonstrated to be a greater foam stabilizer in oil and various salt conditions than SDS foam. Adding sodium chloride (NaCl) increased the half-life and volume of foam more on WPI foam compared to SDS foam. SDS foamability and foam consistency decreased dramatically at 2 wt% of NaCl concentration and above while WPI foam increased. The crude oil affected both foams, but WPI foam has not been affected as much as the SDS foam due to its high strength compared to traditional foams. The study shows that WPI reduced interfacial tension from 38 to 11 mN/m and reduced surface tension (72.3 to 48 mN/m). It was low enough and can be used as a substitute for a foaming agent to enhance the recovery of oil.

Keywords: Foamability, Foam stability, Salinity, Whey protein isolated foam, Oil presence

INTRODUCTION

For several decades, Enhanced Oil Recovery (EOR) techniques have been researched and widely applied. The remaining oil after conventional treatment processes of 70% is still untapped in the reservoir (Nastaj et al. 2020). Many EOR projects in the oil industry have used miscible or immiscible carbon dioxide (CO_2) flooding and have been shown to recover 15% to 25% of the initial oil in place (OOIP) (Mansour et al. 2016, Pogaku et al. 2018, Massarweh et al. 2020). Due to low density, rock heterogeneity, interfacial tension reduction, oil swelling, and the infused CO_2 gas' viscosity

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compared to conventional oil (Farhadi et al. 2016, Farajzadeh et al. 2020, Lv et al. 2016). There are many challenges in the CO_2-based EOR project, such as poor sweep effectiveness and less incremental recovery of oil resulting from viscous instability, fingering and gravity separation (Enick et al. 2012, Farzaneh et al. 2015). One of the most common injection systems in field operations is the Water Alternating Gas (WAG). WAG is useful because it improves the low sweep efficiency of CO_2. The high mobility ratio for oil recovery is not beneficial. It leads to the time before gas bursts through and a little sum of recycled gas in the increased permeability sector. A large difference in density between water/oil and gas often directs to the gas override issue depending on the reservoir's temperature and pressure (Enick et al. 2012, Sagir et al. 2014, Jia et al. 2019). Reservoirs holding oils with large viscosity and small mobility can undergo instabilities and consequently low sweep efficiency when water is injected. They lose their mobility function controlling ability at certain space away from the wellbore (Mishra et al. 2014, Farajzadeh et al. 2019) WAG method will also lead to large water quantities, preventing CO_2 from contacting reservoir pores with oil.

A number of methods have been studied and tested to overcome the CO_2 mobility challenge water alternating gas (WAG), foam generation, and thickeners increase gas viscosity (Heller et al. 1985, Chakravarthy et al. 2004, AlYousef et al. 2020). One frequently used method to overcome the gas mobility problem is in-situ foam generation. Foam can improve gas viscosity and relativity, reducing gas mobility, thereby enhancing the performance of the gas volumetric sweep efficiency (AlYousef et al. 2020, AlYousef et al. 2017).

Surfactants are widely utilized to generate foam for Enhanced Oil Recovery (EOR) to improve oil displacement and profile control (Simjoo et al. 2013, Pu et al. 2017). However, foams are thermodynamically unstable (Chen et al. 2014, Kang et al. 2019). Using foam generated by surfactants is a challenge because of its stability over time (Schulze-Schlarmann et al. 2006). Foam stability at reservoir conditions can be affected by many factors including water salinity, surfactant adsorption on rock surfaces, reservoir temperature, oil effect, degradation of surfactants, and fluid-fluid interactions (AlYousef et al. 2017, Le et al. 2019, Nazari et al. 2020, Skauge et al. 2020). Furthermore, foam stability can diminish over time due to the foam oil interactions. The oil can act as an antifoaming agent by penetrating thin aqueous films, destabilizing, and destroying them (Schramm et al. 1990, AlYousif et al. 2018, Veyskarami et al. 2019). Depending on the surfactant type, crude oil in porous media can significantly impact foam stability and strengthen even at deficient concentrations (Berton-Carabin et al. 2016, Yu et al. 2021).

Protein functionality seems to be a complicated concept which covers techno-functional properties. Proteins can reduce the interfacial tension between the oil and the water because of their amphiphilic nature (Lam et al. 2013). Surface active agents are divided into two groups based on molecular properties: the first group is low molecular weight surfactants (LMW), and the second group is proteins. Protein is a surface-active agent (Van Kempen et al. 2014, Grossmann et al. 2019). Protein molecular changes taking place through protein hydrolysis might end in customized hydrolysates' customized techno-functional performance in contrast to the integral protein like sensory properties, viscosity, foam properties, and altered solubility (Jambrak et al. 2008, Rio et al. 2014). Proteins are of immense interest for the reason of their amphiphilic nature. This nature lets them reduce interfacial tension at the oil and water interface (Lam et al. 2013, Nastaj et al. 2020, Yang et al. 2020). PEOR techniques (Protein Enhanced Oil Recovery) include injection methods of surfactant into the reservoir. The injected fluid reduces the interfacial tension of the crude oil, increasing oil recovery (Alvarez Yela et al. 2016, Samin et al. 2017, Berton-Carabin et al. 2016, Nastaj et al. 2020).

PEOR exists exemplified by the ecological benefits of a green chemistry agent in industrial processes. Proteins are complex macromolecules that hold high molecular weight and high interfacial movement as they dangle at the interfaces to produce high viscoelastic covering in the company of high surface activity (Martinez et al. 2013, Samin et al. 2017). Consequently, it is employed as an emulsifying means in food, chemical, pharmaceutical companies, and EOR in oil reservoirs (Rocha-Pino et al. 2018). Furthermore, also under harsh reservoir conditions, the protein retains ~80-95% of its functionality (Podella et al. 2013). Protein functionality is defined as the rate of catalyzing a chemical reaction, uncoupling of biochemical processes, and lowering of interfacial tension or lowering of critical micelle concentration (Podella et al. 2013, Nastaj et al. 2020). Protein amphipathic molecules are constructed of hydrophobic and hydrophilic moieties that form a micelle (Samin et al. 2017). Protein foam employed as a substitute foaming candidate for EOR processing is owing to its higher steadiness (Samin et al. 2017). This protein film consists of hydrophilic amino and carboxylic groups ($-NH_2$ & -COOH), which bind through hydrogen bonding to water molecules and render water-wet surface; reducing either oil viscosity or interfacial tension through emulsification (Liu et al. 2011). PEOR recorded a recovery factor of 12% OOIP by using bio-surfactants generated from transmembrane proteins (Samin et al. 2017). It is stated that protein foaming could be applied for EOR processing (Aurepatipan et al. 2018, El-hoshoudy 2019).

Commonly, in food-connected applications, protein foam is broadly used. Proteins are important molecules that adsorb at interfaces to form viscoelastic layers with high viscosities of surface shear, as a result of which plateau borders become inflexible (Martinez et al. 2013, Samin et al. 2017). To the author's best knowledge, this specific feature of protein foam to stabilize CO_2 foam for EOR applications has not yet been investigated. As a result, Whey Protein Isolate (WPI) foam is being examined as a foaming agent for making stable CO_2 foam for EOR.

In this study, whey protein isolate foam will be tested as a foaming agent to stabilize CO_2 foam for EOR. The foam's properties were determined by examining the effects of stability, formability, salinity, and the presence of oil. The results from the experiments were compared with the performance of classical surfactant (SDS) foam under the same conditions.

MATERIAL AND METHOD

Materials

Two different surfactants of Sodium Dodecyl Sulfate (SDS) ($C_{12}H_{25}NaO_4S$) and Whey Protein Isolate (WPI) were utilized as foaming agents. SDS contains a molecular mass of 288.4 g/mol, and 100% purity, supplied by the USA's SIGMA-ALDRICH Company. The WPI with a purity of 91% was exclusively imported and distributed by the lush protein company in Singapore. For the salinity effect study, sodium chloride NaCl with a purity of 99.8 percent and 58.44 g/mol molecular weight supplied by USA based company (Sigma) was used. The CO_2 gas employed to generate foam has a purity of 99% and is delivered by Mega Mount Company. Deionized water (DI) was obtained from the water filtration system of Pall Corporation, purified water that has almost all its mineral ions removed. All solutions were prepared using DI water.

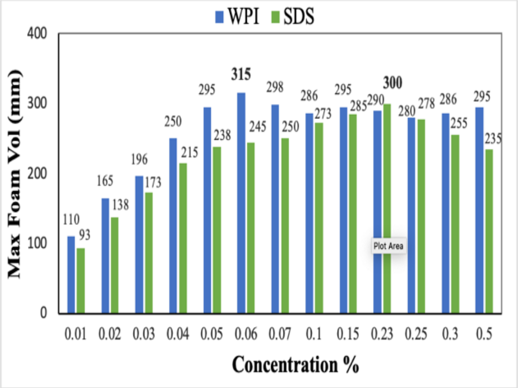


Fig. 1: Maximum foam volume generated using WPI and SDS at various concentrations

Figure 1 illustrates the maximum foam volume generated using WPI and SDS at various concentrations. It can be observed that maximum foam volume for WPI and SDS are recorded at 0.06% concentration and 0.23% concentration, respectively.

Crude Oil

To investigate foam height and foam stability, Libyan crude oil Hamada was used. Hamada oil was evaluated by the National Oil Corporation (NOC). The Akakous company provided the crude oil sample. The sample was collected using the ASTM D4057 standard method. The crude oil sample analysis was carried out using well-recognized standard procedures provided in the methods of ASTM, IP, and UOP. The crude oil distillation was processed using an ASTM D-2892 and ASTM D-1160 batch fractionation unit. Table 1 presents the properties of crude oil.

Table 1. Hamada Oil Specification

Description		Method
Crude Oil density @ 15 °Cg/ml	0.8304	ASTM D-4052
Specific gravity @60/60 °F	0.8311	Calculation
API gravity	38.8	Calculation
Flash point °C	-23	ASTM D93
Reid vapor pressure psi	4.2	ASTM D323
Hydrogen sulphide ppm	17.04	IP 103
Water and sediment content vol.%	0.10	ASTM D-4007
Sulphur content wt.%	0.063	ASTM D-4294
Pour point °C	-18	ASTM D97
Kinematic viscosity @ 70 °F, cSt @ 100 °F, cSt	6.8431 3.5742	ASTM D-445
Asphaltenes content wt.%	0.34	IP 143

Experimental Procedure

Preparing Solutions for Foaming Agent

All the samples of surfactant solutions were formulated in 500ml volumetric flasks. Before transferring the preferred surfactant concentration to a volumetric flask, it was measured on a mass basis. Before the solution's final weight was determined, distilled water was added (0.5kg). Concentrations of surfactant solution were focused on dynamic content. Dissimilar SDS and WPI were used for the analysis with 0.005 wt.% and 0.5 wt percent range. Every sample was mixed for 30 minutes before the actual experiment. Dissimilar surfactant solutions with 1.0 wt% to 5.0 wt% concentrations of

NaCl salt were formulated in the salinity effect investigation. Each sample was mixed for 20 min at room temperature to ensure that salt was fully dissolved.

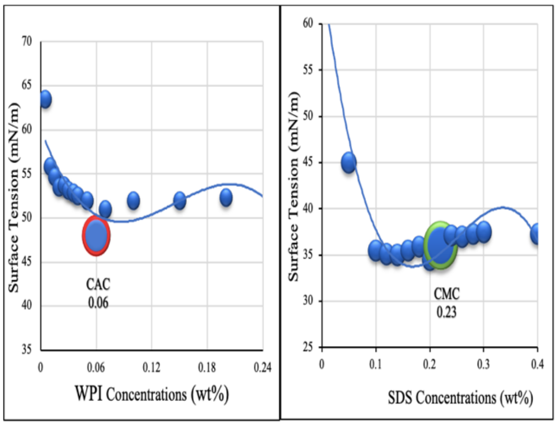
Surface and Interfacial Tension Measurements

Reducing oil-water interfacial tension seems to be an important property in EOR to surfactant formulations (Kumari et al. 2019, Jia et al. 2017). Proteins were affected in recent years by the foaming agent's adsorption at the interface with the air-water and the potential for sound surface tension reduction (Alvarez Yela et al. 2016, Samin et al. 2017). WPI interfacial tension is reduced to examine the ability of surfactants. The primary water/oil interfacial tension was calculated through K20 Force Tensiometer (Kruss) a RI 21 platinum-iridium alloy wire ring employed in the Du Noüy ring method. The concentration of WPI and SDS solutions ranged from 0.005 wt% to 0.5 wt%.

Measurements of surface tension are calculated with different concentrations of SDS along with WPI. The Critical Aggregation Concentration (CAC) and Critical Micelle Concentration (CMC) of WPI, SDS micelle were determined by plotting surface voltage versus concentration. Figures 2(A) and 2(B) show the CAC and CMC values were the surface tension values at the curve's inflection point for SDS and WPI concentration. WPI and SDS concentrations are increasing at this point., and there are no essential alterations in surface tension.

Bulk Foam Stability Experiments

The introductory test to determine the foam stability and foamability for the surfactants WPI and SDS is the static test. Both the surfactant powders were dissolved at a protein concentration of 0.06% and SDS at 0.23% in deionized water. Foams were created by bubbling CO_2 air into a 100 mL protein solution and placing a porous glass disk at the bottom.



(A) (B)

Fig. 2: Surface tension for WPI and SDS solutions in different concentration

Figure 3 shows a detailed diagram of the bulk foam stability experiment. The design consists of a 500 mm high mixer with a 50.8 mm diameter glass cylinder and a CO_2 injection spot located at the base of the blender. By stirring 100 ml of surfactant solution and by blowing CO_2 gas via the injection spot into the liquid solution the foam was produced concurrently.

In the gas cylinder, the produced foam increased, and a measuring string was fixed to determine the height of the foam. From the analysis, a 5.0 ml/min gas flow pace was employed for every state. At an ambient temperature (24±1°C) and atmospheric pressure, every foam bulk stability test was performed. The tests or the experiments were executed at least thrice, and each trial went on for a period of one minute before the gas was shut off and the generation of foam ended. The average value of the experiment was used as the result.

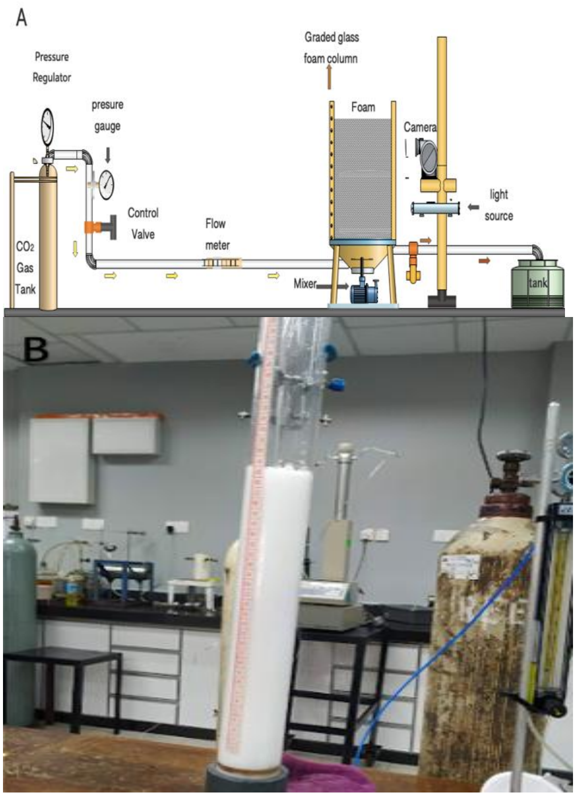


Fig. 3: Experimental setup: (a) Schematic diagram for bulk foam stability and foamability tests and (b) pictorial representation

Foamability and Foam Stability Investigation

Through optical observation of the foam, properties of foamability and foam stability were identified. Foamability of the solution refers to the foam volume straight after the foaming method, which is exemplified by observing the foam column's height (h_o) straight away after the termination of foam generation ($t = 0$). A higher level of foam reflects greater foamability. The stability of foam is determined by observing the foam volume over time as defined as the time required for the foam to be decreased to 50% of its starting height (h_o). Increased half-life shows further stable foam. Optical microscopy was used to verify the bubble distribution and bubble size. In terms of the size and structure of the bubbles, the foam morphology was tracked, and the photographs were obtained using a fixed digital camera 1600X Optical microscope. The effect of salinity (NaCl) on both WPI and SDS foamabilities and foam stabilities was investigated. Using optimum WPI and SDS concentration (0.06 wt% and 0.23 wt%).

Oil Effect

An oil fractional flow test was conducted with Hamada crude oil to examine the oil effect on WPI-CO$_2$ and SDS-CO$_2$ foamabilities foam and stabilities. Figure 4 illustrates the experimental setup utilized for examining the capability of WPI along with SDS to produce stable foams in the existence of oil. This experimental design includes a glass cylinder with a diameter of 4 cm and a height of 40 cm at the bottom filled with a porous frit that has a diameter of 4 cm. The experiment includes oil (WPI, SDS) solution and CO$_2$ gas. The total CO$_2$ flow rate was fixed at 5.0 ml/min. To maintain a consistent flow rate, a mass flow meter connected between the column and the gas supply base is used in conjunction with a pressure regulator.

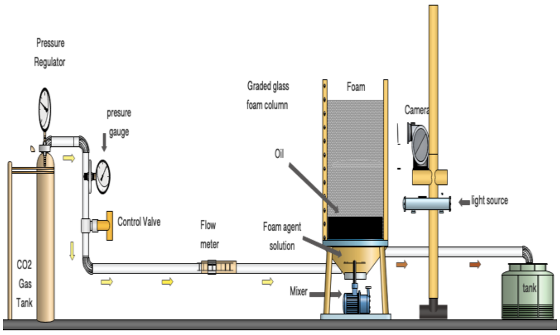


Fig. 4: Pictorial representation of the experimental set-up for oil effects on foam stability and foamability test

Two solutions were prepared and used with a constant concentration of WPI with 0.06 wt% and 0.23 wt% SDS. Different amounts of oil were applied to the surfactant solution prior to the gas usage. Many different amounts of oil have been added to the surfactant solution before it was used with gas. The amount of oil added was determined as a volume fraction of the total solution. The foam was created by sparring 100 ml of the solution tested with CO_2 at a rate of 5.0 ml/min, bypassing the porous fried acrylic tube cylinder. The influence of oil on WPI and SDS foamability and stability was studied.

RESULTS AND DISCUSSION

Surface Tension

Surface and interfacial tension are two parameters that are evaluated for surfactant performance. Fig. 2A and 2B illustrate the surface tension values for various surfactant concentrations. At initial concentrations, the surface tension value decreases dramatically. In the second section, the surface tension value has nearly reached a constant value. WPI and SDS contain hydrophilic and hydrophobic heads, which reduce the surface tension by dissolving the hydrophilic portion within the aqueous phase before the CMC and CAC points, where the surface tension does not decrease. After the CMC and CAC points, increasing the concentration results in the formation of micelles and has no effect on the reduction of surface tension.

The initial surface tension was determined to be 72.3 mN/m between deionized water and air. Figure 1A shows that the WPI of 0.06 wt% decreased surface tension to 48 mN/m. This natural surfactant critical micelle concentration reduced the surface tension from 72.3 to 48 mN/m. Figure 2B shows that the SDS concentration was reduced by 0.23 wt% to 36 mN/m (Nastaj et al. 2020, Mehrabianfar et al. 2021). The outcome shows that interfacial tension among WPI and crude oil was inferior to the estimated interfacial tension acquired among SDS and oil.

The addition (0.06 wt%) of WPI has decreased the initial interfacial tension (IFT) to about 11mN/m while the interfacial tension of SDS (0.23%) was 35.5mN/m. The monovalent and divalent ions present in the brine are the why the decrease of interfacial tension amid the oil and WPI. Exiting ions in the brine accelerate surface-active component distribution from bulk phase to interface. Brine/oil has lower interfacial tension than oil/water.

WPI surfactant was observed to reduce interfacial tension (IFT) and surface tension (ST) between water-oil and water-air measured, as shown in Figure 2. IFT has been lowered from 38 mN/m to 11 mN/m and surface tension reduced from 72.3 mN/m to 48 mN/m. This is consistent with other studies' findings (Jambrak et al. 2008, Jia et al. 2017, Kumari et al. 2019). Therefore, it could be that the interfacial tension of this surfactant possibly will be sufficiently small (11mN/m) (Zhang et al. 2014). IFT has been observed to improve significantly when compared to SDS surfactant. It was low enough to make the EOR improve (Yekeen et al. 2017, Mehrabianfar et al. 2021, Atta et al. 2021).

Critical Micelle Concentration (CMC) and Critical Aggregation Concentration (CAC)

Figure 2 is a demonstration of 19 different surfactant solutions of WPI and SDS which are analyzed to opt for the most appropriate concentration for the recovery of oil. Validating the CMC and CAC is the first step in exemplifying a surfactant. The surface tension existed with the tensiometer to verify the CMC and CAC for various surfactant solutions. This measurement shows the surfactant's ability to reduce interfacial tension and thus improve oil recovery. The surface tension of water (72.3 mN/m) was reduced in both SDS adsorption and WPI on the gas-liquid interface.

Figure 2A shows that 0.23 wt % is the optimum concentration for SDS foam stability. The result agrees with the literature-recognized critical micelle concentration (CMC) of SDS (Kawale et al. 2015, Samin et al. 2017, Pal et al. 2018). SDS molecules have a pattern formed by their polar head, and the tail group is hydrophobic. The pattern causes the surfactants to be adsorbed at the border amid polar and polar mediums.

The surfactants' polar tails reduce the solution surface tension along with an increase in surfactant concentration (Atta et al. 2021). Then till a further increase is visible, the concentrations do not influence the surface tension. The point was named critical micelle concentration. In addition, when the surfactant concentration is higher over CMC, micelles form. The hydrophobic chains of the surfactant from the center of the micelles. Subsequently, no additional surfactant molecules are adsorbed at the interface. Therefore, as the surface tension becomes almost stable, increasing the concentration of surfactants has no effect on the surface tension of water (Kawale et al. 2015, Li et al. 2020).

The highest concentration of WPI foam, 0.06 wt%, was achieved. This particular value is the protein Critical Aggregation Concentration (CAC). This result is consistent with the findings of previous studies (González-Tello et al. 2009, Samin et al. 2017). Supposedly, a micelle is formed by the protein amphipathic molecules. Protein molecules are constructed of hydrophobic and hydrophilic domains. The hydrophilic domains are depicted in the aqueous phase whilst the hydrophobic parts are secured from the aqueous phase in a protein's natural structural arrangement. Nevertheless, the protein molecule is present at the air-liquid interface of the foam reshuffles to depict in the air its hydrophobic regions and conceals hydrophilic regions. The reorganization of structure for lessening the surface energy shows how the protein unfolds at interfaces pursued by protein films or the formation of networks through intermolecular hydrogen bonding interactions (Podella et al. 2013, Olorunsola et al. 2014).

Effect of WPI Concentration on Foamability and Foam Stability

It was found from the result that the surface tension of WPI is decreased when there is an increase in WPI concentration. Likewise, foamability and foam stability were significantly increased until the Critical Aggregation Concentration was reached (CAC). The foamability stayed almost stable due to surface tension stability, and any addition of WPI concentration only increased the foam stability. CAC had a significant impact on WPI foam volume.

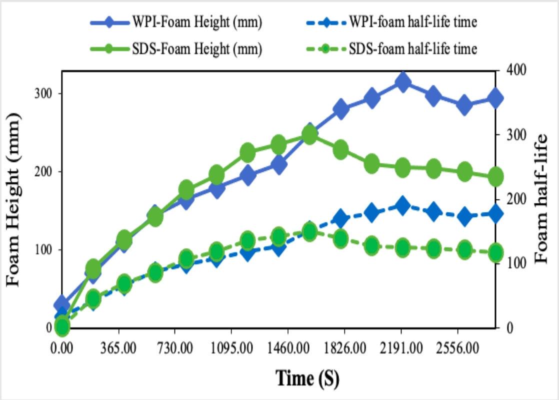


Fig. 5: SDS and WPI Foam height and Stability of the foam versus foaming agent concentration with time.

Figure 5 demonstrates the effects of WPI and SDS concentration foamability and foam stability against time. As WPI concentration increases, the foam height increases. It was discovered that the reason for reaching the highest initial foam height is because 0.06 wt%. The outcome of the surfactant concentration on foaming ability is concluded at a meticulous concentration. The movement of surfactant molecules towards the liquid-gas interface increases as more surfactant molecules become accessible. As a result, foam generation is improved (González-Tello et al. 2009, Marinova et al. 2012, Narsimhan et al. 2018). From the outcome, the foamability is proportional to the amount of WPI present. This is stated for dissimilar surfactants (Samin et al. 2017, Yekeen et al. 2017).

Generally, Figure 5 illustrates that WPI has higher foamability than the SDS, which the effect of surface tension could characterize. Note that surface tension values are reflected in the results of foam height. At 0.06 wt%, the foam has a much higher surface tension than SDS concentrations foams. The foam of WPI has much foam stability compared to SDS foam. It was monitored that WPI foam had smaller bubble sizes and thicker foam lamellae than SDS foam, which had bigger bubble sizes and thinner foam lamellae because of the disproportionate increase in the films' size. However, accelerates the drainage and shoots up the instability. The literature well supports the outcome (Kawale et al. 2015, Braun et al. 2020). The WPI foam's high stability can be attributed to the availability of the aggregates associated with affording rigid, thick viscoelastic film, which is very stable. It slows the flow of liquid, reduces bubble coalescence, and coarsens the surface of the bubbles which directs toward tremendous stable WPI foam (Kawale et al. 2015, Samin et al. 2017). Elasticity and surface tension was sufficient to increase WPI foam stability. WPI elasticity leads a film to normalize its surface tension while disturbed. The films of high elasticity are much more steady compared to the films of low elasticity (Rusanov et al. 2004, Lazidis et al. 2016, Osei-Bonsu et al. 2017).

Salt Concentration effects on Foams

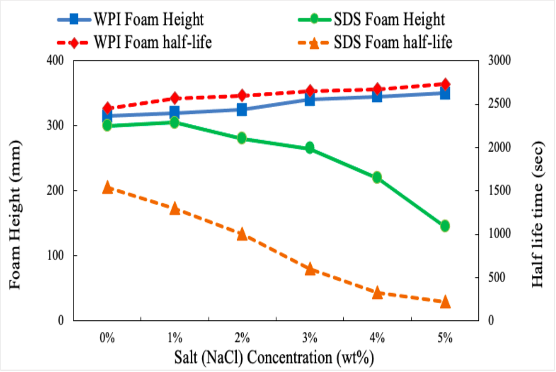


Fig. 6: The influence of NaCl on WPI and SDS foam stability and foamability

The effect of salinity is crucial in understanding the potential oil recovery. Figure 6 shows how different salinity concentrations affect foam volume and stability in WPI and SDS foams. Salinities of 1% to 5% NaCl were investigated for formability and foam stability of WPI and SDS. The surfactant concentration of WPI was 0.06 wt%, and the SDS concentration was 0.23 wt%. At 1% of salinity in both formability of WPI and SDS surfactants appears to increase as the salinity increase slightly. However, at 1% NaCl solution in SDS foam, there is a significant decrease in the initial foam stability. This may be due to the charge interactions between the negative anions in the salt and the positive cations in the surfactant. The charge imbalance can create instability and, therefore, poor initial foam (Samin et al. 2017). At low salinity concentrations, both WPI and SDS foams demonstrated improved foamability. Generally, the surface tension of a surfactant solution decreases as the concentration of NaCl in the solution increases, and water molecules' cohesion increases, thereby increasing the foamability (Li et al. 2016, Samin et al. 2017). NaCl salt concentration increases, and the surface tension decreases. Adding more salt makes the WPI foam more stable. (Behera et al. 2014, Varade et al. 2017). The reduction in surface tension and increase in salt concentration was observed and SDS micelles' surface charge was reduced. As a result, it's worth noting that salts damage stability and foam production (Obisesan et al. 2021).

When NaCl salt (2% to 5%) concentrations increase, the salt makes surface tension rise (Samin et al. 2017, Anazadehsayed et al. 2018). As a result of the salt screening the electrostatic double-layer forces, the equilibrium films were thinner (Jiang et al. 2018, Obisesan et al. 2021). As a result, the rate of foam destruction increased, while SDS stability and foamability decreased dramatically. SDS foam height and foam half-life can be easily observed to decrease with salt concentration. Similar results have been reported that salt addition to foam increases the collapse rate to destabilize the foam (Samin et al. 2017, Yekeen et al. 2018, Anazadehsayed et al. 2018). However, adding salt (2%-5%) concentration to WPI foams increases foamability and stability. WPI-stabilized foam, the electrostatic repulsion force. NaCl reduces WPI molecules adsorbed and non-adsorbed by broadcasting the charged WPI molecules. It aided in adsorption at the air-water interface and increased the foam's stability (Jambrak et al. 2008, Jia et al. 2017). The foam height and foam half-life result for WPI-stabilized foam were examined comparatively in the research still at all NaCl concentrations. When the salinity was increased, WPI foam increased (Schramm et al. 1990, Jia et al. 2017, Samin et al. 2017). Electrostatic repulsion mitigation amongst the bubble surfaces the presence of salt, which is charged, causes foam height and foam half-life. Electrostatic repulsion is reduced when salt concentrations are high. As a result, the foamability and stability of the foam have improved (Zhou et al. 2020).

Generally, NaCl concentrations increased the foam height and foam half-life of WPI Foam. At 5 % NaCl, the half-life of the conventional foam WPI-foam increased from 2566 to 2733 times, while SDS foam decreased from 1302 to 221 times.

Astonishingly, the results show increasing in WPI foam half-life. Due to the existence of salt generated inside the lamina, an electrostatic double layer (EDL). The main cause for the decreasing coalescence is the screening effect of this EDL. It stabilizes the foam for an extended period due to the development of smaller and resistant bubbles (Kumari et al. 2019, Mehrabianfar et al. 2021). This turn offers rigid packing of the liquid lamella amongst the bubbles, as clarified by Xu et al. As the solution's solubility of gas decreases with the addition of NaCl salt. Therefore, it lessens the hydrophobic interaction, and increases the foam stability limiting the rate of coalescence bubbles (Firouzi et al. 2014, Samin et al. 2017, Kumari et al. 2019).

Oil Fraction

The experiments were performed to compare the oil effect on both foaming agents WPI of 0.06 wt% and SDS of 0.23 wt%. After that, their foam properties were explored. The foam volume undergoes some damage in each case with oil, where the damage is conspicuous in SDS, as shown in Figure 7. The SDS ceased to produce foam in an oil fraction of 30%, whereas WPI prolonged to produce foam till 35%. The oil effect destabilized was further pronounced for SDS foam compared to WPI foam. For this reason WPI has a high molecular mass and randomly disseminated hydrophobic and hydrophilic groups (Muherei et al. 2009).

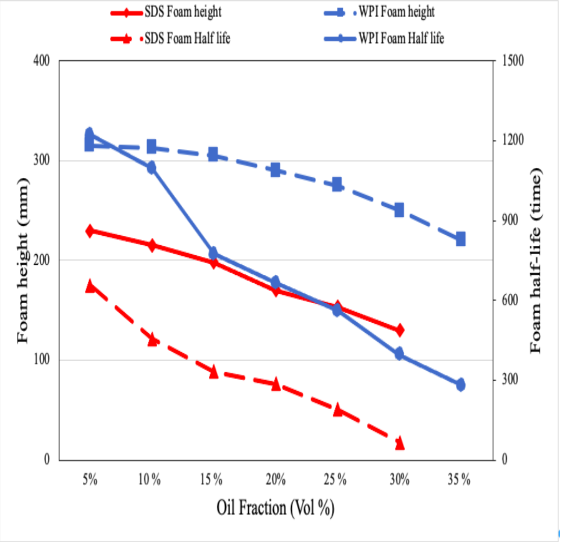


Fig. 7: Hamada oil effect on WPI and SDS foam stability and foamability

In the presence of oil, Figure 8 illustrates the decay profiles of WPI foams. In contrast, Figure 9 shows that SDS foams were damaging. The foam stability and foamability of the produced foams were lower than the crude oil. Besides, the foam half-life and the foam height decrease during the oil fraction concentration increase. Around the same time, when the crude oil amount percentage increases, the foaming agent solution's water volume percentage will fall.

Therefore, reducing gas or the volume of foam will be reduced by using liquid films (Samin et al. 2017). SDS foam stability with oil could accelerate the mass transfer in oil-sensitive foam. At the same time, the performance of the foam is extremely reliant on the properties of the oil.

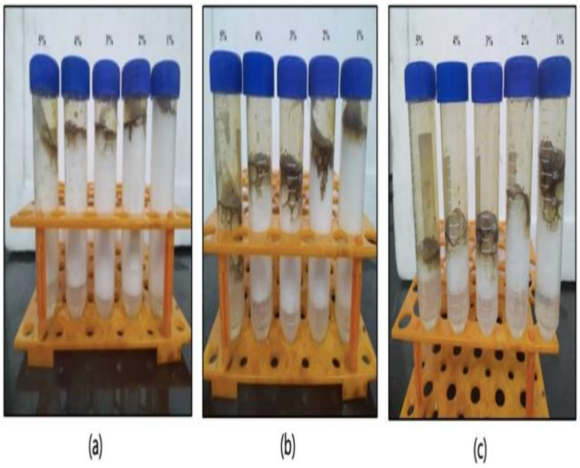


Fig. 8: Foam decay with time 0.06 wt% of WPI in the presence of oil at 25°C using DI water and NaCl. (a) The initial foam was generated at 15 min, (b) The foam after 25 min, and (c) The foam after 40 min

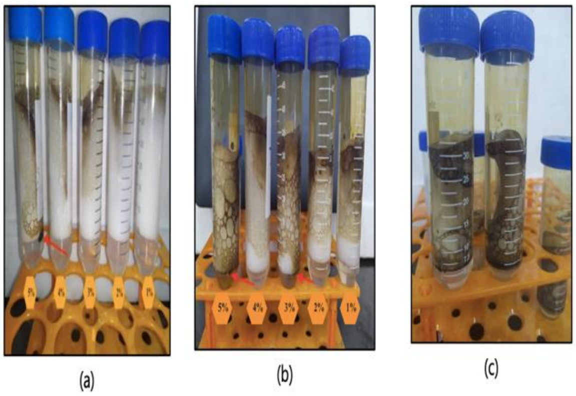


Fig. 9: Foam decay with 0.23wt% SDS in oil at 25°C. At 10 min, the first foam appeared. (b) 15 min foam, and (c) 18 min foam

The lowering viscosity of the oil used for investigation demonstrates its destabilizing effect on the foam. From this analysis, it is clear that oil can hasten the liquid drainage, causes the collapse of the film of SDS foam and lessen its foam performance (Phukan et al. 2020). SDS foam's oil-destabilizing effect was much more evident than the WPI foam. The WPI was more stable in oils than the SDS foam with its foamability and foam stability (Samin et al. 2017). Thus, this is the reason

WPI having high molecular mass and unevenly scattered hydrophobic and hydrophilic groups.

Results show that the SDS stopped making foam at 30% oil, but the WPI kept making foam until it was at 35%. For SDS foam, the destabilizing oil effect was also stronger than for foam made with the WPI method. WPI contains a large number of hydrophobic and hydrophilic groups that are distributed irregularly. The polymeric amphiphilic compounds of WPI produce thick and bendy films and are sturdily anchored into the oil-water interface in nearly all cases (see Figure 10). Moreover, WPI has both hydrophobic as well as hydrophilic areas. It is adsorbed on an oil-water line, which provides a structural hold to oil drops due to electrostatic and steric interaction (Nicorescu et al. 2008, Nicorescu et al. 2011, Samin et al. 2017). Protein in the constant phase increases the viscosity of the emulsion, lessening the mobility and dispersion of oil drops in the emulsion (Lam et al. 2013, Samin et al. 2017). WPI adsorption at the interface will generate layers of high viscoelasticity along with shear viscosities of high surface, ensuing in extremely inflexible plateau restricted boundaries and solid film (Pal et al. 2018, Alavi et al. 2021). This provides WPI foams further stability compared to SDS with the existence of oil. Based on earlier studies, the viscosity of whey protein reduces the amount of gas dispersed, resulting in smaller bubbles (Lexis et al. 2014, Audebert et al. 2019). Elasticity prevents the division of bubbles and mitigates the effect of hydrodynamic forces on bubble break-up. Due to an additional force that stabilizes bubbles against break-up, the effect of WPI elasticity appears on bubble diameter and thickness (Kawale et al. 2015, Hinderink et al. 2020, Susanti et al. 2021). Additionally, elasticity plays a positive role in because it prevents coalescence while maintaining smaller bubbles. On foaming, the elasticity of the WPI promotes bubble stabilization, which results in additional shear protection. This results in a more stable viscoelastic foam. This may result in increased foaming efficiency (Narchi et al. 2008, Audebert et al. 2019, Alavi et al. 2021).

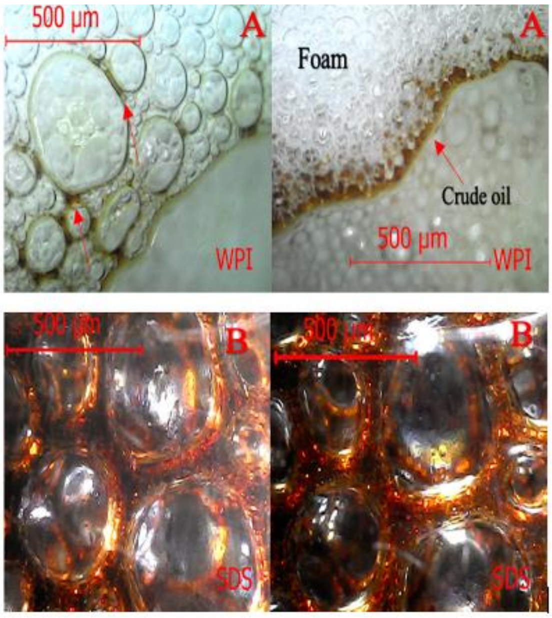


Fig. 10: (a) WPI film interface hampered the entry and spread. (b) Oil quickly enters and spreads through SDS foam lamella, destroying them.

CONCLUSIONS

WPI foam has been systematically analyzed, and it is assessed as a foaming agent for CO_2 foam to stabilize the application of enhanced oil recovery. Foam half-life at different salinities was measured experimentally with crude oil. The surface tension measurements were reduced to 48 mN/m by 0.06 wt% WPI concentration. In contrast, SDS at 0.23 wt% lowers the surface tension to 34.5 mN/m. However, 0.06 Wt% of WPI has reduced the initial interfacial tension (IFT) to roughly about 11mN/m while the interfacial tension of SDS (0.23%) was 35.5

mN/m. Static foam tests: WPI surfactant exhibited better foamability and stability than SDS surfactant. WPI with the absence of crude oil showed foam height, and foam half-life increased with increasing concentration of WPI dependent on a threshold. However, any increase in WPI will increase foam half-life and viscosity. The accretion of NaCl develops the foam stability and foamability of foams. When added (1-5%) NaCl, static WPI foaming tests had longer foam stability and more excellent formability. The foam stability of SDS was reduced, while in NaCl the foam volume stability at 1% was increased. WPI foam was less affected than SDS foam in crude oil. It is because WPI aggregates and connects to grant viscoelastic thick and stable films. Furthermore, raising the volume of crude oil significantly reduces SDS's foamability and stability as high ionic strength reduces the stability of the foam.

NOMENCLATURE

cSt : centistokes unit for kinematic viscosity
D : diameter [m]
$\mathrm{g/mol}$: grams per mole
$ASTM$: The American society for testing and materials
IP : The Institute of petroleum
UOP : universal oil products
p : pressure [Pa]
T : temperature [^{O}C]
t : time [s]
kg : a unit of force and weight [kilogram]
mm : millimetre
ml : a unit of capacity equal to one-thousandth of a liter
mN/m : a millinewton meter
$wt\%$: weight percent

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