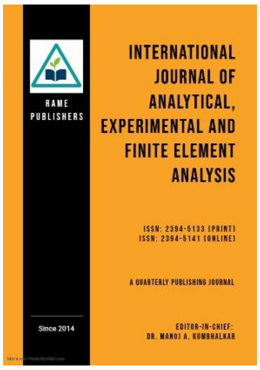
International Journal of Analytical, Experimental and Finite Element Analysis
Volume 13, Issue 3, August 2026, pp 118-138
https://doi.org/10.26706/ijaefea.13.3.20260802

Techno-Economic Analysis of CO_2-Soluble Surfactants for Enhanced Oil Recovery (EOR) and Carbon Dioxide (CO_2) Sequestration in Carbonate Reservoirs

Sajjad Ali Azeez



Department of Petroleum Engineering, College of Engineering, Al-Hikma University, Baghdad, Iraq

Correspondence: Sagad20062000@gmail.com

Abstract- Economic analysis of the application of CO_2-soluble surfactants in carbon dioxide enhanced oil recovery (CO_2-EOR) and carbon capture, utilization, and storage (CCUS) demonstrates that this technology not only improves reservoir technical performance but also offers significant potential to enhance the profitability of oil projects while reducing environmental **costs.** This study evaluated the major economic components, including capital expenditure (CAPEX), operational expenditure (OPEX), revenues generated from incremental oil production and carbon credits, engineering economic indicators, sensitivity analysis, and cost-reduction strategies. The results indicate that the project CAPEX is approximately USD 60 million**,** while the annual OPEX is approximately USD 13 million, primarily associated with CO_2 injection facilities, compressors, transmission pipelines, surfactant procurement, and gas compression operations. The economic assessment further reveals that the application of CO_2-soluble surfactants increases the oil recovery factor by 8%, generates 12 million barrels of incremental oil production, enables the geological storage of 5 million tonnes of CO_2**,** and produces total revenues of approximately USD 1.09 billion**,** consisting of USD 840 million from additional oil production and USD 250 million from carbon credits. Moreover, the key economic indicators—including a Net Present Value (NPV) **of** USD 320 million, an Internal Rate of Return (IRR) of 23%, a Benefit-to-Cost (B/C) ratio of 2.4, a payback period of 5.2 years, an incremental oil production cost of USD 14 per barrel, and a CO_2 storage cost of USD 22 per tonnedemonstrate the economic viability of this technology under the base-case scenario. Sensitivity analysis identified crude oil price, surfactant price, CO_2 supply and transportation costs, discount rate, incremental oil production, and carbon credit value as the most influential parameters affecting project profitability. Increasing the oil price from USD 50 to USD 90 per barrel raises the NPV from USD 95 million to USD 545 million and the IRR from 13% to 33%, whereas increases in surfactant or CO_2 costs reduce project profitability. Furthermore, the development of low-cost surfactants, the implementation of hybrid surfactant systems, surfactant recycling, optimization of injection concentration, intelligent reservoir management, and optimized injection pattern design can reduce operational costs by up to 18% while increasing the NPV by approximately 10%**.** Overall, the findings indicate that despite moderate increases in capital and operating expenditures, the application of CO_2-soluble surfactants represents a competitive approach for the development of carbonate reservoirs by increasing oil production, improving CO_2 utilization efficiency, reducing the cost of incremental oil production, generating additional revenue through carbon credits, and enhancing overall economic performance. Nevertheless, reducing surfactant production costs, developing stable carbon markets, conducting pilot-scale studies, and implementing intelligent reservoir management technologies remain essential prerequisites for improving the commercial viability and facilitating the large-scale industrial deployment of this technology in the future

Keywords: CO_2-enhanced oil recovery (CO_2-EOR), CO_2-philic fluorine-free surfactants, Economic evaluation, Discounted cash flow (DCF), Net present value (NPV), Carbonate reservoirs, Sensitivity analysis.

Article – Peer Reviewed
Received: 30 May 2026
Accepted: 10 August 2026
Published: 24 August 2026

Cite this article: Sajjad Ali Azeez, “Techno-Economic Analysis of CO_2-Soluble Surfactants for Enhanced Oil Recovery (EOR) and Carbon Dioxide (CO_2) Sequestration in Carbonate Reservoirs”, *International Journal of Analytical, Experimental and Finite Element Analysis*, RAME Publishers, vol. 13, issue 3, pp. 118-138, 2026.
https://doi.org/10.26706/ijaefea.13.3.20260802

1. Introduction

The continuous growth in global energy demand, increasing consumption of fossil fuels, and escalating concerns over climate change have intensified the need for technologies capable of simultaneously ensuring energy security and mitigating greenhouse gas emissions. Carbon dioxide (CO_2), the predominant greenhouse gas generated by industrial activities, is a major contributor to climate change, and reducing its emissions has become a central objective of energy and environmental policies over recent decades. In this context, Carbon Capture, Utilization and Storage (CCUS) has emerged as one of the most promising strategies for mitigating carbon emissions. Integrating CCUS with CO_2-enhanced oil recovery (CO_2-EOR) represents a synergistic approach that not only enhances oil production from mature reservoirs but also enables the long-term geological sequestration of CO_2. Consequently, this integrated technology has the potential to play a pivotal role in facilitating the transition of the oil and gas industry toward a low-carbon future (Bui et al., 2018; IEA, 2020; Global CCS Institute, 2024).

Carbonate reservoirs, which account for a substantial proportion of the world's petroleum reserves, are of particular importance in enhanced oil recovery (EOR) research. However, their complex characteristics—including pronounced heterogeneity, the presence of natural fractures, significant variations in porosity and permeability, complex wettability behavior, and multiphase rock–fluid interactions—make the prediction of gas injection performance particularly challenging. Under such conditions, improving sweep efficiency and controlling CO_2 mobility within the porous medium are among the most critical challenges in reservoir engineering. Consequently, CO_2 mobility-control techniques, such as foam injection, water-alternating-gas (WAG) injection, and the application of surfactants, have attracted considerable attention.

Among these approaches, surfactant-stabilized foams have emerged as an effective strategy for controlling CO_2 mobility. By reducing interfacial tension, altering rock wettability, enhancing foam-film stability, and decreasing the relative permeability of CO_2, surfactants increase the apparent viscosity of the gas phase and reduce the CO_2/oil mobility ratio. As a result, the injected CO_2 is distributed more uniformly throughout the reservoir rather than preferentially channeling through high-permeability pathways, thereby improving contact with the remaining oil. This mechanism enhances sweep efficiency, delays CO_2 breakthrough, and increases ultimate oil recovery. Recent studies have demonstrated that foams formulated with CO_2-compatible surfactants can substantially improve gas mobility control and enhance the efficiency of CO_2-EOR processes.

Nevertheless, conventional surfactants, which are primarily designed for aqueous environments, often exhibit limited performance under harsh reservoir conditions, including elevated pressure and temperature, high formation-water salinity, and the presence of hydrocarbons. These limitations include reduced stability, excessive adsorption onto rock surfaces, and poor injectivity. Consequently, the development of CO_2-soluble or CO_2-philic surfactants has attracted increasing attention as a new generation of surface-active agents. Owing to their molecular structures specifically tailored for compatibility with the CO_2 phase, these surfactants exhibit superior performance under supercritical CO_2 conditions and can effectively control CO_2 mobility without requiring large volumes of the aqueous phase. Recent research has focused on the development of fluorine-free, nonionic surfactants incorporating CO_2-philic functional groups to maintain technical performance while reducing production costs and minimizing environmental concerns.

Despite significant advances in the development of CO_2-philic surfactants, economic uncertainty remains one of the primary barriers to their large-scale industrial implementation. The incremental oil recovery achieved through surfactant-assisted CO_2 injection must be sufficient to offset the additional costs associated with surfactant production and supply, injection facilities, CO_2 capture, transportation and compression, reservoir monitoring, and the long-term management of geological carbon storage. Therefore, evaluating the technical performance of these surfactants alone is insufficient for industrial decision-making. A comprehensive assessment of their economic viability using established financial metrics, including Discounted Cash Flow (DCF) analysis, Net Present Value (NPV), Internal Rate of Return (IRR), and sensitivity analysis, is essential.

The economic performance of CO_2-EOR/CCUS projects is governed by numerous interrelated factors. Among the most influential are crude oil price, surfactant cost, CO_2 supply and compression costs, discount rate, incremental oil production, the volume of permanently stored CO_2, and the market value of carbon credits. Previous studies have demonstrated that although higher oil prices and stronger carbon markets can substantially improve the economic feasibility of these projects, chemical costs and uncertainties associated with reservoir performance remain major obstacles to the commercialization of advanced CO_2-EOR technologies.

Accordingly, a significant research gap exists in the lack of integrated studies that quantitatively evaluate the relationship between the technical performance of CO_2-soluble surfactants, incremental oil recovery, CO_2 storage capacity, and the resulting economic outcomes. Most previous investigations have primarily focused on the physicochemical properties of surfactants or their laboratory-scale performance, whereas the successful translation of laboratory findings to field-scale applications requires an integrated techno-economic assessment.

In the present study, a discounted cash flow (DCF)-based economic assessment was conducted to evaluate the application of immiscible CO_2 injection in conjunction with fluorine-free, CO_2-philic nonionic surfactants, namely C4(PO)6 and C41H83O19, in carbonate reservoirs. The primary objective of this study was to quantify the economic impact of enhanced oil recovery resulting from wettability alteration, interfacial tension reduction, and improved CO_2 mobility control on the economic performance of CO_2-enhanced oil recovery (CO_2-EOR) projects. Within this framework, the effects of incremental oil production, surfactant consumption cost, CO_2 supply cost, and other key economic parameters on project profitability were systematically evaluated to identify the conditions required for the economically viable and sustainable implementation of this technology.

2. Theoretical Background

Enhanced oil recovery (EOR) encompasses a range of advanced technologies designed to increase oil recovery beyond that achieved through primary and secondary production processes. Among the various EOR techniques, carbon dioxide-enhanced oil recovery (CO_2-EOR) has emerged as one of the most effective methods due to its ability to reduce crude oil viscosity, induce oil swelling, lower interfacial tension, and improve the miscibility between the injected fluid and reservoir oil. Under appropriate pressure and temperature conditions, CO_2 enters a supercritical state, exhibiting the combined properties of liquids and gases, which enables high penetration and mobility within the porous reservoir medium. These characteristics enhance oil displacement efficiency while simultaneously facilitating the long-term geological sequestration of CO_2. Consequently, CO_2-EOR is recognized not only as an effective technique for increasing oil production but also as a key component of Carbon Capture, Utilization and Storage (CCUS) strategies.

Despite its significant advantages, the application of CO_2-EOR in carbonate reservoirs is associated with several technical challenges. Carbonate reservoirs exhibit complex flow behavior due to their pronounced heterogeneity, extensive natural fracture networks, wide variations in porosity and permeability, and predominantly oil-wet wettability characteristics. The high mobility contrast between CO_2 and reservoir oil often leads to unfavorable displacement phenomena such as viscous fingering, gas channeling, and poor volumetric sweep efficiency. Consequently, a considerable portion of the remaining oil becomes trapped within low-permeability zones or isolated pore spaces, limiting the overall recovery factor. These challenges have driven the development of CO_2 mobility-control technologies as a major research focus in the field of enhanced oil recovery.

In this context, CO_2-soluble surfactants have emerged as a new generation of surface-active agents that play a pivotal role in enhancing the performance of CO_2 injection processes. These surfactants are specifically designed to dissolve in supercritical CO_2 while simultaneously reducing the interfacial tension among the oil, water, and gas phases and promoting the formation of stable foams that reduce the mobility ratio of the injected gas. Foam generation increases the flow resistance of CO_2 within the porous medium, suppresses preferential gas flow through high-permeability channels, and promotes a more uniform distribution of the injected fluid throughout the reservoir. In addition, certain surfactants are capable of altering reservoir rock wettability from oil-wet toward water-wet conditions, thereby reducing capillary forces, mobilizing trapped oil, and improving displacement efficiency. Consequently, the performance of CO_2-soluble surfactants is governed by a combination of synergistic physicochemical mechanisms that collectively enhance both the oil recovery factor and the efficiency of geological CO_2 storage.

From an economic perspective, the application of CO_2-soluble surfactants requires a balance between the additional costs associated with chemical utilization and the economic benefits derived from improved reservoir performance. Capital expenditures (CAPEX) include injection facilities, surfactant preparation and mixing units, CO_2 compression equipment, and reservoir monitoring systems. Operating expenditures (OPEX), on the other hand, comprise surfactant procurement, CO_2 supply and transportation, operational and maintenance costs, as well as process monitoring expenses. These additional expenditures are offset by several economic benefits, including increased cumulative oil production, a reduced gas–oil ratio (GOR), improved sweep efficiency, lower CO_2 requirements to achieve production targets, and potential revenues generated through carbon credit markets. Accordingly, the economic evaluation of CO_2-soluble surfactants is typically based on financial performance indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), Benefit–Cost (B/C) ratio, and sensitivity analysis to quantify the effects of key variables—including crude oil price, surfactant cost, CO_2 supply cost, and the economic value of carbon sequestration—on overall project profitability.

Accordingly, the theoretical framework of this study is based on the premise that the application of CO_2-soluble surfactants, through improved CO_2 mobility control, reduced interfacial tension, wettability alteration, and enhanced sweep efficiency, not only improves the technical performance of CO_2-enhanced oil recovery but also increases the amount of permanently sequestered CO_2 in carbonate reservoirs. Furthermore, when capital and operating costs are effectively managed, this technology has the potential to substantially improve the economic feasibility of integrated CO_2-EOR and geological carbon storage projects.

3. Research Significance

The gradual decline in production from mature oil reservoirs, increasing global energy demand, and growing environmental concerns associated with greenhouse gas emissions have highlighted the necessity of developing technologies capable of simultaneously enhancing oil production and reducing carbon dioxide emissions. In this regard, carbon dioxide injection for enhanced oil recovery (CO_2-EOR) is recognized as one of the most effective EOR techniques, as it not only improves oil recovery factors but also enables long-term CO_2 storage within geological formations. However, the effectiveness of this technology in carbonate reservoirs is significantly constrained by complex reservoir characteristics, including severe heterogeneity, natural fractures, predominantly oil-wet conditions, and the substantial mobility contrast between CO_2 and reservoir oil. These limitations result in poor sweep efficiency and increased volumes of residual oil remaining trapped within the reservoir.

One promising approach to overcoming these limitations is the application of CO_2-soluble surfactants, which can enhance oil displacement efficiency and CO_2 storage capacity through mechanisms such as interfacial tension reduction, stable foam generation, gas mobility control, and wettability alteration. Despite the demonstrated technical advantages of this technology in laboratory investigations and several field-scale applications, the relatively high cost of surfactant production and consumption, process design complexity, and economic uncertainties—particularly in carbonate reservoirs—remain major challenges for its industrial-scale implementation.

Furthermore, the expansion of global carbon mitigation policies, the development of carbon credit markets, and the transition of the oil industry toward low-carbon technologies have increased the economic and strategic importance of integrated carbon storage and enhanced oil recovery projects (CCUS-EOR). Under such circumstances, investment decisions regarding these projects require a comprehensive understanding of the relationship between capital and operating expenditures, incremental oil production, the amount of permanently stored CO_2, and key economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period.

Considering the significant contribution of carbonate reservoirs to global petroleum reserves and their importance in major oil-producing regions, conducting a comprehensive investigation into the economic assessment of CO_2-soluble surfactant applications can bridge the existing gap between technical performance evaluations and economic decision-making. The outcomes of this research can provide a framework for the economic evaluation of this emerging technology and support the optimization of EOR strategies, reduction of investment risks, improvement of oil field productivity, and advancement of carbon emission management policies by researchers, petroleum companies, and energy policymakers.

4. Components of Economic Analysis

Economic analysis is one of the most critical stages in the evaluation of emerging technologies in the oil and gas industry, aiming to determine financial feasibility, reduce investment risks, and identify the most optimal field development strategy. In enhanced oil recovery projects utilizing CO_2-soluble surfactants, economic analysis is not limited merely to the comparison of costs and revenues; rather, it involves an integrated framework that considers a combination of technical, economic, and environmental parameters.

Since this technology not only enhances oil recovery but also enables long-term geological storage of carbon dioxide, its economic evaluation should account for both the benefits associated with incremental oil production and the economic value derived from carbon emission reductions. Within this framework, project costs are generally categorized into two main groups: capital expenditures (CAPEX) and operating expenditures (OPEX). The combination of these costs provides the basis for developing the project cash flow model and calculating key economic indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), Benefit–Cost (B/C) ratio, marginal cost of incremental oil production per barrel, and Payback Period.

4.1. Capital Expenditures (CAPEX)

Capital expenditures (CAPEX) include all expenses incurred prior to the commencement of operations for the design, construction, installation, and commissioning of the infrastructure required for project implementation. These costs are characterized by their long-term nature and are typically paid only once at the beginning of the project; however, their impacts persist throughout the economic life of the field. In CO_2 injection projects assisted by surfactants, CAPEX constitutes a significant portion of the initial investment and plays a decisive role in investment decision-making.

The first major component of CAPEX is CO_2 injection facilities, which include high-pressure compressors, injection pumps, injection wells, control valves, wellhead equipment, pressure control systems, and preliminary processing units. Since CO_2 must be injected at pressures above its critical pressure (approximately 7.38 MPa), the design and construction of these facilities require compliance with specific technical and safety standards. Compressor capacity, energy efficiency, equipment resistance to CO_2-induced corrosion, and the reliability of injection systems are among the primary factors governing the capital costs associated with this component.

The second major component is the surfactant preparation and mixing unit. This facility comprises chemical storage tanks, mixing systems, dosing equipment, chemical injection pumps, concentration control systems, and solution transfer facilities. The efficient operation of this unit is essential for achieving stable foam generation, controlling CO_2 mobility, and minimizing surfactant losses. The design of this section must consider factors such as surfactant chemical stability, compatibility with supercritical CO_2, and operational performance under reservoir temperature and pressure conditions.

Reservoir monitoring and management systems also represent a significant portion of capital expenditures. These systems include pressure and temperature sensors, downhole data acquisition equipment, four-dimensional seismic monitoring (4D Seismic), fluid sampling facilities, CO_2 leakage monitoring systems, and reservoir simulation software. The implementation of such technologies enables continuous evaluation of process performance, optimization of injection strategies, and assurance of safe and effective CO_2 storage.

Other CAPEX components include transportation pipelines and surface facilities, such as CO_2 transmission pipelines, pressure booster stations, storage tanks, processing facilities, separation units, safety systems, power supply infrastructure, instrumentation equipment, and centralized control systems. The contribution of these components to the initial investment depends on factors including the distance between the CO_2 source and the oil field, transportation capacity, geographical conditions, geological characteristics, and environmental requirements. In many CCUS projects, transportation infrastructure and surface facilities represent one of the largest components of the initial capital investment.

Table 1. Capital Expenditures (CAPEX)

Component	Cost (Million USD)	Share (%)
CO_2 Injection Facilities	18	30
Compressors and Pumps	12	20
Surfactant Preparation Unit	6	10
CO_2 Pipelines and Surface Facilities	15	25
Monitoring and Control Systems	9	15
Total CAPEX	60	100

4.2. Operational Expenditures (OPEX)

Operational expenditures (OPEX) encompass all costs incurred after project start-up and throughout the operational period to maintain system performance. Unlike CAPEX, these expenses are directly dependent on production rates, injection volumes, operational duration, and field conditions, and they constitute a significant contribution to the final cost of incremental oil production.

Surfactant procurement is generally considered the largest component of OPEX in this technology. CO_2-soluble surfactants, particularly fluorinated and silicone-based formulations, involve complex manufacturing processes and are associated with relatively high costs. The required amount of surfactant depends on reservoir volume, optimum injection concentration, rock and fluid properties, formation water salinity, and injection duration. Therefore, selecting a surfactant with high performance and the minimum effective concentration is one of the most critical factors for reducing operational costs and improving project profitability.

CO_2 compression and transportation costs represent another major component of OPEX. Significant energy consumption is required to compress CO_2 for transportation and injection under supercritical conditions. These costs are influenced by energy prices, compressor efficiency, transportation distance, reservoir pressure, and injection rate. In many projects, compressor energy consumption accounts for more than half of the CO_2-related operating costs. Therefore, improving energy efficiency and implementing heat recovery strategies can have a substantial impact on reducing operational expenditures.

Injection and production operation costs include expenses associated with specialized personnel, energy consumption, consumable materials, technical services, process control, well management, and implementation of injection programs. These costs vary depending on the number of wells, injection duration, production rate, and operational complexity, and they directly affect the annual project cash flow.

Equipment maintenance and repair costs include periodic inspections, preventive maintenance, replacement of deteriorated components, pipeline corrosion control, compressor servicing, instrumentation maintenance, and control system management. Considering the corrosive nature of CO_2 in the presence of water, the application of corrosion-resistant materials and implementation of preventive maintenance programs are essential for extending equipment lifetime and minimizing unplanned operational downtime.

The final component of OPEX is reservoir monitoring, evaluation, and management costs, which include fluid sampling, petrophysical analyses, CO_2 behavior monitoring, dynamic reservoir modeling, process simulation, production data analysis, and assessment of the amount of stored carbon dioxide. Although these activities increase operational expenditures, they play a crucial role in improving economic performance and reducing investment risks by providing accurate information for process optimization, uncertainty reduction, and prevention of project failure.

Overall, the economic structure of projects involving CO_2-soluble surfactants is governed by the interaction among capital expenditures, operational expenditures, revenues generated from incremental oil production, and benefits associated with geological CO_2 storage. Therefore, comprehensive evaluation of these components and sensitivity analysis with respect to key variables, including oil price, surfactant cost, CO_2 supply cost, discount rate, and carbon credit value, provide the fundamental basis for determining the economic feasibility of deploying this technology in carbonate reservoirs.

Table 2. Annual Operating Expenditures (OPEX)

Component	Cost (Million USD/year)	Share (%)
Surfactant Purchase	5	38.5
CO_2 Supply and Transportation	3.5	26.9
Energy and Compression	2	15.4
Maintenance	1.5	11.5
Reservoir Monitoring and Management	1	7.7
Total OPEX	13	100

5. Economic Advantages

The application of CO_2-soluble surfactants in enhanced oil recovery processes provides not only improvements in reservoir performance indicators but also significant economic implications at the project, oil field, and broader energy and environmental policy levels. In integrated enhanced oil recovery and geological carbon storage projects, economic performance is not solely governed by incremental oil production; rather, it is influenced by the interaction among enhanced recovery factors, reduced operational costs, optimized CO_2 utilization, mitigation of environmental risks, and the generation of additional revenues from carbon markets.

In other words, CO_2-soluble surfactants can transform the project cash flow structure by improving the technical efficiency of the recovery process. Through increased revenues and cost reductions, these surfactants contribute to the enhancement of key economic indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), Benefit–Cost Ratio (B/C), Payback Period, and the marginal cost of incremental oil production.

Table 3. Economic Benefits of the Project

Parameter	Value
Incremental Oil Recovery	8%
Incremental Oil Production	12 Million barrels
Oil Revenue (70 USD/bbl)	840 Million USD

CO_2 Stored	5 Million tonnes
Carbon Credit Revenue (50 USD/tCO_2)	250 Million USD
Total Revenue	1,090 Million USD

5.1. Increase in Cumulative Oil Production and Operating Revenues

The primary economic advantage of applying CO_2-soluble surfactants is the enhancement of cumulative oil production and, consequently, the increase in revenue generated from oil sales. In conventional CO_2 injection processes, the significant mobility contrast between gas and oil promotes preferential flow pathways, early gas breakthrough, and reduced volumetric sweep efficiency. As a result, a considerable fraction of the remaining oil remains trapped in low-permeability regions or within small pore spaces of the rock matrix. CO_2-soluble surfactants mitigate these limitations through foam generation, interfacial tension reduction, and wettability alteration, leading to a more uniform distribution of the injected fluid, improved microscopic and macroscopic displacement efficiency, and ultimately an increased recovery factor.

From an engineering economic perspective, even a 1–3% increase in recovery factor in large carbonate reservoirs can represent millions of additional barrels of oil, with an economic value several times greater than the cost of surfactant procurement. The increase in cumulative oil production also enhances annual cash flow, improves investment return rates, and increases the overall economic value of the reservoir. This advantage is particularly significant in mature fields with limited development opportunities, as increasing production from existing infrastructure generally requires substantially lower costs compared with the development of new fields.

5.2. Improvement of CO_2 Utilization Efficiency and Reduction of Injection Cycle Costs

One of the most important indicators for evaluating the economic performance of CO_2-EOR projects is carbon dioxide utilization efficiency, which is typically assessed based on the amount of oil produced per ton of injected or stored CO_2. CO_2-soluble surfactants improve gas mobility control, delay premature breakthrough of the injected phase, and enhance contact between CO_2 and reservoir oil, thereby reducing the amount of CO_2 required to achieve a specific production target.

This improvement has significant economic implications because the costs associated with CO_2 separation, purification, compression, transportation, storage, and injection represent a substantial portion of total project expenditures. Any reduction in CO_2 consumption or enhancement of CO_2 utilization efficiency can decrease the marginal cost of oil production and improve overall project profitability. Furthermore, reducing the volume of circulating CO_2 can lower equipment degradation, energy consumption, and maintenance requirements, thereby increasing the reliability and operational stability of CO_2 injection systems.

5.3. Reduction of Gas–Oil Ratio and Improvement of Surface Facility Efficiency

Another significant economic benefit of this technology is the reduction of the gas–oil ratio (GOR). In many CO_2 injection projects, early gas breakthrough leads to increased costs associated with gas separation, recovery, recompression, and reinjection. Foam generation induced by surfactants reduces CO_2 mobility within the porous medium and prevents the development of preferential high-permeability flow channels. Consequently, the amount of produced gas relative to oil decreases, resulting in improved performance of surface processing facilities.

A lower GOR reduces energy consumption in processing units, decreases the required compressor capacity, extends the operational lifetime of surface equipment, and lowers operating costs. From an economic perspective, these improvements reduce the cost of oil production and enhance the profit margin of the project.

5.4. Extension of Field Economic Life and Improvement of Capital Efficiency

One of the significant outcomes of increasing the recovery factor is the extension of the economic life of oil fields. When oil production can be maintained at economically viable levels for a longer period, greater utilization of existing infrastructure becomes possible, allowing the initial investment to be depreciated over an extended operational timeframe. This leads to a reduction in capital cost per unit of produced oil and improves overall investment efficiency.

Extending field life also reduces the need for premature development of new oil fields, which is highly significant from a macroeconomic energy perspective. The development of new fields generally requires substantial capital investment, involves considerable technical risks, and requires a long period to achieve economically viable production. Therefore, enhancing recovery from existing fields can represent one of the most economically attractive strategies for increasing long-term oil supply.

5.5. Reduction of Environmental Costs and Enhancement of Economic Value through Carbon Management

In recent years, costs associated with greenhouse gas emissions have become a significant component of energy project economics. The implementation of policies such as carbon taxes, emission trading systems, and environmental regulations has resulted in carbon emission reductions acquiring direct economic value. The application of CO_2-soluble surfactants can enhance the efficiency of geological CO_2 storage by reducing the likelihood of CO_2 re-migration to the surface and increasing the amount of permanently sequestered carbon within the geological formation.

This improvement can reduce costs associated with carbon taxes, environmental penalties, mitigation measures, and regulatory compliance requirements. Furthermore, the implementation of low-carbon projects can enhance companies' positions in environmental, social, and governance (ESG) assessments, improve access to green financing, and reduce risks associated with future environmental regulatory changes. Collectively, these factors provide substantial long-term economic benefits.

5.6. Revenue Generation from Carbon Credit Markets

The expansion of carbon credit markets represents one of the most significant economic developments in the energy sector over the past decade. In many countries, projects capable of storing a verifiable amount of CO_2 in geological formations are eligible to receive carbon credits or financial incentives. These credits can be traded in domestic and international markets and may serve as an independent revenue stream in addition to income generated from oil production.

In projects involving CO_2-soluble surfactants, enhanced foam stability and improved sweep efficiency increase the amount of CO_2 permanently retained within the reservoir; consequently, the economic value derived from carbon credits is also increased. In many economic assessments, revenue generated from carbon credits plays a decisive role in achieving a positive Net Present Value (NPV) and reducing the payback period, particularly under conditions of fluctuating oil prices or high CO_2 supply costs.

5.7. Reduction of Economic Risk and Enhancement of Investment Sustainability

Another important economic advantage of this technology is the reduction of investment risk. Improving injection process efficiency, enhancing reservoir performance predictability, reducing uncertainty in oil recovery potential, and increasing confidence in CO_2 storage security can contribute to lower fluctuations in project cash flows. This, in turn, reduces the cost of capital, enhances project attractiveness for investors, and facilitates access to financing through financial institutions and investment funds.

Overall, the application of CO_2-soluble surfactants not only increases oil production but also significantly enhances the economic value of CO_2-EOR and carbon storage projects through improved CO_2 utilization efficiency, reduced operational costs, extended field economic life, lower environmental compliance costs, additional revenues from carbon credit markets, and reduced investment risks. Therefore, a comprehensive assessment of these advantages should be considered as a fundamental component of economic feasibility studies for the design and development of CO_2-EOR projects in carbonate reservoirs.

6. Economic Evaluation Indicators

Economic evaluation is an integral component of feasibility studies for enhanced oil recovery and geological carbon dioxide storage projects, playing a decisive role in investment decision-making, technology selection, and oil field development planning. Although the technical performance of CO_2-soluble surfactant-based technologies can be assessed through indicators such as increased recovery factor, improved sweep efficiency, and enhanced CO_2 retention, industrial implementation of these technologies requires that the associated economic benefits compensate for the capital and operational expenditures throughout the project life cycle.

Accordingly, the economic assessment of this technology is conducted based on discounted cash flow analysis, the time value of money concept, cost–benefit analysis, risk assessment, and sensitivity analysis. Within this framework, all capital expenditures (CAPEX), operational expenditures (OPEX), revenues generated from incremental oil production, benefits associated with geological CO_2 storage, economic incentives related to carbon emission reductions, and the opportunity cost of capital are evaluated using engineering economic indicators.

These indicators not only quantify project profitability but also assess the capability of the project to generate sustainable cash flows, recover initial investments, and withstand economic uncertainties arising from fluctuations in oil prices, CO_2 costs, and surfactant prices. The most commonly applied indicators for the economic evaluation of this technology include Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), Benefit–Cost (B/C) ratio, cost of incremental oil production per barrel, and the cost of CO_2 storage per ton.

Table 4. Economic Evaluation Indicators

Indicator	Value
Net Present Value (NPV)	320 Million USD
Internal Rate of Return (IRR)	23%
Payback Period	5.2 years
Benefit–Cost Ratio (B/C)	2.4
Incremental Oil Production Cost	14 USD/bbl
CO_2 Storage Cost	22 USD/tCO_2

6.1. Net Present Value (NPV)

Net Present Value (NPV) is considered the most reliable and comprehensive indicator in engineering economics for evaluating investment projects. This indicator is determined by calculating the difference between the present value of a project's cash inflows and the present value of its cash outflows, considering the discount rate, and represents the economic value generated for the investor.

The theoretical basis of NPV relies on the principle that the value of money changes over time; therefore, a monetary unit available today has a higher value than the same amount received in the future due to its potential for investment and return generation.

In projects involving CO_2-soluble surfactants, cash inflows include revenues generated from incremental oil production, reductions in operational expenditures, savings resulting from improved CO_2 utilization efficiency, revenues obtained from carbon credit markets, and other associated economic benefits. On the other hand, cash outflows include initial capital investments for facility construction, surfactant procurement costs, expenses related to CO_2 supply, transportation and compression, energy consumption, repair and maintenance operations, reservoir monitoring, and potential environmental costs.

A positive NPV indicates that the present value of project benefits exceeds the present value of project costs, meaning that implementation of the project increases the investor's wealth. The higher the NPV value, the greater the economic attractiveness of the project. Since NPV simultaneously incorporates all project cash flows, the time value of money, and the cost of capital, it is regarded as the most appropriate criterion for comparing different CO_2 injection scenarios, selecting suitable surfactant types, and defining reservoir development strategies.

6.2. Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is defined as the discount rate at which the Net Present Value (NPV) of a project becomes zero and represents the maximum rate of return generated by an investment. This indicator demonstrates the project's capability to generate profit relative to the initial investment and is commonly compared with the cost of capital or the minimum acceptable rate of return.

In CO_2-EOR projects, improvements in oil recovery efficiency, enhanced CO_2 utilization performance, reductions in operational costs, and the generation of revenues from carbon credit markets increase annual cash flows and consequently improve the project's internal rate of return. If the IRR exceeds the cost of capital, the project is considered economically viable.

The main advantage of IRR is its ability to facilitate comparison among projects with different investment scales. However, in projects involving unconventional or multi-stage cash flow patterns, IRR interpretation should be performed in conjunction with NPV analysis to ensure more accurate investment decisions.

6.3. Payback Period

The Payback Period is defined as the time required for the cumulative cash flows generated by a project to recover the initial investment. This indicator is one of the simplest tools for investment risk assessment and represents the rate at which the initial capital can be recovered.

In projects involving CO_2-soluble surfactants, although the initial costs associated with equipment installation and chemical procurement may be relatively high, the increase in oil production and the resulting revenues can significantly reduce the payback period. A shorter payback period indicates lower economic risk, greater financial flexibility, and enhanced project attractiveness for investors, particularly under conditions of significant oil price volatility.

However, this indicator, in its conventional form, does not consider cash flows generated after the recovery of the initial investment or the time value of money. Therefore, its application should be complemented by discounted cash flow-based economic indicators to achieve a more comprehensive evaluation.

6.4. Benefit–Cost Ratio (B/C)

The Benefit–Cost Ratio (B/C) is one of the important indicators in economic analysis, calculated as the ratio of the present value of project benefits to the present value of project costs. This indicator represents the economic benefit generated per unit of investment and, therefore, serves as an appropriate criterion for evaluating the efficiency of resource allocation.

In CO_2-soluble surfactant projects, the benefits include increased oil production, extension of field economic life, reduction of operational costs, mitigation of environmental costs, improved CO_2 utilization efficiency, and revenues generated from carbon credits. In contrast, the associated costs comprise initial capital investment, chemical procurement, injection operations, equipment maintenance, and reservoir monitoring expenditures.

A B/C ratio greater than one indicates that the project is economically feasible, and a higher ratio reflects greater economic efficiency of the investment. This indicator is particularly useful for comparing alternative projects and prioritizing investment options.

6.5. Incremental Oil Production Cost

In enhanced oil recovery projects, an increase in oil production alone is not a sufficient criterion for economic evaluation; rather, it is necessary to determine the cost at which this additional production is achieved. The incremental oil production cost is calculated by dividing the total capital and operational expenditures of the project by the additional oil produced compared with the base-case scenario. This indicator reflects the economic efficiency of a technology in converting investment into incremental production.

This parameter enables direct comparison among different enhanced oil recovery technologies, including water injection, gas injection, polymer flooding, alkaline–surfactant–polymer (ASP) flooding, nanofluid applications, and CO_2-soluble surfactant-based methods. A reduction in this indicator represents improved economic efficiency of the applied technology.

If the incremental oil production cost is lower than the profit margin obtained from oil sales, the project can be considered economically feasible. Therefore, this indicator is one of the key decision-making criteria for selecting the most suitable technology for the development of mature reservoirs.

6.6. Cost of CO_2 Storage

With the development of Carbon Capture, Utilization, and Storage (CCUS) technologies, the cost of storing each ton of CO_2 has become one of the key indicators in carbon economics. This indicator represents the total cost required for the capture, transportation, compression, injection, monitoring, and permanent immobilization of each ton of carbon dioxide within a geological formation.

In CO_2-EOR projects, the application of CO_2-soluble surfactants enhances gas–reservoir contact efficiency, reduces gas migration and leakage, improves CO_2 retention, and increases the amount of permanently stored carbon dioxide. Consequently, the average cost of CO_2 storage per ton can be reduced.

This indicator plays a crucial role in evaluating the competitiveness of CCUS projects, determining eligibility for financial incentives, assessing carbon credit revenues, and supporting carbon pricing policies. Furthermore, comparison of this parameter among different projects provides a fundamental basis for investment allocation decisions in greenhouse gas emission reduction initiatives.

7. Economic Sensitivity Analysis of the Project

Sensitivity analysis is one of the fundamental components of economic feasibility studies for complex and capital-intensive oil and gas projects. It is performed to evaluate the extent to which existing uncertainties influence the economic performance of a project. In projects involving CO_2-soluble surfactants for enhanced oil recovery and carbon dioxide storage in carbonate reservoirs, economic decision-making is influenced by a wide range of technical, economic, and environmental variables. Variations in each of these parameters can significantly affect project profitability, investment risk, and the commercial viability of the technology.

Since these projects involve substantial initial investments, long operational periods, dependence on global energy prices, and direct interactions with climate policies, economic evaluations that neglect uncertainties associated with key parameters may result in unrealistic investment decisions.

Sensitivity analysis evaluates variations in economic indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, incremental oil production cost, and CO_2 storage cost per ton, in response to changes in input parameters. This analysis identifies the economic vulnerability or resilience of the project, enables the recognition of critical variables, supports the prioritization of risk mitigation strategies, and determines the threshold conditions required for achieving economic feasibility.

In surfactant-assisted CO_2-EOR projects, the most influential parameters affecting project economics include global oil price, surfactant cost, CO_2 supply and transportation costs, discount rate, volume of incremental oil production, amount of stored CO_2, and carbon credit price.

Table 5. Sensitivity Analysis: Effect of Oil Price

Oil Price (USD/bbl)	NPV (Million USD)	IRR (%)
50	95	13
60	205	18
70	320	23
80	430	28
90	545	33

7.1. Effect of Global Oil Price on Project Economic Feasibility

Global oil price is considered the most important revenue-related factor in enhanced oil recovery projects, as a major portion of the project's positive cash flow is generated from the sale of additional oil production. Variations in oil prices directly influence the economic value of incremental oil, annual revenues, and ultimately key economic indicators such as NPV and IRR.

Under conditions of increasing oil prices, the value of each produced barrel rises, and the additional revenue generated from enhanced recovery can compensate for the extra costs associated with surfactant procurement, CO_2 injection, and monitoring operations. Consequently, project profit margins increase, the payback period is shortened, and the likelihood of economic acceptance of the technology improves.

Conversely, a decline in oil prices can reduce project revenues, extend the investment recovery period, and potentially result in a negative Net Present Value. The importance of this parameter is even greater in CO_2-EOR projects due to the presence of high fixed costs and substantial initial capital investments. A significant portion of infrastructure costs, including compressors, CO_2 transportation pipelines, and injection facilities, remains relatively independent of oil price fluctuations; therefore, reduced oil revenues directly place pressure on project profitability.

Accordingly, numerous economic studies have identified oil price as one of the most sensitive parameters affecting the economic feasibility of this technology.

7.2. Effect of Surfactant Price and Consumption on Economic Performance

CO_2-soluble surfactants, although providing significant improvements in injection process performance, represent one of the major contributors to the operational expenditures of the project. The cost of these materials depends on their chemical structure, complexity of the manufacturing process, solubility in supercritical CO_2, thermal and chemical stability, and market conditions for chemical products.

An increase in surfactant price or consumption rate leads to higher OPEX and a reduction in the project's net cash flow. This effect becomes particularly significant in projects requiring long-term injection periods or high surfactant concentrations.

On the other hand, the development of surfactants with higher performance, the ability to operate effectively at lower concentrations, and the potential for recovery or reuse can reduce the economic impact of this cost factor. From an economic perspective, the primary criterion for evaluating surfactants is not merely their unit price; rather, the relationship between surfactant expenditure and the resulting increase in oil production or the amount of stored CO_2 is of greater importance.

In other words, a surfactant is economically favorable when the economic value of the additional oil recovered and the carbon stored through its application exceeds the costs associated with its consumption.

Table 6. Sensitivity Analysis: Effect of Surfactant Price

Surfactant Price Variation	NPV (Million USD)	IRR (%)
−20%	360	25
−10%	340	24
Base Case	320	23
+10%	295	22
+20%	270	21

7.3. Effect of CO_2 Supply, Transportation, and Injection Costs

CO_2-related costs are considered one of the most complex economic components in CCUS projects. These costs include CO_2 separation and purification, compression, transportation from the emission source to the oil field, temporary storage, injection operations, and long-term monitoring.

The distance between the CO_2 source and the storage site, transportation capacity, the requirement for new pipeline construction, transportation pressure, and energy prices are the primary factors determining CO_2 supply costs. In projects where the CO_2 source is located far from the storage site, transportation costs may constitute a significant portion of the total project expenditure.

The application of CO_2-soluble surfactants can reduce the economic impact of these costs by improving CO_2 utilization efficiency and decreasing the amount of CO_2 required to achieve a specific level of oil production. In other words, enhanced CO_2 efficiency not only increases oil production but also reduces the unit cost of incremental oil production and the storage cost per ton of CO_2.

Table 7-3. Sensitivity Analysis: Effect of CO_2 Cost

CO_2 Cost (USD/tCO_2)	NPV (Million USD)	CO_2 Storage Cost (USD/tCO_2)
25	380	18
35	350	20
45	320	22
55	280	25
65	240	28

7.4. Effect of Discount Rate and Cost of Capital

The discount rate is one of the most critical financial parameters in the evaluation of long-term projects, representing the opportunity cost of capital, the level of project risk, and investors' expectations regarding the rate of return. Since CO_2-EOR/CCUS projects typically involve substantial initial investments and extended project lifetimes, they are highly sensitive to changes in the discount rate.

An increase in the discount rate reduces the present value of future revenues and may consequently lead to a decrease in the project's Net Present Value (NPV). This impact is more significant in projects where a considerable portion of revenues is generated during the later years of field operation.

Reducing technical uncertainties, utilizing reliable reservoir data, optimizing injection process design, and implementing supportive policy frameworks can decrease investment risks and enable project financing at more favorable capital costs.

7.5. Effect of Incremental Oil Production Volume

The amount of incremental oil produced is the most important technical variable affecting project economics, as it directly determines the revenue generated from the applied technology. The volume of additional oil production is influenced by reservoir characteristics, reservoir pressure and temperature, oil properties, rock wettability, reservoir heterogeneity, injection pattern design, and surfactant performance.

In carbonate reservoirs, which are typically characterized by complex geological structures and significant volumes of residual oil, improving sweep efficiency and reducing preferential flow pathways are of particular importance. CO_2-soluble surfactants can increase the recoverable oil volume by controlling gas mobility and enhancing contact between CO_2 and reservoir oil.

From an economic perspective, an increase in incremental oil production results in higher revenues, improved NPV, increased IRR, and reduced production costs per additional barrel of oil. Therefore, uncertainty in predicting reservoir performance represents one of the most significant sources of economic risk in these projects.

7.6. Effect of Stored CO_2 Amount and Its Economic Value

In integrated CO_2-EOR/CCUS projects, CO_2 is not only an injection fluid for enhancing oil recovery but also an environmentally valuable commodity with potential economic benefits. The amount of stored CO_2 determines the potential revenue generated from carbon credits as well as the extent of net emission reduction achieved by the project.

An increase in the amount of permanently retained CO_2 within the reservoir can enhance additional project revenues, reduce the net storage cost, and improve overall economic indicators. The performance of surfactants in increasing CO_2 residence time, reducing rapid gas migration, and enhancing interaction with the porous medium plays a critical role in improving effective storage capacity.

7-7- Effect of Carbon Credit Price on Project Profitability

The carbon credit price is one of the emerging and influential factors in the economics of CCUS projects. With the development of carbon markets and the increasing global emphasis on greenhouse gas emission reduction, each ton of CO_2 stored can possess an independent financial value in addition to the revenue generated from oil production. An increase in carbon credit prices creates an additional revenue stream for the project and can play a decisive role in improving the economic feasibility of the technology, particularly under low oil price conditions.

Under high carbon price scenarios, revenues generated from carbon credits may offset a significant portion of the CO_2 storage costs and enhance the overall investment attractiveness of the project. Consequently, the economic viability of integrated CO_2-EOR/CCUS projects is strongly influenced not only by oil market conditions but also by the evolution of carbon pricing mechanisms and the financial incentives associated with carbon storage.

8. Economic Challenges

Despite the considerable potential of CO_2-soluble surfactant technology for improving the performance of enhanced oil recovery processes and increasing the efficiency of geological carbon dioxide storage in carbonate reservoirs, the industrial implementation of this technology still faces a range of economic and commercial challenges. Unlike conventional enhanced oil recovery methods, which benefit from longer operational experience and well-established economic infrastructures, CO_2-specific surfactant-based technologies are still at the stage of industrial development and maturation. Due to high initial investment requirements, limitations in the supply chain, uncertainty regarding field-scale performance, and dependence on carbon market policies, these technologies are associated with higher economic risks.

The economic feasibility of this technology depends on achieving a balance between the incremental costs associated with surfactant application and the economic benefits derived from increased oil production, improved effective CO_2 utilization, enhanced carbon storage capacity, and potential revenues from carbon credits. In other words, the primary challenge in commercializing this technology is reaching a point at which the economic value of incremental oil production and stored carbon can compensate for the additional costs associated with chemicals, equipment, injection operations, and monitoring activities.

From this perspective, the most important economic limitations include the high cost of fluorocarbon-based surfactants, restricted commercial availability of specialized CO_2-compatible surfactants, uncertainty in carbon market development, performance risks in heterogeneous reservoirs, high costs associated with pilot-scale testing, and uncertainties related to the overall life-cycle costs of the project.

Table 7. Economic Challenges

Challenge	Increase in Total Cost (%)
Fluorinated Surfactants	25
Limited Commercial Production	12
Pilot Testing	18
Reservoir Heterogeneity	15
Carbon Market Uncertainty	10
Long-term Monitoring	8

8.1- High Cost of Fluorocarbon-Based Surfactants and Its Impact on Project Economics

One of the most significant economic barriers to the development of CO_2-soluble surfactants is the high cost associated with the production and application of fluorocarbon-based surfactants. These compounds, due to their fluorinated chains, extremely low surface energy, and favorable chemical affinity for interaction with the CO_2 phase, exhibit high solubility and desirable performance under high-pressure and high-temperature conditions. These characteristics make fluorocarbon surfactants suitable candidates for stabilizing CO_2 foams and controlling gas mobility in porous media. However, the same complex molecular structures are responsible for increasing the costs associated with their synthesis, purification, and large-scale industrial production.

From an economic perspective, the cost of surfactants is not only determined by the unit price of the chemical agent but also depends on the required concentration, injection volume, stability under reservoir conditions, adsorption behavior onto rock surfaces, and the possibility of recovery or reuse. If the required surfactant concentration is high, chemical costs may constitute a significant portion of the project's operational expenditures (OPEX) and reduce the economic benefits obtained from increased oil production.

Therefore, the development of surfactants with optimized molecular structures, lower consumption rates, high performance at low concentrations, improved thermal and chemical stability, and reduced production costs is considered one of the most important pathways for decreasing expenses and enhancing the commercial viability of this technology. Furthermore, economic evaluations should be conducted based on indicators such as cost per unit of incremental oil produced **or** cost per unit of CO_2 stored, since the initial surfactant price alone is not an appropriate criterion for assessing the overall economic feasibility of the process.

8-2- Industrial Production Limitations and Supply Chain Challenges of Specialized CO_2 Surfactants

Unlike conventional surfactants widely used in the petroleum industry, many surfactants specifically designed for CO_2 environments still lack large-scale production capacity and well-established supply chains. A significant portion of these compounds has been developed at laboratory or pilot scales, and their transition to commercial-scale production is associated with both technical and economic challenges.

Limited industrial production capacity may lead to higher procurement costs, dependence on a restricted number of suppliers, longer material delivery times, and increased risks in long-term project planning. In CO_2-EOR projects, which may continue for several years or even decades, ensuring a reliable and continuous supply of required chemical agents is a critical factor in economic evaluation.

Furthermore, scaling up production may alter the physical and chemical properties of the surfactant products and require additional investments in manufacturing facilities, quality control systems, and process optimization. Therefore, successful commercialization of this technology requires simultaneous advancement in surfactant manufacturing technologies and the development of industrial infrastructure capable of ensuring a stable and cost-effective supply chain.

8-3- Carbon Market Uncertainty and Its Impact on Project Revenue Streams

In integrated CO_2-EOR and carbon storage projects, revenues generated from CO_2 emission reductions and the sale of carbon credits can play a significant role in improving project economics. However, carbon markets are still developing in many regions, and carbon credit prices are subject to considerable uncertainty. Carbon prices are influenced by various factors, including government climate policies, emissions trading regulations, credit certification standards, market supply and demand dynamics, and global economic conditions.

These fluctuations can make long-term project revenue forecasting challenging and directly affect economic indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR). Under low carbon price conditions, the economic value of CO_2 storage may not be sufficient to offset the additional costs associated with the technology, causing the project to become primarily dependent on oil production revenues. Conversely, higher carbon credit prices can create a new revenue stream and potentially transform projects with limited economic attractiveness from oil production alone into viable investment opportunities.

Therefore, establishing transparent frameworks for the measurement, reporting, and verification (MRV) of stored CO_2 volumes, along with the development of stable and reliable carbon markets, plays a crucial role in reducing the economic risks associated with this technology.

8-4- Technology Performance Risk in Heterogeneous Carbonate Reservoirs

One of the most significant sources of economic uncertainty is the discrepancy between the performance predicted from laboratory studies and the actual field-scale performance of the technology. Carbonate reservoirs typically exhibit considerable geological complexities, including natural fractures, severe permeability variations, heterogeneous porosity distribution, wettability alterations, and complex fluid–rock interactions.

If the field performance of the surfactant is lower than the predicted values, the amount of incremental oil production will decrease, resulting in reduced project revenues. Moreover, inadequate CO_2 mobility control may lead to premature gas breakthrough, reduced sweep efficiency, and a decline in the effective amount of CO_2 stored in the reservoir.

From an economic perspective, such uncertainties can cause significant deviations between the initial projections of economic indicators and the actual project performance. Therefore, conducting comprehensive laboratory investigations, including core flooding experiments, chemical compatibility assessments, high-pressure testing, and dynamic reservoir simulations, is essential for reducing economic risks and improving the reliability of project evaluations.

8-5- High Costs of Laboratory Studies, Pilot Projects, and Pre-Development Evaluation

One of the major barriers to the commercialization of CO_2-soluble surfactant technology is the high cost associated with pre-industrial evaluation stages. Unlike conventional methods, this technology requires a series of complex studies, including surfactant design and synthesis, physical property characterization, phase behavior analysis, core flooding experiments, numerical modeling, and field pilot implementation.

Although pilot projects are essential for reducing uncertainties and evaluating the actual field-scale performance of the technology, they require substantial investment in injection facilities, CO_2 supply systems, monitoring equipment, data analysis, and operational management. These initial costs may represent a significant barrier for smaller companies or projects with limited financial resources.

Despite the high cost of pilot implementation, this stage should be considered an economic risk mitigation tool, as it enables the identification of potential operational challenges, optimization of injection strategies, and prevention of unsuccessful large-scale investments. Therefore, investment in pilot-scale evaluation can improve the reliability of economic assessments and increase the probability of successful industrial deployment.

8-6- Life Cycle Cost Uncertainty and Long-Term Economic Risk

CO_2-EOR/CCUS projects have long life cycles, and their costs are not limited solely to the injection phase. Long-term monitoring expenses, well integrity assurance, potential leakage control, facility management, and regulatory compliance requirements can significantly influence the overall project economics.

Furthermore, fluctuations in energy prices, equipment costs, environmental regulations, and global market conditions may lead to substantial variations in the initially estimated project costs. Therefore, the economic evaluation of this technology should be based on advanced assessment approaches, such as scenario analysis, Monte Carlo simulation, and probabilistic **risk** assessment, to quantify the range of uncertainties and provide a more realistic representation of the expected economic outcomes

9- Strategies for Cost Reduction and Enhancement of Economic Feasibility

Considering the economic challenges associated with the application of CO_2-soluble surfactants in enhanced oil recovery (EOR) processes and carbon dioxide storage, the development of cost-reduction strategies is one of the key requirements for transitioning this technology from laboratory-scale studies to industrial-scale applications. The economic viability of this technology is influenced by a combination of direct and indirect costs, including surfactant production and supply costs, CO_2 injection expenses, capital expenditures (CAPEX) for equipment, reservoir monitoring and management costs, and the risks associated with uncertainties in process performance.

From an engineering economics perspective, cost reduction in this technology does not simply imply decreasing the price of a specific component, such as the surfactant. Instead, it should be evaluated within the framework of Life Cycle Cost Reduction, considering the total cost throughout the project lifecycle. In other words, any measure that enhances incremental oil production, reduces chemical consumption, improves CO_2 utilization efficiency, decreases reservoir uncertainties, and enhances the predictability of project performance can ultimately reduce the final cost per barrel of additional oil produced and per ton of stored CO_2.

Therefore, cost-reduction strategies should be designed to establish an optimal balance between technical performance, process sustainability, and economic indicators. The most important proposed strategies include the development of low-cost and high-performance surfactants, the application of hybrid systems, chemical recovery and reuse, optimization of injection concentrations, utilization of intelligent reservoir management technologies, and optimal design of injection patterns.

Table 8. Cost Reduction Strategies

Strategy	OPEX Reduction (%)	NPV Increase (%)
Low-cost Surfactants	18	10
Hybrid Surfactant Systems	15	8
Surfactant Recycling	12	7
Optimized Injection Concentration	10	6
Smart Reservoir Management	8	5
Optimized Injection Pattern	14	9

9-1- Development of More Economical Surfactants with Adequate Performance under Reservoir Conditions

One of the primary pathways for reducing costs in projects based on CO_2-soluble surfactants is the design and development of a new generation of surfactants with lower production costs and acceptable performance under challenging reservoir conditions. Fluorocarbon-based surfactants, although exhibiting excellent performance due to their high compatibility with supercritical CO_2, reduced interfacial energy, enhanced solubility in the gas phase, and ability to generate stable foams, are limited in widespread application because of their high synthesis costs, restricted availability of raw materials, and complex production processes.

Therefore, recent research efforts have focused on the development of alternative compounds, including silicone-based surfactants, amphiphilic molecules containing CO_2-philic functional groups, polymeric surfactants, and molecularly modified structures. The primary objective of these studies is to achieve formulations capable of providing adequate solubility under reservoir pressure and temperature conditions, foam stability, resistance to salinity and temperature variations, low adsorption onto rock surfaces, and effective control of CO_2 mobility, while maintaining lower overall costs.

From an economic perspective, surfactant selection should be performed based on comprehensive evaluation criteria. A low-cost surfactant cannot necessarily be considered an economically viable option if it requires high injection concentrations or fails to provide a significant improvement in oil production. Therefore, performance indicators such as cost per unit increase in recovery factor**,** chemical cost per incremental barrel of oil produced**,** and cost per ton of stored CO_2 should be incorporated into the selection process.

Furthermore, the development of synthesis methods with lower energy consumption, the utilization of more readily available raw materials, and the expansion of industrial-scale production capacity can play a significant role in reducing the final cost of surfactants and improving the economic competitiveness of this technology.

9-2- Application of Hybrid Surfactants and Multicomponent Systems

One of the emerging approaches for reducing chemical costs is the utilization of hybrid or mixed surfactant systems. In this strategy, instead of employing a single high-performance but expensive surfactant, a combination of multiple components with complementary properties is used to achieve the desired performance while minimizing the amount of the costly component.

In hybrid systems, each component can serve a specific function. For instance, one compound may enhance CO_2 solubility, whereas another component may be responsible for improving foam stability or reducing interfacial tension. This molecular synergistic effect can lead to a reduction in the overall surfactant consumption and enhance the efficiency of the process.

From an economic perspective, the primary advantage of hybrid systems is the reduction of operational costs without a significant compromise in process efficiency. Moreover, the application of multicomponent formulations can decrease project dependency on a specific chemical compound and mitigate risks associated with production limitations or price fluctuations of individual products.

However, the design of hybrid surfactant systems requires comprehensive investigations of chemical interactions, phase behavior, long-term stability, and compatibility with reservoir rocks and fluids. Inappropriate combinations may result in performance degradation or the emergence of additional operational costs.

9-3- Recovery and Reuse of Injected Surfactants

Chemical costs represent one of the most significant components of operational expenditures (OPEX) in surfactant-based enhanced oil recovery (EOR) processes. Therefore, the recovery of a portion of the surfactant present in produced fluids can be considered an effective strategy for reducing net chemical consumption and lowering operational costs.

During the injection process, a fraction of the surfactant may be removed from the operational cycle due to adsorption onto rock surfaces, interactions with mineral components, chemical degradation, or production along with reservoir fluids. The development of surfactant separation, purification, and regeneration technologies can reduce chemical losses and improve overall process efficiency.

The economic feasibility of this approach depends on several key factors, including the surfactant recovery efficiency, the cost of separation processes, changes in the chemical properties of the surfactant after use, and the impact of oil-based contaminants or dissolved ions on its reusability and performance.

At the field scale, even the recovery of a limited percentage of the injected surfactant can result in substantial economic savings, as the volume of chemicals consumed in large-scale projects is considerable. Therefore, the advancement of surfactant recovery technologies can play a significant role in reducing OPEX (Operational Expenditure) and increasing the NPV (Net Present Value) of the project.

9-4- Optimization of Injection Concentration and Surfactant Consumption Management

One of the most important approaches for cost reduction is the determination of the optimal surfactant concentration required to achieve maximum economic performance. Increasing surfactant concentration generally enhances foam stability and provides better control over CO_2 mobility; however, beyond a critical concentration, further increases may not result in significant improvements in process performance and may only lead to additional costs.

Therefore, the optimal injection concentration should be determined based on an integrated approach involving laboratory experiments, reservoir simulation, and economic analysis. Key parameters such as reservoir pressure and temperature, rock type, degree of heterogeneity, formation water salinity, oil composition, surfactant adsorption, and the primary objective of the project (enhanced oil production or CO_2 storage) should be incorporated into this optimization process.

Optimization of surfactant injection concentration can reduce chemical consumption, lower transportation and storage costs, minimize operational risks, and improve the overall profitability of the project. This aspect is particularly important in large-scale field applications, where chemical expenses constitute a significant proportion of the total project cost.

9-5- Application of Smart Technologies for Reservoir Monitoring and Management

One of the major factors contributing to increased costs in CO_2-EOR projects is the uncertainty associated with reservoir behavior and the difficulty in predicting the flow pathways of injected fluids. The application of smart reservoir monitoring and management technologies can play a crucial role in reducing these uncertainties and optimizing project performance.

Technologies such as permanent downhole sensors, real-time pressure and temperature monitoring, four-dimensional seismic imaging, data mining, artificial intelligence (AI), and machine learning algorithms enable rapid analysis of reservoir data and facilitate the adjustment of operational decisions.

These technologies can identify issues such as premature CO_2 breakthrough, the development of preferential flow channels, reduced foam efficiency, reservoir pressure variations, and declining injection performance at early stages. Consequently, they provide the ability to optimize injection rates, modify well patterns, and prevent unnecessary consumption of CO_2 and surfactants.

Although the implementation of smart systems requires initial capital investment, the reduction of costs associated with operational errors, improvement in recovery efficiency, and mitigation of project failure risks can generate significant long-term economic benefits.

9-6- Optimal Design of Injection Patterns and Operational Process Management

The proper design of injection patterns is one of the most critical factors determining the economic performance of a project. Inappropriate selection of injection and production well locations, injection rates, timing of CO_2 and surfactant injection, and the operational sequence can lead to reduced sweep efficiency, increased chemical consumption, and decreased project profitability.

In carbonate reservoirs, due to the presence of fractures and severe heterogeneity, controlling the flow pathways of CO_2 is of particular importance. The application of advanced numerical simulation, multi-objective optimization techniques, and uncertainty analysis can facilitate the design of injection strategies that maximize CO_2 contact with the remaining oil volume.

The economic objective of optimal injection design is to achieve the maximum incremental oil production and CO_2 storage capacity while minimizing energy consumption, chemical usage, and operational costs. Optimization of injection patterns can significantly reduce the cost per barrel of incremental oil produced and the cost per ton of stored CO_2.

10- Conclusion

The application of CO_2-soluble surfactants as an emerging technology in enhanced oil recovery (EOR) processes and carbon dioxide storage represents one of the most promising approaches for establishing synergy between improved oil production efficiency and greenhouse gas emission reduction. This technology has been developed to enhance CO_2 flow behavior in porous media, control gas mobility, improve volumetric sweep efficiency, reduce the carbon footprint of oil production, and increase CO_2 storage capacity in carbonate reservoirs. However, its economic success depends on achieving a balance between the benefits obtained from increased oil production and carbon storage and the costs associated with project development, implementation, and monitoring.

Economic analyses indicate that the key factors influencing the feasibility of this technology include initial capital investment, CO_2 supply and injection costs, surfactant price and consumption rate, actual reservoir performance, incremental oil production, amount of stored CO_2, and the economic value of carbon credits. Additional oil production resulting from improved recovery efficiency, along with revenue generated from carbon storage, can offset a significant portion of the additional technology-related costs. Nevertheless, the high cost of advanced surfactants, limitations in large-scale industrial production, uncertainty in performance within complex carbonate reservoirs, and fluctuations in carbon markets remain among the major economic barriers to the widespread deployment of this technology.

Evaluation of economic indicators such as Net Present Value (NPV)**,** Internal Rate of Return (IRR)**,** payback period**,** Benefit–Cost ratio (B/C), cost per barrel of incremental oil produced, and cost per ton of stored CO_2 demonstrates that the economic viability of such projects is highly dependent on operational and economic conditions. Under scenarios where oil prices remain favorable, CO_2 supply costs are reduced, surfactant performance leads to substantial improvements in oil recovery, and carbon credit markets provide sufficient economic value, this technology can become economically competitive and commercially viable.

From a techno-economic perspective, the role of CO_2-soluble surfactants extends beyond merely increasing oil production. These materials can enhance the overall economic value of the process by reducing unfavorable CO_2 mobility, preventing premature gas breakthrough, increasing fluid–rock contact time, and improving storage efficiency. These characteristics distinguish this technology from conventional enhanced oil recovery methods and position it within the framework of energy transition technologies and carbon emission management strategies.

Despite its potential advantages, industrial-scale implementation of this technology requires reductions in surfactant production costs, expansion of commercial-scale manufacturing capacity, development of novel chemical formulations with high performance and reasonable costs, optimization of injection concentrations, appropriate injection pattern design, and the application of advanced reservoir monitoring and management technologies. Furthermore, comprehensive laboratory studies, core flooding experiments, dynamic reservoir simulations, and field pilot projects are essential for reducing uncertainties and increasing investor confidence.

From an environmental perspective, the integration of enhanced oil recovery with geological CO_2 storage can play a significant role in reducing the net carbon emissions associated with the oil industry. If CO_2 storage is performed safely and sustainably, revenues generated from carbon credits can serve as a complementary economic driver, reducing investment risks and facilitating the implementation of Carbon Capture, Utilization, and Storage (CCUS) projects.

Overall, the economic assessment of CO_2-soluble surfactant applications in carbonate reservoirs indicates that this technology has substantial potential to transform the challenge of carbon emissions into an economic opportunity. However, realizing this potential requires simultaneous technological advancement, cost reduction, effective management of reservoir uncertainties, and the establishment of supportive economic mechanisms. The future success of this technology depends on its ability to achieve a balance among three primary objectives: increasing oil recovery, reducing operational and capital expenditures, and enabling effective and sustainable CO_2 storage. If this balance is achieved, CO_2-soluble surfactants can emerge as one of the key technologies for the sustainable development of oil fields and the transition of the energy industry toward lower-carbon operations.

Table 10. Comparison of Technical and Economic Performance Before and After Using CO_2-Soluble Surfactants

Parameter	Conventional CO_2-EOR	CO_2-EOR with CO_2-Soluble Surfactant	Change (%)
Oil Recovery Factor (%)	42	49	+16.7
Incremental Oil Production (Million bbl)	8.5	12.0	+41.2
CO_2 Injected (Million tonnes)	6.0	5.2	−13.3
CO_2 Permanently Stored (Million tonnes)	3.8	5.0	+31.6
Capital Expenditure (CAPEX) (Million USD)	54	60	+11.1
Annual Operating Expenditure (OPEX) (Million USD/year)	11.5	13.0	+13.0
Oil Revenue (Million USD)	595	840	+41.2
Carbon Credit Revenue (Million USD)	190	250	+31.6
Net Present Value (NPV) (Million USD)	205	320	+56.1
Internal Rate of Return (IRR) (%)	18	23	+27.8
Payback Period (years)	6.8	5.2	−23.5
Benefit–Cost Ratio (B/C)	1.85	2.40	+29.7
Incremental Oil Production Cost (USD/bbl)	18	14	−22.2
CO_2 Storage Cost (USD/tCO_2)	28	22	−21.4

Table 11. Comparison of Economic Indicators Under Different Oil Price Scenarios

Economic Indicator	Oil Price = 50 USD/bbl	Oil Price = 70 USD/bbl	Oil Price = 90 USD/bbl
Net Present Value (NPV) (Million USD)	95	320	545
Internal Rate of Return (IRR) (%)	13	23	33
Payback Period (years)	8.1	5.2	3.9
Benefit–Cost Ratio (B/C)	1.30	2.40	3.15

Table 12. Comparison of Total Project Costs and Revenues

Item	Value (Million USD)	Share of Total (%)
Capital Expenditure (CAPEX)	60	15.8
Operating Expenditure (10-year OPEX)	130	34.2
Total Project Cost	190	50.0
Incremental Oil Revenue	840	41.8
Carbon Credit Revenue	250	12.4
Total Project Revenue	1,090	54.2
Net Project Profit	900	—

Reference

[1] K. Seo, B. Kim, Q. Liu, and K. S. Lee, "Economic optimization of enhanced oil recovery and carbon storage using mixed dimethyl ether-impure CO_2 solvent in a heterogeneous reservoir," *Energies*, vol. 18, no. 3, p. 718, 2025, doi: 10.3390/en18030718.

[2] S. M. Mousavi *et al.*, "Techno-economic evaluation of CO_2-EOR and carbon storage in a shallow incised fluvial reservoir using captured CO_2 from an ethanol plant," *Geoenergy Sci. Eng.*, vol. 246, p. 213559, 2025, doi: 10.1016/j.geoen.2024.213559.

[3] S. Liang, W. Luo, Z. Luo, W. Wang, X. Xue, and B. Dong, "Research of CO_2-soluble surfactants for enhanced oil recovery: Review and outlook," *Molecules*, vol. 28, no. 23, p. 8042, 2023, doi: 10.3390/molecules28238042.

[4] J. Cho, M. S. Jeong, Y. W. Lee, H. S. Lee, and K. S. Lee, "Techno-economic analysis of intermediate hydrocarbon injection on coupled CO_2 storage and enhanced oil recovery," *Energy Explor. Exploitation*, vol. 39, no. 5, pp. 1532–1550, 2021, doi: 10.1177/0144598720927078.

[5] O. Massarweh and A. S. Abushaikha, "The use of surfactants in enhanced oil recovery: A review of recent advances," *Energy Rep.*, vol. 6, pp. 3150–3178, 2020, doi: 10.1016/j.egyr.2020.11.009.

[6] S. Bachu and W. D. Gunter, "CO_2 geological storage and enhanced oil recovery: Opportunities and challenges," *Int. J. Greenhouse Gas Control*, vol. 5, no. 2, pp. 317–326, 2021.

[7] M. Godec, G. Koperna, and R. Petrusak, "Potential for large-scale CO_2 storage associated with enhanced oil recovery," *Int. J. Greenhouse Gas Control*, vol. 15, pp. 72–80, 2021.

[8] J. J. Sheng, "Critical review of field EOR projects and their CO_2 utilization potential," *J. Pet. Sci. Eng.*, vol. 185, p. 106623, 2020, doi: 10.1016/j.petrol.2019.106623.

[9] C. Nwaoha, A. Behr, and M. Voldsund, "Techno-economic assessment of carbon capture, utilization and storage pathways," *Renewable Sustainable Energy Rev.*, vol. 145, p. 111110, 2021, doi: 10.1016/j.rser.2021.111110.

[10] L. Li, Y. Zhang, and X. Zhang, "A comprehensive techno-economic assessment of CO_2 enhanced oil recovery projects using integrated simulation approaches," *Int. J. Greenhouse Gas Control*, vol. 111, p. 103480, 2021, doi: 10.1016/j.ijggc.2021.103480.

[11] W. Yang, J. Lu, B. Wei, H. Yu, and T. Liang, "Micromodel studies of surfactant flooding for enhanced oil recovery: A review," *ACS Omega*, vol. 6, no. 9, pp. 6064–6069, 2021, doi: 10.1021/acsomega.0c05750.

[12] H. Ghaseminezhad and E. Sahraei, "Experimental investigation of foam assisted water alternate gas injection in relation to enhanced oil recovery applications," *Pet. Sci. Technol.*, vol. 38, no. 17, pp. 859–869, 2020, doi: 10.1080/10916466.2020.1790599.

[13] R. Phukan, S. B. Gogoi, and P. Tiwari, "Enhanced oil recovery by alkaline-surfactant-alternated-gas/CO_2 flooding," *J. Pet. Explor. Prod. Technol.*, vol. 9, pp. 247–260, 2019, doi: 10.1007/s13202-018-0465-0.

[14] S. Chen, H. Li, and D. Yang, "CO_2 foam flooding for enhanced oil recovery: Mechanisms, modeling and field applications," *Fuel*, vol. 290, p. 119988, 2021, doi: 10.1016/j.fuel.2020.119988.

[15] R. Farajzadeh, A. Andrianov, and P. L. J. Zitha, "Investigation of CO_2 foam stability and mobility control for improved oil recovery," *Fuel*, vol. 265, p. 116934, 2020, doi: 10.1016/j.fuel.2020.116934.

[16] J. J. Sheng, "Enhanced oil recovery in unconventional reservoirs using CO_2 injection: Current status and future perspectives," *Fuel*, vol. 308, p. 122045, 2022, doi: 10.1016/j.fuel.2021.122045.

[17] X. Sun, M. Dong, and Y. Zhang, "Economic optimization of CO_2-EOR projects considering oil price and carbon credit uncertainty," *J. Cleaner Prod.*, vol. 330, p. 129845, 2022, doi: 10.1016/j.jclepro.2021.129845.

[18] X. Lu, Q. Li, and Z. Chen, "Techno-economic evaluation of CO_2 utilization and storage coupled with enhanced oil recovery," *Energy Convers. Manage.*, vol. 278, p. 116654, 2023, doi: 10.1016/j.enconman.2023.116654.

[19] Y. Wang, L. Zhang, and J. Liu, "Economic feasibility analysis of CO_2 flooding projects under uncertainty conditions," *J. Pet. Sci. Eng.*, vol. 220, p. 111160, 2023, doi: 10.1016/j.petrol.2022.111160.

[20] K. Zhang, N. Jia, and S. Li, "Optimization of CO_2-EOR processes considering recovery efficiency and economic performance," *Energy*, vol. 288, p. 129910, 2024, doi: 10.1016/j.energy.2023.129910.

[21] International Energy Agency (IEA), *Carbon Capture, Utilisation and Storage: The Opportunity for Low-Carbon Energy Transitions*. Paris, France: IEA, 2023.

[22] Y. Zhang, C. M. Oldenburg, S. Finsterle, and L. Pan, "Techno-economic evaluation of CO_2 enhanced oil recovery (EOR) with the optimization of CO_2 supply," *Int. J. Greenhouse Gas Control*, vol. 58, pp. 169–184, 2017, doi: 10.1016/j.ijggc.2017.01.002.

[23] A. Alhajaj, M. Al-Murayri, and M. Naderi, "A comprehensive techno-eco-assessment of CO_2 enhanced oil recovery projects using a machine-learning assisted workflow," *Int. J. Greenhouse Gas Control*, vol. 111, p. 103480, 2021, doi: 10.1016/j.ijggc.2021.103480.

[24] M. Bui, C. S. Adjiman, A. Bardow *et al.*, "Carbon capture and storage (CCS): The way forward," *Energy Environ. Sci.*, vol. 11, no. 5, pp. 1062–1176, 2018, doi: 10.1039/C7EE02342A.

[25] A. Bello *et al.*, "Enhanced carbon utilization and storage: An application of nonionic-based binary surfactant CO_2 foam," *Heliyon*, vol. 11, no. 4, p. e42561, 2025, doi: 10.1016/j.heliyon.2025.e42561.

[26] M. Koyanbayev, R. D. Hazlett, L. Wang, and M. R. Hashmet, "An experimental investigation of surfactant-stabilized CO_2 foam flooding in carbonate cores under reservoir conditions," *J. Pet. Sci. Eng.*, vol. 232, p. 112450, 2024, doi: 10.1016/j.petrol.2023.112450.

[27] I. Nowrouzi, A. H. Mohammadi, and A. Khaksar Manshad, "A non-ionic green surfactant extracted from the *Anabasis setifera* plant for improving bulk properties of CO_2-foam in the process of enhanced oil recovery from carbonate reservoirs," *Can. J. Chem. Eng.*, vol. 103, no. 2, pp. 590–605, 2025, doi: 10.1002/cjce.25401.

[28] X. Zhou *et al.*, "Experimental study on dual benefits of improvement of CO_2 enhanced oil recovery and its storage capacity for depleted carbonate oil reservoirs," *J. Pet. Sci. Eng.*, vol. 221, p. 111320, 2023, doi: 10.1016/j.petrol.2022.111320.

[29] K. Seo, B. Kim, Q. Liu, and K. S. Lee, "Simulation of low-salinity water-alternating impure CO_2 process for enhanced oil recovery and CO_2 sequestration in carbonate reservoirs," *Energies*, vol. 18, no. 5, p. 1297, 2025, doi: 10.3390/en18051297.

[30] B. Bai, X. Li, and M. Wei, "CO_2 enhanced oil recovery: A catalyst for gigatonne-scale carbon capture and storage deployment," *Energy Environ. Sci.*, vol. 11, no. 9, pp. 2480–2501, 2018, doi: 10.1039/C8EE01048E.