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作品名稱　Nanoparticles and Aqueous Amine-Based Formulation to Develop CO2 Foam for Sequestration and Oil Recovery

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Nanoparticles and Aqueous Amine-Based Formulation to Develop CO_2 Foam for Sequestration and Oil Recovery

1. Introduction

Carbon dioxide (CO_2) is an important greenhouse gas that helps trap heat in our atmosphere; without it, our planet would be inhospitably cold [1]. It is the fourth most abundant gas in the Earth's atmosphere. It is a byproduct of normal cell function when breathed out of the body, and produced when fossil fuels and organic wood compounds are burned [2]. However, an increase in CO_2 concentration in the atmosphere can contribute to climate change and ocean acidification, and exposure to high levels of CO_2 can produce a variety of health effects [3]. Human progress and economic innovation have led to increased emissions, causing climate change and affecting all living creatures. Current levels are 36.8 Gt CO_2 in 2023 and are expected to reach 54-56 Gt CO_2 by 2030 [4]. Figure 1 displays the current atmospheric CO_2 measurements at Mauna Loa Observatory without seasonal variations [5].

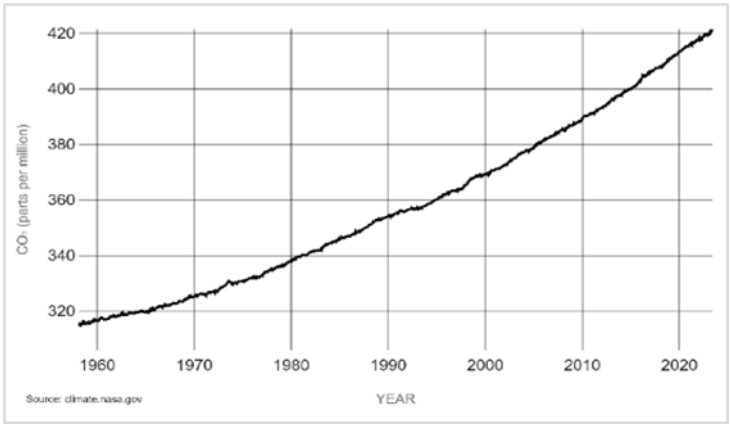


Figure 1: Current atmospheric CO_2 measurements at Mauna Loa Observatory without seasonal variations [11].

To prevent these problems, it's necessary to take measures to reduce CO_2 concentration in the environment. Carbon capture, utilization, and storage (CCUS) have emerged as a crucial strategy to mitigate CO_2 emissions, garnering considerable attention. In essence, the process of injecting CO_2 for enhanced oil recovery (EOR) is widely acknowledged as an efficacious approach to augment oil production subsequent to water flooding or pressure depletion, total EOR production is projected to reach approximately 4 million barrels per day (mb/d) by 2040 in the Sustainable Development Scenario [6]. Furthermore, this technique serves the dual purpose of sequestering substantial volumes of CO_2

within subsurface reservoirs. EOR techniques can include steam injection to improve oil flow, heat injection, chemicals, CO_2, or other gases, potentially reversing the decline of mature fields [7].

In spite of the advantages of using CO_2 in EOR, its performance can frequently be impaired by a variety of challenges, such as the low viscosity of CO_2 compared to oil, which can cause several problems with conformance and mobility, as well as instability in the displacement front resulting in premature gas breakthrough and inefficient gas utilization. Another challenge of using CO_2 in EOR is the low density of CO_2 that results in migration towards the upper part of the pay zone, this condition known as gravity override, causes more oil to be missed [8].

Foam has emerged as a promising method for EOR due to its ability to control mobility. It is garnering attention as an effective and promising approach for EOR, notably in CO_2 foam flooding, and currently, petroleum engineers are heavily focused on foam stability in order to create stable foam for EOR applications [9]. The application of nanoparticles (NPs) in EOR to enhance foam stability is an emerging field of study, with particular importance placed on their application in conjunction with CO_2 foam [10].

In this research project, surfactant and aqueous amine-based formulations stabilized with NPs will be prepared to produce CO_2 foam sequestration and EOR applications.

2. Literature review

2.1. Foam

Foam in EOR is a technique that uses foam to improve the efficiency of oil recovery from reservoirs. The main challenge in foam assisted EOR is the stability of foam during its flow in porous media [12]. CO_2 foam can be utilized to boost oil recovery in the EOR process. However, surfactant-based foam is not stable enough and has low sweep efficiency [13].

2.2. Role of surfactant

Surfactants, also called surface-active agents, exhibit a bipartite character, featuring a water-attracting (hydrophilic) head and a water-repelling (hydrophobic) tail. The hydrophilic segment might be nonionic, negatively charged (anionic), positively charged (cationic), or both positively and negatively charged (zwitterionic) [14]. Conversely, the hydrophobic section typically comprises a succinct polymer,

extended hydrocarbon, siloxane, or fluorocarbon. Central to these compounds are active moieties like sulfates, sulfonates, polyethylene oxide sequences, carboxylates, alcohols, or quaternary ammonium compounds, which dictate the surfactant's amphipathic nature and its proficiency in lowering the surface tension at the liquids and solids interface [14].

2.3. Cetyltrimethylammonium bromide

Cetyltrimethylammonium bromide (CTAB) surfactant has a cationic head and hydrocarbon tail, one of the most common and well-studied surfactants in the literature. A study was conducted to investigate the stability of foam produced by two surfactants, sodium dodecylbenzene sulfonate surfactant (SDBS) and CTAB, at varying concentrations of surfactants. The results indicated that the foam supported by CTAB exhibited greater stability compared to the tested SDBS surfactants [15]. Another study discussed the importance of CTAB in CO_2 for EOR application. These articles stated that CTAB can be used as a surfactant to improve its properties when combined with nanoparticle additives.

2.4. Sodium dodecyl sulfate

Sodium dodecyl sulfate (SDS) is one of the most used anionic alkyl sulfate surfactants. It has great surface-active properties that make it a good foaming agent. A study employed molecular dynamics simulations to investigate the behavior of CO_2 foam films containing SDS under varying conditions, including surfactant concentration, temperature, and pressure. The findings indicate that the inclusion of SDS in the CO_2 foam formulation can significantly decrease the interfacial tension between CO_2 and oil, thereby enhancing the efficacy of EOR. Additionally, the study reveals that the effectiveness of SDS as a surfactant is contingent upon its concentration, temperature, and pressure. Specifically, higher concentrations of SDS can lead to the formation of micelles, which can further reduce the interfacial tension between CO_2 and oil. However, at elevated temperatures and pressures, the stability of the foam may be compromised, thereby diminishing the effectiveness of SDS surfactant [16].

2.5. Role of diethanolamine

Diethanolamine (DEA) is a secondary alkanolamine that can react with CO_2 to produce a carbamate, which is a reversible reaction that promotes the creation of CO_2 foam. DEA's strength and stability make it an excellent choice for developing CO_2 foam for EOR. The characteristics of DEA (such as its

responsiveness and ability to form stable compounds) contribute to the efficiency and effectiveness of CO_2 foam for EOR [17].

2.6. Role of nanoparticles in foam

Nanoparticles (NPs) can be used to reinforce foam systems and improve foam mobility control for EOR applications to improve foam stability [18]. Moreover, the use of NPs can improve the efficiency of CO_2 storage and enhance foam performance [19]. One of the most promising NPs in this field is silica nanoparticles (SiO_2 NPs). SiO_2 NPs can form compact coherent particle shells at the gas-liquid interface, thus resulting in improved foam stability by resisting film deformation [20]. SiO_2 NPs-stabilized foam was found to be the most stable foam due to its thicker lamellae, which can lead to enhanced pore plugging and oil recovery [21].

3. Research Objectives

3.1. Objectives

This research project aims to develop CO_2 foam that can absorb significant quantity of CO_2 while maintaining stability and cost-efficiency to be applied in EOR. This promising concept can decrease CO_2 amounts in the atmosphere by sequestrating CO_2 in the developed foam and injecting it into reservoirs for EOR applications.

3.2. Research issues

- How can surfactants be optimized to maximize CO_2 foam production in an aqueous amine-based formulation?
- What is the role of surfactant concentration in the performance of CO_2 foam for sequestration and oil recovery?
- What is the role of diethanolamine (DEA) to enhance CO_2 uptake in the developed foam?
- How can the use of NPs affect the stability and efficiency of developed foam?

3.3. Hypothesis

This project hypothesizes that:

- Adding DEA to CTAB and SDS surfactant formulations for foam preparation will enhance the quality of sequestrated CO_2 foam by enhancing the solubility and stability of CO_2 gas in the foam for sequestration and EOR applications.
- Use of NPs in the generated amine-based CO_2 foam will enhance its stability.

3.4. Novelty

This research project simultaneously focuses on CO_2 sequestration and enhanced oil recovery using an innovative DEA-based formulation. We are developing stabilized and cost-effective foam formulations using commercial surfactants & NPs for fracking & EOR processes, which shows the novel aspects of this research.

4. Methodology

4.1. Variables

- **Independent variable:** Surfactant, NPs, DEA
- **Dependent variables:** Solubility of CO_2, Stability of CO_2 foam
- **Control Variables:** DEA amount, temperature, pressure, and foam height.

4.2. Materials

- Cetyltrimethylammonium bromide (CTAB)
- Sodium dodecyl sulfate (SDS)
- Diethanolamine (DEA)
- Silica nanoparticles (SiO_2)
- Deionized water (H_2O)
- CO_2 gas

4.3. Instrumentation

- X-Ray Diffraction (XRD)
- Scanning Electron Microscopy (SEM)
- Transmission Electron Microscopy (TEM)
- Turbiscan Formulation
- Dynamic Foam Analyzer (DFA-100)
- Ultrasonic Bath Sonicator

4.4. Experimental work

4.4.1. Sample preparation

Stock solutions of SDS (1.0 M) and CTAB (1.0 M) were prepared by dissolving one mole of each CTAB and SDS in one liter of deionized water. A bath sonicator was used to ensure thorough mixing and prevent any lumps from dissolving in the aqueous solution.

4.4.2. Addition of DEA

Three 50.0 mL aliquots of SDS stock solution were taken, and 0.1, 0.2, and 0.3 wt.% of DEA were added to them. Then, three 50.0 mL aliquots of CTAB stock solution were taken, and 0.1, 0.2, and 0.3 wt.% of DEA were added to them. The formulations were dispersed using a bath sonicator.

4.4.3. Use of dynamic foam analyzer

The dynamic foam analyzer started pumping carbon dioxide gas to generate foam sample. Then, volumetric measurements of gas and liquid were performed, generating images of the foam structure of the samples and obtaining the half-life times of the samples.

4.4.4. Use of silica NPs in CO_2 foam

At this stage, SiO_2-NPs are used in the foam to enhance its stability and efficiency. Three 50.0 mL samples were taken, and SiO_2 (7 nm) was added with 0.01, 0.005, and 0.001 wt.% concentrations. The prepared NP-based formulations were tested in the dynamic foam analyzer.

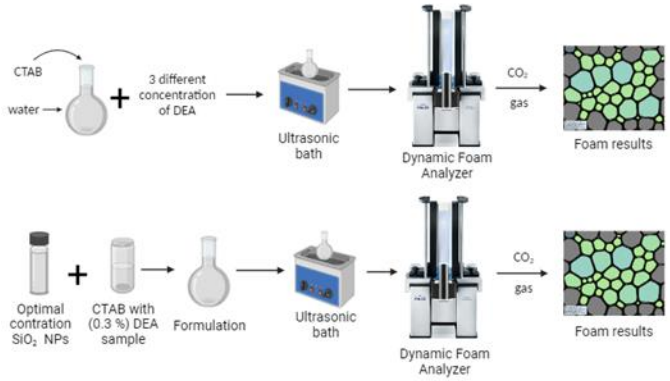


Figure 2: A straightforward methodology to prepare various formulations and generate CO_2 foam using dynamic foam analyzer.

5. Results

5.1. Characterization of Nanoparticles

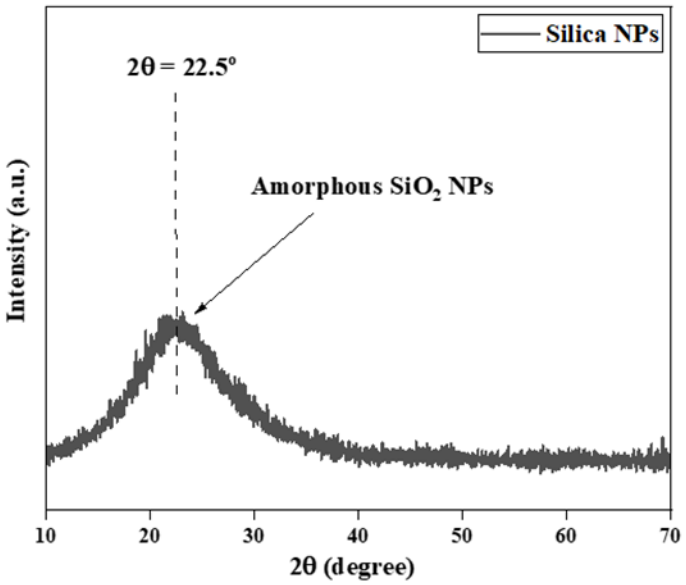


Figure 3. XRD pattern of SiO_2 NPs showing its amorphous nature.

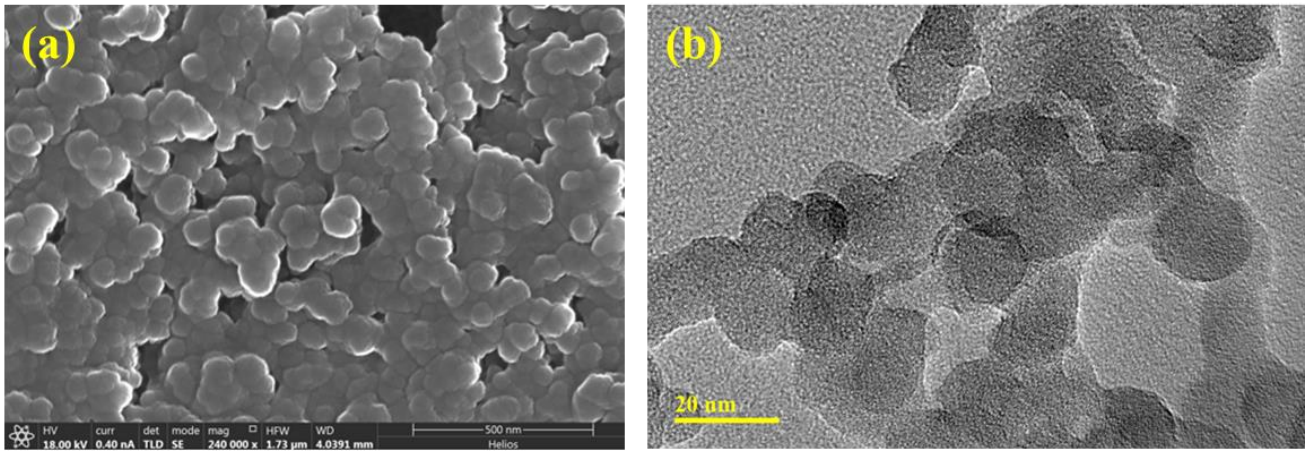


Figure 4. High-resolution (a) SEM image and (b) TEM image of SiO_2 NPs.

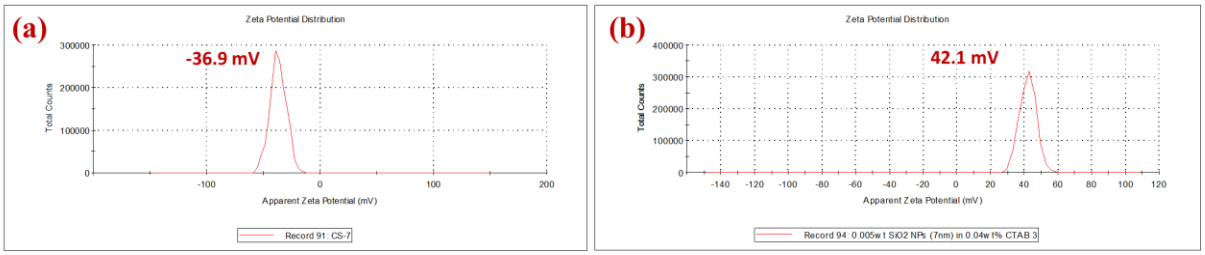


Figure 5. Zeta potential measurements of SiO_2 NPs and SiO_2+CTAB formulation.

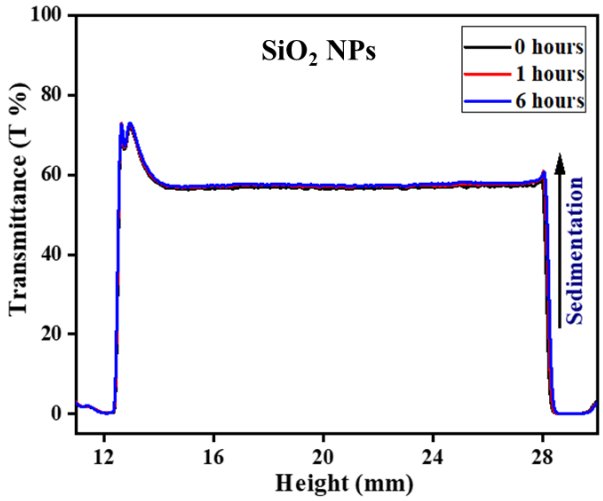


Figure 6. Time-dependent transmittance spectra of SiO_2 NPs based formulation.

5.2. Definition of Abbreviations

Table 5.1. Definition of various abbreviations	
$\mathbf{t_{max}}$	Time of maximum foam height
$\mathbf{V_{foam\ max}}$	Maximum foam volume
$\mathbf{V_{liquid\ foam\ max}}$	Liquid volume bound in the foam at t_{max}
$\mathbf{V_{total\ max}}$	Total volume at t_{max}
$\mathbf{V_{gas}}$	Gas volume used for foaming
FC	Ratio of the maximum foam volume to the gas volume used for foaming
MD	Ratio of the liquid volume in foam at t_{max} to the maximum foam volume
ER	Ratio of the maximum foam volume to the maximum liquid foam volume
$\mathbf{t_{FVS\ 50\%}}$	Foam half-life time
$\mathbf{t_{FLS\ 50\%}}$	Drainage half-life time

5.3. CTAB samples comparison

Table 5.2: (a) CTAB samples comparison with different concentrations of DEA (part 1)					
Measurement	**Method**	**V_{gas} [mL]**	**$V_{total\ max}$ [mL]**	**$V_{foam\ max}$ [mL]**	**t_{max}/t_{ref} [s]**
CTAB-DEA (0.0 wt.%)	Sparging	405.4	237.3	219.5	85.98
CTAB-DEA (0.1 wt.%)	Sparging	462.6	247	218.9	96.79
CTAB-DEA (0.2 wt.%)	Sparging	488.9	248.8	219.0	102.08
CTAB-DEA (0.3 wt.%)	Sparging	510.1	247	218.7	106.33

Table 5.2: (b) CTAB samples comparison with different concentrations of DEA (part 2)						
Measurement	**FC**	**ER**	**MD**	**$V_{liquid\ foam\ max}$ [mL]**	**$t_{FLS\ 50\%}$ [s]**	**$t_{FVS\ 50\%}$ [s]**
CTAB-DEA (0.0 wt.%)	0.5	6.8	0.1	32.2	116.5	442
CTAB-DEA (0.1 wt.%)	0.5	10	0.1	21.9	123.3	412.3
CTAB-DEA (0.2 wt.%)	0.4	10.8	0.1	20.2	126.1	395.6
CTAB-DEA (0.3 wt.%)	0.4	10.1	0.1	21.7	142.3	393.3

5.4. SDS Samples comparison

Table 5.3: (a) SDS samples comparison with different concentrations of DEA (part 1)					
Measurement	**Method**	**V_{gas} [mL]**	**$V_{total\ max}$ [mL]**	**$V_{foam\ max}$ [mL]**	**t_{max}/t_{ref} [s]**
SDS-DEA (0.0 wt.%)	Sparging	370.1	222.5	219.3	80.59
SDS-DEA (0.1 wt.%)	Sparging	408.3	226.3	218.3	85.64
SDS-DEA (0.2 wt.%)	Sparging	419.7	222	219.5	89.51
SDS-DEA (0.3 wt.%)	Sparging	430.8	222	219.5	91.22

Table 5.3: (b) SDS samples comparison with different concentrations of DEA (part 2)						
Measurement	**FC**	**ER**	**MD**	**$V_{liquid\ foam\ max}$ [mL]**	**$t_{FLS\ 50\%}$ [s]**	**$t_{FVS\ 50\%}$ [s]**
SDS-DEA (0.0 wt.%)	0.6	4.7	0.2	46.8	123.1	242.6
SDS-DEA (0.1 wt.%)	0.5	5.2	0.2	42	117.1	349.6
SDS-DEA (0.2 wt.%)	0.5	4.6	0.2	47.4	127.5	330
SDS-DEA (0.3 wt.%)	0.5	4.6	0.2	47.4	131.2	312.7

5.5. Comparison of CTAB and SDS foam stability without SiO_2 NPs

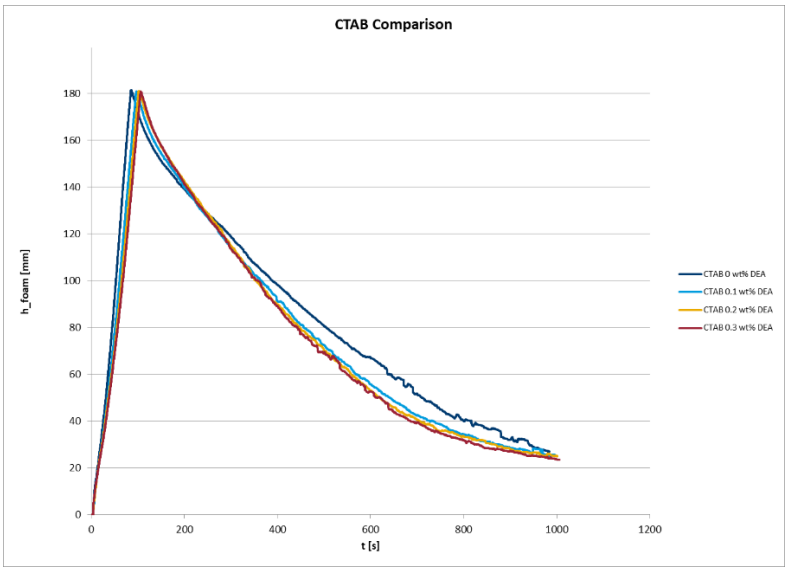


Figure 7: Comparison of CTAB foam stability with various formulations such as CTAB-DEA (0.1 wt.%), CTAB-DEA (0.2 wt.%), and CTAB-DEA (0.3 wt.%).

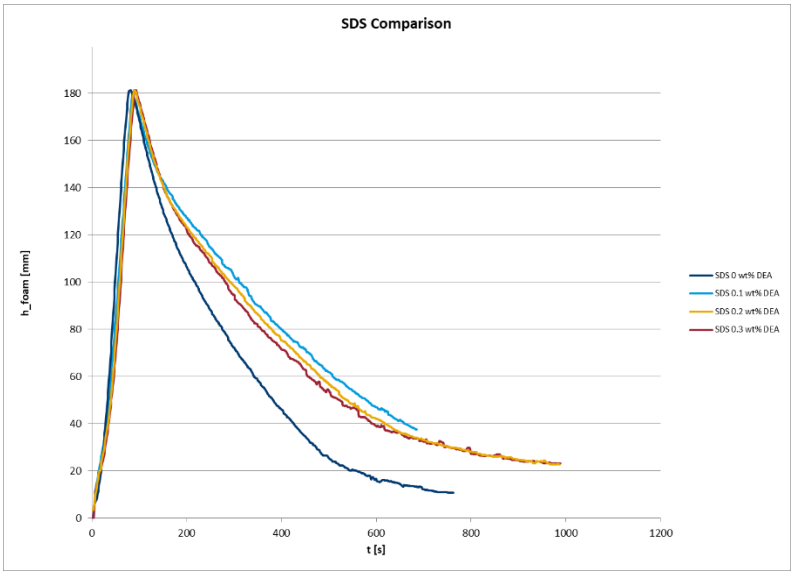
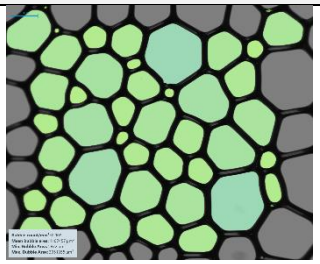
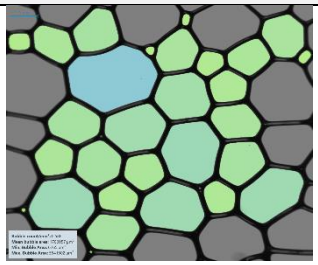
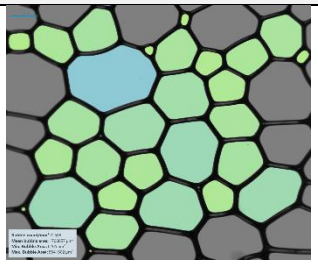
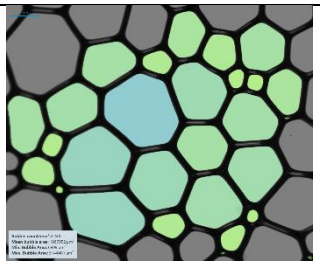
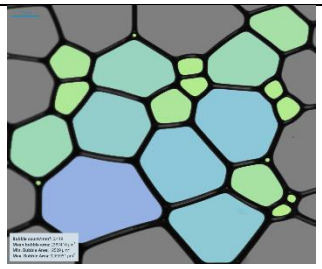
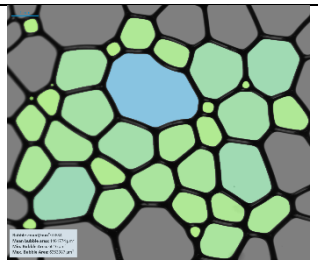
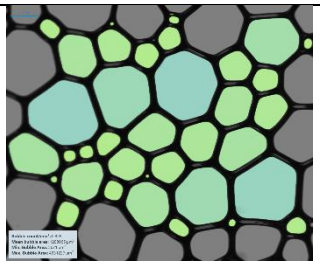
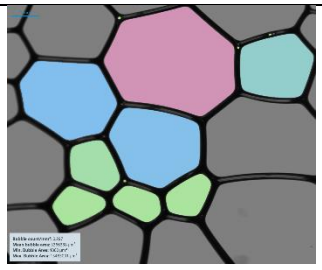
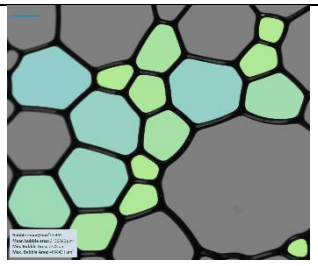
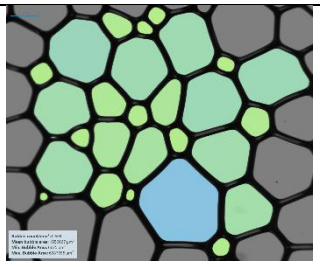
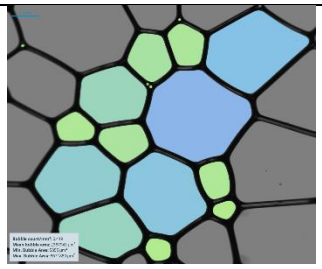
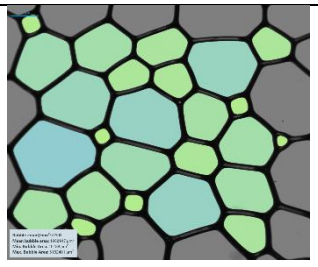


Figure 8: Comparison of SDS foam stability with various formulations such as SDS-DEA (0.1 wt.%), SDS-DEA (0.2 wt.%), and SDS-DEA (0.3 wt.%).

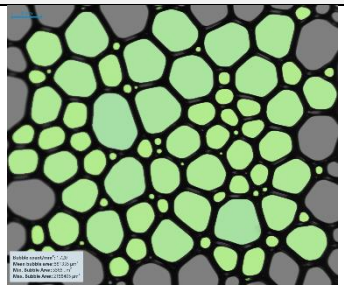
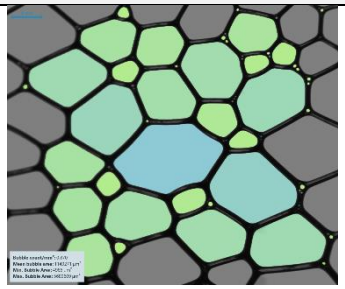
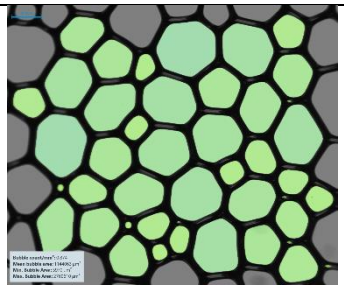
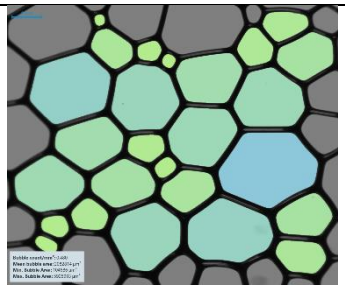
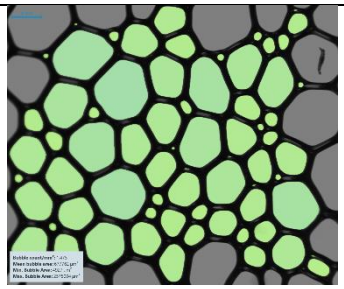
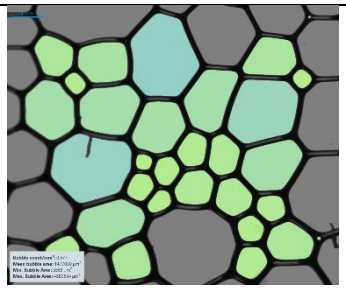
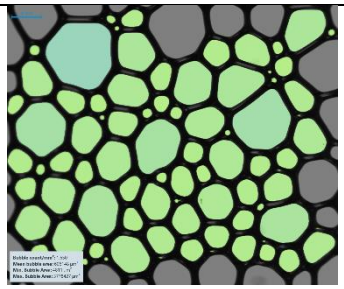
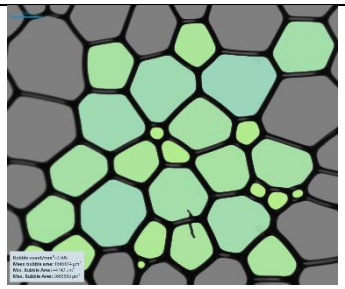
5.6. CTAB Foam structure

Table 5.4. CTAB foam structure with different DEA concentrations at various time intervals.

Measurement	Foam structure at 200s	Foam structure at 400s	Foam structure at 600s
CTAB-DEA (0.0 wt.%)			
CTAB-DEA (0.1 wt.%)			
CTAB-DEA (0.2 wt.%)			
CTAB-DEA (0.3 wt.%)			

5.7. SDS Foam structure

Table 5.5. SDS foam structure with different DEA concentrations at various time intervals.

Measurement	Foam structure at 200s	Foam structure at 400s
SDS-DEA (0.0 wt.%)		
SDS-DEA (0.1 wt.%)		
SDS-DEA (0.2 wt.%)		
SDS-DEA (0.3 wt.%)		

5.8. Comparison of Produced Foam Statistics at 400s

Table 5.6. Various parameters such as bubble count and bubble area.

CTAB	Statistics at 400s	SDS	Statistics at 400s
CTAB-DEA (0.0 wt.%)	**Bubble count/mm²:** 0.300 **Mean bubble area:** 3329023 µm² **Min. Bubble Area:** 5445 µm² **Max. Bubble Area:** 10143825 µm²	SDS-DEA (0 wt.%)	**Bubble count/mm²:** 0.870 **Mean bubble area:** 1149271 µm² **Min. Bubble Area:** 4985 µm² **Max. Bubble Area:** 5689609 µm²
CTAB-DEA (0.1 wt.%)	**Bubble count/mm²:** 0.419 **Mean bubble area:** 2387410 µm² **Min. Bubble Area:** 12589 µm² **Max. Bubble Area:** 9265951 µm²	SDS-DEA (0.1 wt.%)	**Bubble count/mm²:** 0.480 **Mean bubble area:** 2082814 µm² **Min. Bubble Area:** 104686 µm² **Max. Bubble Area:** 5925993 µm²
CTAB-DEA (0.2 wt.%)	**Bubble count/mm²:** 0.297 **Mean bubble area:** 3366388 µm² **Min. Bubble Area:** 4860 µm² **Max. Bubble Area:** 13483001 µm²	SDS-DEA (0.2 wt.%)	**Bubble count/mm²:** 0.677 **Mean bubble area:** 1477030 µm² **Min. Bubble Area:** 5565 µm² **Max. Bubble Area:** 4580554 µm²
CTAB-DEA (0.3 wt.%)	**Bubble count/mm²:** 0.419 **Mean bubble area:** 2387943 µm² **Min. Bubble Area:** 5855 µm² **Max. Bubble Area:** 8671880 µm²	SDS-DEA (0.3 wt.%)	**Bubble count/mm²:** 0.608 **Mean bubble area:** 1645614 µm² **Min. Bubble Area:** 44749 µm² **Max. Bubble Area:** 3665568 µm²

5.9. CTAB with SiO_2 NPs comparison

Table 5.7: (a) CTAB samples comparison with different concentrations of NPs (Part 1)

Measurement	Method	V_{gas} [mL]	$V_{total\ max}$ [mL]	$V_{foam\ max}$ [mL]	t_{max}/t_{ref} [s]
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.0 wt.%)	Sparging	510.1	247	218.7	106.33
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.001 wt.%)	Sparging	528.4	249.1	218.6	109.53
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.005 wt.%)	Sparging	535.8	252.0	218.7	110.95
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.010 wt.%)	Sparging	525.0	251.4	219	109.3

Table 5.7: (b) CTAB samples comparison with different concentrations of NPs (Part 2)

Measurement	FC	ER	MD	$V_{liquid\ foam\ max}$ [mL]	$t_{FLS\ 50\%}$ [s]	$t_{FVS\ 50\%}$ [s]
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.0 wt.%)	0.4	10.1	0.1	21.7	142.3	393.3
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.001 wt.%)	0.4	11.2	0.1	19.4	139.5	430.5
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.005 wt.%)	0.4	13.1	0.1	16.7	147.9	416.9
CTAB-DEA (0.3 wt.%) + SiO_2 NPs (0.010 wt.%)	0.4	12.4	0.1	17.6	145.8	453.3

6. Discussion

6.1. Interpretation of silica nanoparticles

The crystal structure, phase, and purity of SiO_2 NPs were examined by X-ray diffraction (XRD) analysis. Figure 3 exhibits XRD pattern of powdered SiO_2 NPs, having a hexagonal crystal structure. The amorphous nature of SiO_2 NPs was confirmed by a broad diffraction peak at 2θ position ~22.5º (JCPDS No., 00-001-0649) (Khan et al., 2019; Rehman et al., 2019). Moreover, no further peaks were found in the XRD pattern showing the high purity of SiO_2 NPs.

The surface morphology, particle size, and aggregation behaviour of SiO_2 NPs were examined via scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Figure 4(a) exhibits the high-resolution SEM image of SiO_2 NPs. It was observed that silica NPs are spherical and homogenous, with some aggregation due to the presence of attractive forces between silica particles. Figure 4(b) exhibits a TEM image of spherical-shaped SiO_2 NPs with an average diameter of ~12 nm.

Zeta potential can significantly affect the properties of foamed suspensions. Positioning more NPs at the gas-liquid interface increases the surface tension and, in turn, increases the bubble strength of the produced foam. Considering the importance of silica NPs' surface charge and their interaction with CTAB surfactant, zeta potential values of SiO_2 NPs and SiO_2+CTAB formulation were recorded (Figure 5). The results reveal that SiO_2 NPs are negatively charged, having a zeta potential value of -36.9 mV. Meanwhile, the SiO_2+CTAB formulation shows positively charged micelles with a zeta potential value of 42.1 mV. The comparison indicates that SiO_2+CTAB formulation further improves the stability of SiO_2 NPs in the aqueous system.

The dispersion stability of NP-based formulations is crucial to developing stable drilling fluids. Therefore, the dispersion stability of SiO_2 NPs was investigated in the CTAB solution by measuring the percent transmittance intensity. Figure 6 exhibits the transmittance (T%) spectra of SiO_2-based formulation. It can be seen that there is no change in transmittance intensity even after six hours, and no sedimentation behavior is observed during the measurement. The sedimentation rate depends on various factors, including particle size, density, and the fluid's viscosity. The comparison indicates that SiO_2 NPs (~12 nm) can produce a more stable formulation and would be a promising material for CO_2 foam stabilization.

6.2. CO_2 dissolution

Various abbreviations and terminologies used in foam stabilization studies are defined in Table 5.1. The addition of DEA to the CTAB formulation has a positive impact on CO_2 dissolution. Before adding DEA, the gas volume was 405.4 mL. However, after adding DEA, the gas volume increased to 462.6 mL for CTAB-DEA (0.1 wt.%), 488.9 mL for CTAB-DEA (0.2 wt.%), and 510.1 mL for CTAB-DEA (0.3 wt.%) [Table 5.2(a)]. The addition of DEA to SDS formulation has a positive impact on CO_2 dissolution. Before adding DEA, the gas volume was 370.1 mL. However, after adding DEA, the gas volume increased to 408.3 mL for SDS containing 0.1 wt.% DEA, 419.7 mL for SDS-DEA (0.2 wt.%), and 430.8 mL for SDS-DEA (0.3 wt.%) [Table 5.3(a)].

The optimal concentration of DEA is (0.3 wt. %) for CTAB-based formulation. Similarly, the optimal concentration of DEA is (0.3 wt. %) for SDS-based formulation [Table 5.2a-5.3a].

6.2. Foam Stability

The addition of DEA to the CTAB formulation has a negative impact on CO_2 foam stability. Before adding DEA, the foam half-life time was 442.0s, but after adding DEA, the foam half-life time decreased to 412.3s for CTAB-DEA (0.1 wt.%), 395.6s for CTAB-DEA (0.2 wt.%), and 393.3s for CTAB-DEA (0.3 wt.%) [Table 5.2(b)]. On the other hand, adding DEA to the SDS formulation initially has a positive impact on the stability of CO_2 foam. Before adding DEA, the foam half-life was 242.6s; after adding DEA, the foam half-life time increased to 349.6s for SDS containing 0.1 wt.% DEA. Then, the foam half-life time decreased to 330.0s for SDS-DEA (0.2 wt.%) and 312.7s for SDS-DEA (0.3 wt.%) [Table 5.3(b)]. The decrease in foam half-life time upon addition of DEA is due to increased CO_2 gas pressure, which ruptures the lamella phases of bubbles quickly. In order to increase CO_2 foam stability, further optimization is required. Therefore, we decided to use NPs in the formulation to increase the foam's stability.

6.3. Foam structure and statistics at 400s

The CO_2 foam structures with different DEA concentrations at various time intervals are provided in Table 5.4 (CTAB) and Table 5.5 (SDS). The addition of DEA to the CTAB formulation impacted the bubble count. Before adding DEA, the bubble count for CTAB was $0.300/mm^2$; the bubble count

increased to 0.419/mm^2 for 0.1 wt.% DEA. After adding 0.2 wt.% DEA, the bubble count decreased to 0.297/mm^2. After adding 0.3 wt.% DEA, the bubble count increased to 4.19 /mm^2 [Table 5.6]. The addition of DEA to the SDS formulation has a negative impact on the bubble count. Before adding DEA, the bubble count for SDS was 0.870/mm^2. The bubble count decreased to 0.480/mm^2 for SDS with 0.1 wt.% DEA. After adding 0.2 wt.% DEA, the bubble count increased to 0.677/mm^2. After adding 0.3 wt.% DEA, the bubble count decreased to 0.607/mm^2 for SDS [Table 5.6].
The comparison indicates that CTAB is a more promising surfactant than SDS surfactant while preparing the CO_2-based formulation using DEA.

6.4. Foam stability and capability after adding SiO_2 NPs

The addition of SiO_2 NPs to the formulation has a positive impact on CO_2 foam stability. Before adding NPs to the optimal concentration of DEA (0.3 wt.% DEA), the foam half-life time was (393.3s), then after adding SiO_2 NPs (0.001 wt.%), the stability increased to (430.5s), then decreased to (416.9s) for (0.005 wt% NPs), followed by increased to (453.3s) for 0.01 wt.% SiO_2 NPs [Table 5.7(a)].

Regarding CO_2 dissolution, adding SiO_2 NPs to the formulation has a positive impact. Before adding SiO_2 NPs, the maximum gas volume was 510.1 mL at the optimal concentration of DEA (0.3 wt.%). After adding SiO_2 NPs, the gas volume increased to (528.4 mL) for (0.001 wt% NPs), then rose to (535.8 mL) for 0.005 wt.% NPs, followed by a decrease to (525.0 mL) for 0.01 wt.% NPs [Table 5.7(b)].

Overall, the optimal concentration is [CTAB + DEA (0.3 wt.%) + SiO_2 NPs (0.01 wt.%)] because it has more balanced formulation to produce in stable CO_2 foam having maximum gas volume.

7. Conclusion and future work

This research project studied the effect of using NPs and an aqueous amine-based formulation to produce CO_2 foam for sequestration and EOR applications. Different samples were prepared with varying concentrations of CTAB and SDS surfactants in the presence of DEA and SiO_2 NPs to obtain the optimal formulation of CO_2 foam with better foam structure, longer half-life, and more gas volume sequestrated in the foam, which makes the foam more efficient for CO_2 sequestration and EOR.

When comparing the role of CTAB and SDS in the foam formulation, the CTAB-based formulation having (0.3 wt.% DEA with 0.01 wt.% SiO_2 NPs) created a larger volume of sequestrated gas and a more stable foam structure. *The comparison indicates that 30% increase in CO_2 sequestration using innovative optimized DEA-based formulation having SiO_2 NPs.*

The work is based on experiments to obtain the optimal formulation of foam, and more tests at HTHP will be conducted to prove the project objectives. This research project constitutes a promising solution to the world's most critical environmental problems in our current era and the coming eras. We expect further progress in solving these problems by continuing research and experiments in CO_2 foam sequestration and EOR.

8. References

[1] Ritchie, H., & Roser, M. (2020). CO2 emissions. Our World in Data. https://ourworldindata.org/co2-emissions

[2] Wisconsin Department of Health Services. (2018, January 2). Carbon Dioxide. Wisconsin Department of Health Services. https://www.dhs.wisconsin.gov/chemical/carbondioxide.htm

[3] Carbon Dioxide - an overview | ScienceDirect Topics. (n.d.). Www.sciencedirect.com. Retrieved January 17, 2021, from https://www.sciencedirect.com/topics/earth-and-planetary-sciences/carbon-dioxide

[4] Yu, D., Soh, W., Amin Noordin, B. A., Dato Haji Yahya, M. H., & Latif, B. (2022). The impact of innovation on CO2 emissions: The threshold effect of financial development. Frontiers in Environmental Science, 10. https://doi.org/10.3389/fenvs.2022.980267

[5] NASA. (2023). Carbon Dioxide Concentration | NASA Global Climate Change. Climate Change: Vital Signs of the Planet; NASA. https://climate.nasa.gov/vital-signs/carbon-dioxide/

[6] McGlade, C., Sondak, G., & Han, M. (2018, November 28). Whatever happened to enhanced oil recovery? – Analysis. IEA. https://www.iea.org/commentaries/whatever-happened-to-enhanced-oil-recovery

[7] Abdelaal, A., Gajbhiye, R., & Al-Shehri, D. (2020). Mixed CO2/N2 Foam for EOR as a Novel Solution for Supercritical CO2 Foam Challenges in Sandstone Reservoirs. ACS Omega, 5(51), 33140–33150. https://doi.org/10.1021/acsomega.0c04801

[8] Valluri, S., Claremboux, V., & Kawatra, S. (2022). Opportunities and challenges in CO2 utilization. Journal of Environmental Sciences, 113, 322–344. https://doi.org/10.1016/j.jes.2021.05.043

[9] Bhatt, S., Saraf, S., & Bera, A. (2023). Perspectives of Foam Generation Techniques and Future Directions of Nanoparticle-Stabilized CO2 Foam for Enhanced Oil Recovery. Energy & Fuels, 37(3), 1472–1494. https://doi.org/10.1021/acs.energyfuels.2c02988

[10] Ahmadi, A., Abbas Khaksar Manshad, Kolo, K., Iglauer, S., S. Mohammad Sajadi, Keshavarz, A., & Mohammadi, A. H. (2022). Insight into Nano-chemical Enhanced Oil Recovery from Carbonate Reservoirs Using Environmentally Friendly Nanomaterials. ACS Omega, 7(41), 36165–36174. https://doi.org/10.1021/acsomega.2c03076

[11] NASA. (2023). Carbon Dioxide Concentration | NASA Global Climate Change. Climate Change: Vital Signs of the Planet; NASA. https://climate.nasa.gov/vital-signs/carbon-dioxide/

[12] Majeed, T., Kamal, M. S., Zhou, X., & Solling, T. (2021). A Review on Foam Stabilizers for Enhanced Oil Recovery. Energy & Fuels, 35(7), 5594–5612. https://doi.org/10.1021/acs.energyfuels.1c00035

[13] Bhatt, S., Saraf, S., & Bera, A. (2023). Perspectives of Foam Generation Techniques and Future Directions of Nanoparticle-Stabilized CO2 Foam for Enhanced Oil Recovery. Energy & Fuels, 37(3), 1472–1494. https://doi.org/10.1021/acs.energyfuels.2c02988

[14] Massarweh, O., & Abushaikha, A. S. (2020). The use of surfactants in enhanced oil recovery: A review of recent advances. Energy Reports, 6, 3150–3178. https://doi.org/10.1016/j.egyr.2020.11.009

[15] K. Kirtivardhan, & Abhijit Kakati. (2023). Surfactant Selection for Foam Generation: Implications for CO2 Geo-Sequestration. https://doi.org/10.2118/214231-ms

[16] Fan, C., Jia, J., Peng, B., Liang, Y., Li, J., & Liu, S. (2020). Molecular Dynamics Study on CO2 Foam Films with Sodium Dodecyl Sulfate: Effects of Surfactant Concentration, Temperature, and Pressure on the Interfacial Tension. Energy & Fuels, 34(7), 8562–8574. https://doi.org/10.1021/acs.energyfuels.0c00965

[17] Clark, J. A., & Santiso, E. E. (2018). Carbon Sequestration through CO2 Foam-Enhanced Oil Recovery: A Green Chemistry Perspective. Engineering, 4(3), 336–342. https://doi.org/10.1016/j.eng.2018.05.006

[18] Briceño-Ahumada, Z., Soltero-Martínez, J. F. A., & Castillo, R. (2021). Aqueous foams and emulsions stabilized by mixtures of silica nanoparticles and surfactants: A state-of-the-art review. Chemical Engineering Journal Advances, 7, 100116. https://doi.org/10.1016/j.ceja.2021.100116

[19] Srivastava, A., Qiao, W., Wu, Y., Li, X., Bao, L., & Liu, C. (2017). Effects of silica nanoparticles and polymers on foam stability with sodium dodecylbenzene sulfonate in water–liquid paraffin oil emulsions at high temperatures. Journal of Molecular Liquids, 241, 1069–1078. https://doi.org/10.1016/j.molliq.2017.06.096

[20] Chen, J., Huang, X., He, L., & Luo, X. (2019). Foaming of Oils: Effect of Poly(dimethylsiloxanes) and Silica Nanoparticles. ACS Omega, 4(4), 6502–6510. https://doi.org/10.1021/acsomega.9b00347

[21] Fan, C., Jia, J., Peng, B., Liang, Y., Li, J., & Liu, S. (2020). Molecular Dynamics Study on CO2 Foam Films with Sodium Dodecyl Sulfate: Effects of Surfactant Concentration, Temperature, and Pressure on the Interfacial Tension. Energy & Fuels, 34(7), 8562–8574. https://doi.org/10.1021/acs.energyfuels.0c00965

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The study explores the use of amine-based, SiO_2 nanoparticle (NP)-incorporated foams as an advanced method for enhanced oil recovery (EOR) and CO_2 sequestration. These foams are designed to reduce the mobility of injected gaseous phases, improving the efficiency of the process. Future research should address key issues, such as modifying nanoparticles by examining the effects of surface groups and hydrophobicity. This could involve incorporating various functional groups or long-chain molecules under different conditions to optimize performance.