

Optimal Miscible CO₂ Injection for Enhanced Oil Recovery: A Case Study of the Asmari Formation in the Abu Ghirab Oil Field, Southeastern Iraq

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Abstract

This study focuses on optimizing the implementation of miscible CO₂ injection to enhance production from the Asmari Formation in the Abu Ghirab Field, southeastern Iraq, using CMGTM simulation software. Various scenarios were simulated to evaluate the effectiveness of miscible CO₂ injection and identify areas where it could be applied successfully. Key factors such as porosity, permeability, and reservoir thickness were considered, as they significantly influence the success of miscible CO₂ flooding. The results were compared between primary production and enhanced oil recovery using miscible CO₂ injection. The original oil in place (OOIP) is estimated at 89,331 MSTB, indicating a reduction in reserves in the southern dome of the field. Simulations of miscible CO₂ injection from 2024 to 2030 revealed that miscible CO₂ injection would not affect the field until the third quarter of 2026. Therefore, miscible CO₂ flooding should begin in September 2026 to achieve optimal results. The study also observed an increase in the gas-oil ratio starting in the third quarter of 2027. However, a decline in oil production is expected from late 2028 to 2030, suggesting that an alternative enhanced oil recovery (EOR) method should be considered for continued oil recovery beyond this period.

Introduction

Enhanced oil recovery (EOR) refers to the process of extracting oil through the injection of a fluid that is not naturally present in the reservoir. It is used to prolong the productive life of oil fields that are depleted or no longer economically viable. EOR techniques are typically employed after more conventional, less complex methods—such as pressure depletion and water flooding have been exhausted (Shao and Chen 2024). One of the most established EOR methods is the injection of carbon dioxide (CO₂), which has been widely applied in the oil and gas industry for several years (Davoodi et al. 2024). CO₂ injection is generally carried out after primary recovery has extracted 10% to 20% of the original oil in place, followed by secondary recovery that contributes an additional 10% to 20% (Hoteit et al. 2019). CO₂ typically functions as a solvent when injected into the reservoir, enhancing the extraction of remaining oil (Zhou et al. 2024). When injected under reservoir conditions, CO₂ mixes with the oil to become miscible, which helps reduce the oil's viscosity and facilitates smoother flow through the reservoir (Wang et al. 2023). A typical CO₂ flooding process, demonstrating miscibility, is shown in **Figure 1** (Feather and Archer 2010).

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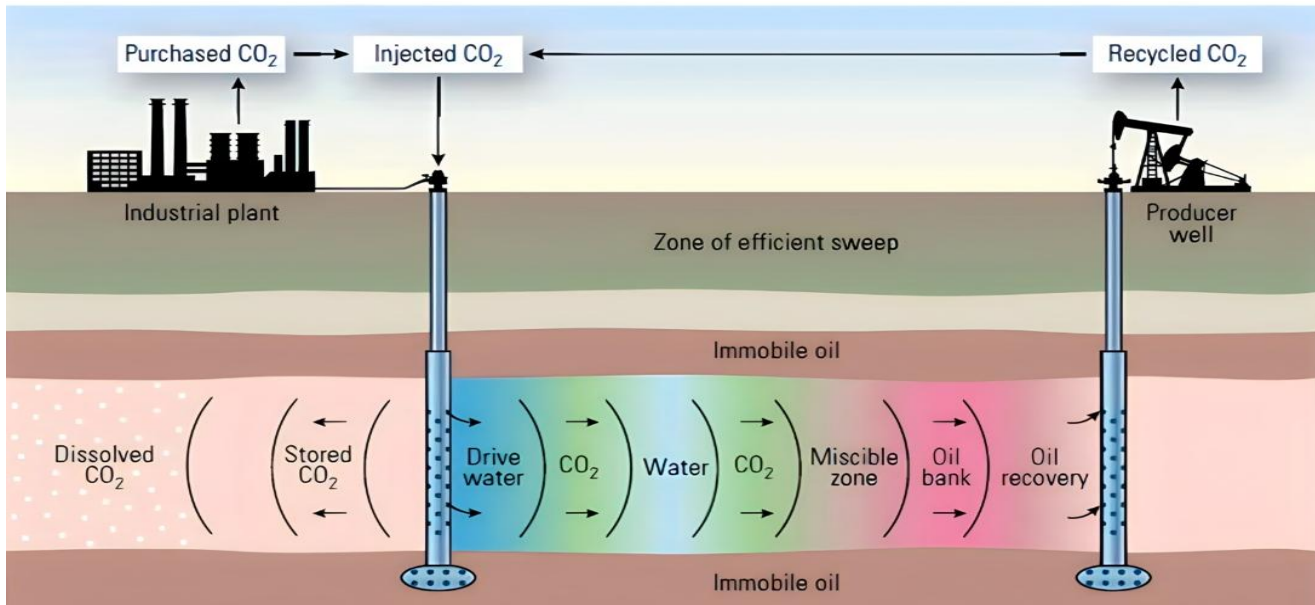


Figure 1—Miscible CO₂ flooding (Feather and Archer 2010).

A large share of the world's remaining oil is found in tight formations, commonly of carbonate origin, and these formations exhibit significant heterogeneity (Radwan et al. 2021). The goals of Enhanced Oil Recovery (EOR) vary considerably depending on the types of hydrocarbons involved (Figure 2) (Thomas 2008).

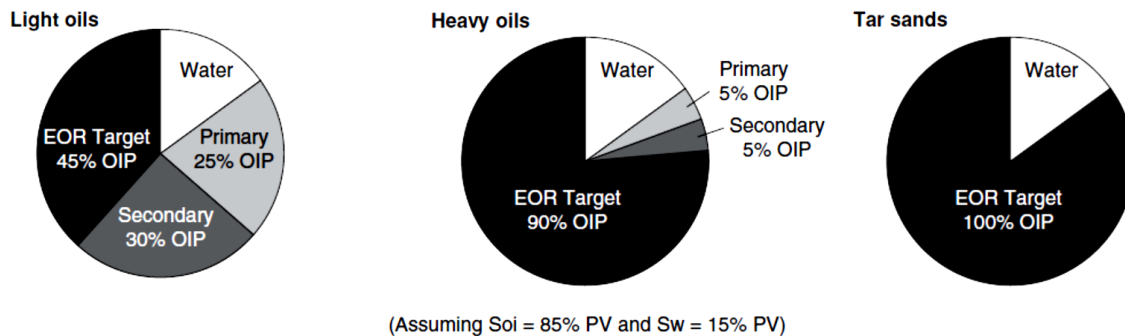


Figure 2—Targets for Enhanced Oil Recovery according to the type of hydrocarbon (Thomas 2008).

Gas is injected into the reservoir oil at or above the minimum miscibility pressure (MMP) to achieve complete mixing of the two (Li and Luo 2017). This process is referred to as miscible gas injection. If the gas injection occurs below the MMP, it is termed immiscible gas injection (Figure 3) (Tileuberdi et al. 2024).

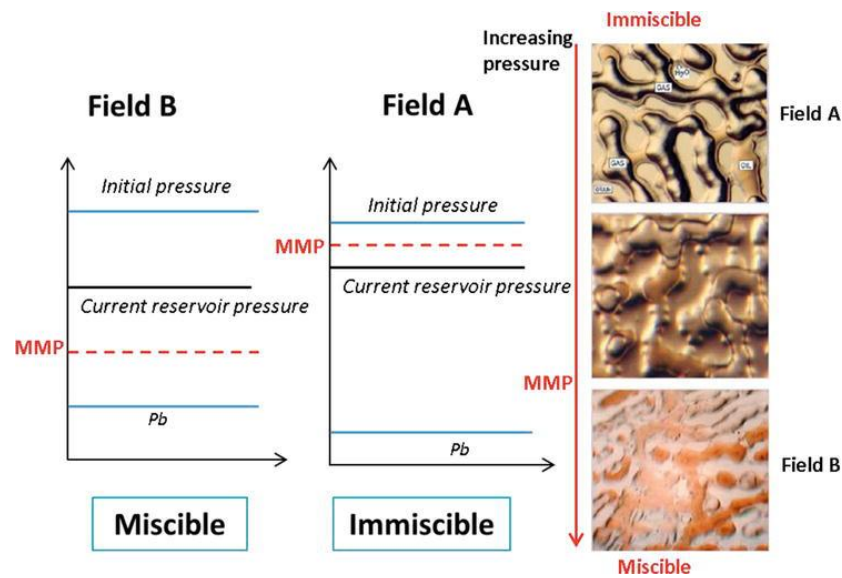


Figure 3—Evolution of CO₂ injection miscibility in oil at both miscible and immiscible pressures (Asgarpour 1994).

While most CO₂ enhanced oil recovery (EOR) projects operate under miscible conditions, immiscible conditions can also be utilized to extract oil from a reservoir (Chukwudeme and Hamouda 2009; Steinsbø et al. 2014; Cooney et al. 2018; Seyyedi and Sohrabi 2020; Chen et al. 2023). However, not every reservoir is suitable for CO₂ injection (Janna and Le-Hussain 2020). Factors such as oil composition, depth, temperature, and other reservoir characteristics must be carefully evaluated when considering CO₂ injection (Kumar et al. 2022; Eyinla et al. 2023). Precise determination of the minimum miscibility pressure (MMP) for CO₂ flooding can greatly enhance reservoir recovery (Song et al. 2024). This is typically effective at depths greater than 2500 feet, with oils having an API gravity greater than 22 degrees and a viscosity less than 10 cp. Additionally, the oil's saturation should exceed 20% of the pore volume (Abdullah and Hasan 2021). The recovery factor for the miscible CO₂ injection was higher than for the immiscible, indicating that the miscible injection was more effective. However, reaching miscible conditions in heavy oil reservoirs proved challenging (Zhang et al. 2010; Abedini et al. 2015; Kudapa and Krishna 2023). Simulated PVT experiments revealed that miscible CO₂ injection with rich gases yields higher oil recovery than the injection with lean gases (Zarei and Azdarpour 2017).

This case study on CO₂ injection for enhanced oil recovery in an Iraqi oil field highlights its potential to boost oil recovery and extend the field's productive life by promoting miscibility with the oil, CO₂ injection enhances extraction efficiency, leading to higher production rates. Additionally, this method supports global efforts to reduce carbon emissions by beneficially utilizing CO₂ instead of releasing it into the atmosphere. The case study also offers valuable insights into the feasibility, challenges, and benefits of CO₂ injection in similar oil fields globally, contributing to advancements in sustainable energy practices and resource management.

Geological setting

The Abu Ghirab oil field is situated in the Missan governorate in southeastern Iraq, near the Iranian border (Asad et al. 2024). It spans approximately 30 km in length and 5 km in width, with coordinates ranging from 3575000-360000 Northing and 71,000-73,500 Easting (Asad and Hamd-Allah 2022). The field features two domes (northern and southern) separated by a saddle zone, as depicted in Figure 4 (Al-Mamouri et al. 2022). The Asmari Formation is characterized by heterogeneity, and fracture distribution and requires water control in later stages of development (Alsinbili et al. 2013; Daraei et al. 2023), using cased hole perforation for vertical and directional wells. The reservoir primarily consists of carbonate rocks from the Cretaceous and Tertiary periods (Haghighat et al. 2021). Located within the transitional zone between the Zagros Mountains and the Arabian Plate in the

southern Mesopotamian basin (Sang et al. 2017), the field lies about 350 km southeast of Baghdad and 175 km north of Basra, as shown in **Figure 4**.

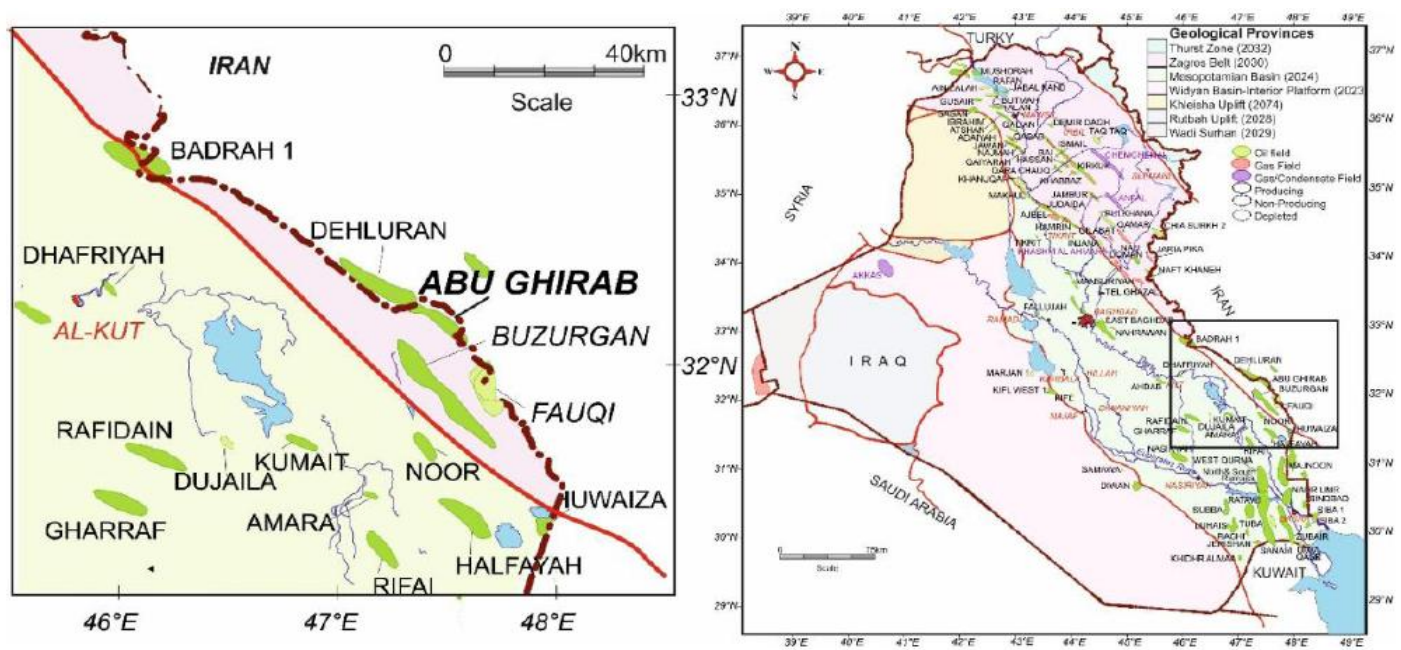


Figure 4—Abu Ghirab oil Field, Southeastern Iraq (Al-Mamouri et al. 2022).

The Asmari Formation is part of Tertiary deposits (Oligocene-Lower Miocene) in southeastern Iraq (Al-Saad 2010; Fouad 2012; Al-Saad and Al-Shahwan 2019; Al-Baldawi 2020). The Kirkuk Group consists of three sub-zones: A) The Upper Kirkuk, which includes limestone, dolomite, and some sandstone (Karim et al. 2020); B) The Buzurgan Member, comprising dolomite, sandstone, limestone, and upper shale in the upper section (Al-Baldawi 2020). Pre-geological studies of the Abu Ghraib structure reveal the influence of two distinct forces caused by folding movements (Alwan et al. 2017). These forces created tension in the upper part of the structure and compression in the lower portions, resulting in tangential deformation and a longitudinal shape. Deformation was most intense along the limbs, while the anticline axis experienced less deformation (Al-Baldawi 2020). **Figure 5** shows the stratigraphic column of the area (Al-Khafaji et al. 2019).

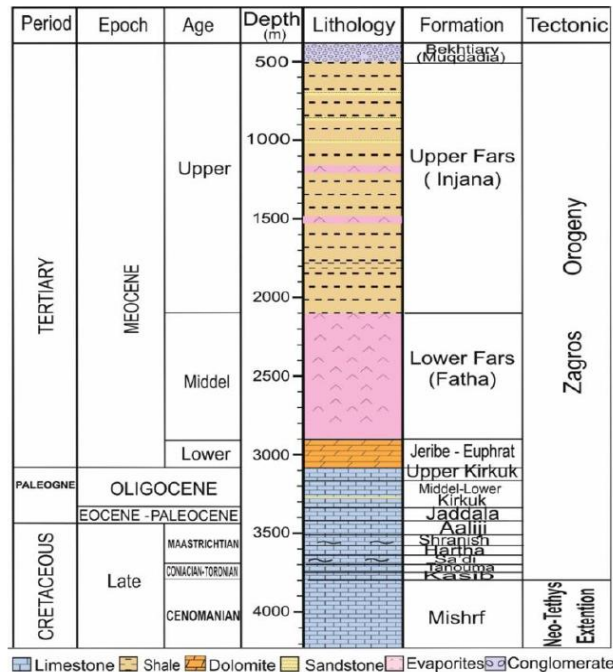


Figure 5—Stratigraphic column of Abu Ghirab (Al-Khafaji et al. 2019)

Data and Methods

This study offers a detailed analysis of enhanced oil recovery (EOR) methods applied to the Asmari Formation in the Abu Ghirab Field, concentrating on optimizing oil production through various injection techniques. **Figure 6** depicts the wells investigated in the Asmari formation within the Abu Ghirab field. The research utilizes a comprehensive dataset obtained from core analyses of the 22 wells, which includes essential reservoir properties such as porosity, permeability, water saturation, and relative permeability for both oil and water phases. These properties are critical for understanding fluid flow dynamics within the reservoir and modeling recovery processes.

Figure 7 provides oil and water relative permeability for different units of Asmari formation by core flooding. The core flooding experiments were conducted under reservoir conditions to accurately capture the flow behavior of oil and water. The relative permeability curves depicted in Figure 7 illustrate the varying degrees of mobility for oil and water phases across different units, highlighting the impact of rock heterogeneity on fluid flow. These curves serve as a fundamental input for reservoir simulation models, enabling more precise predictions of oil recovery efficiency and optimization of production strategies.

In addition to core data, the study incorporates production data, which encompasses historical oil and gas production rates, as well as pressure-volume-temperature (PVT) data (**Figure 8**). PVT data is vital for characterizing fluid behavior under varying reservoir conditions. It provides insights into the physical properties of the reservoir fluids, such as oil and gas densities, bubble point pressure, and formation volume factors, all of which are crucial for accurately modeling the reservoir's response to enhanced recovery techniques. The integration of core, production, and PVT data serves as the foundation for evaluating the reservoir performance and informs the selection of the most effective EOR strategies for the Asmari Formation.

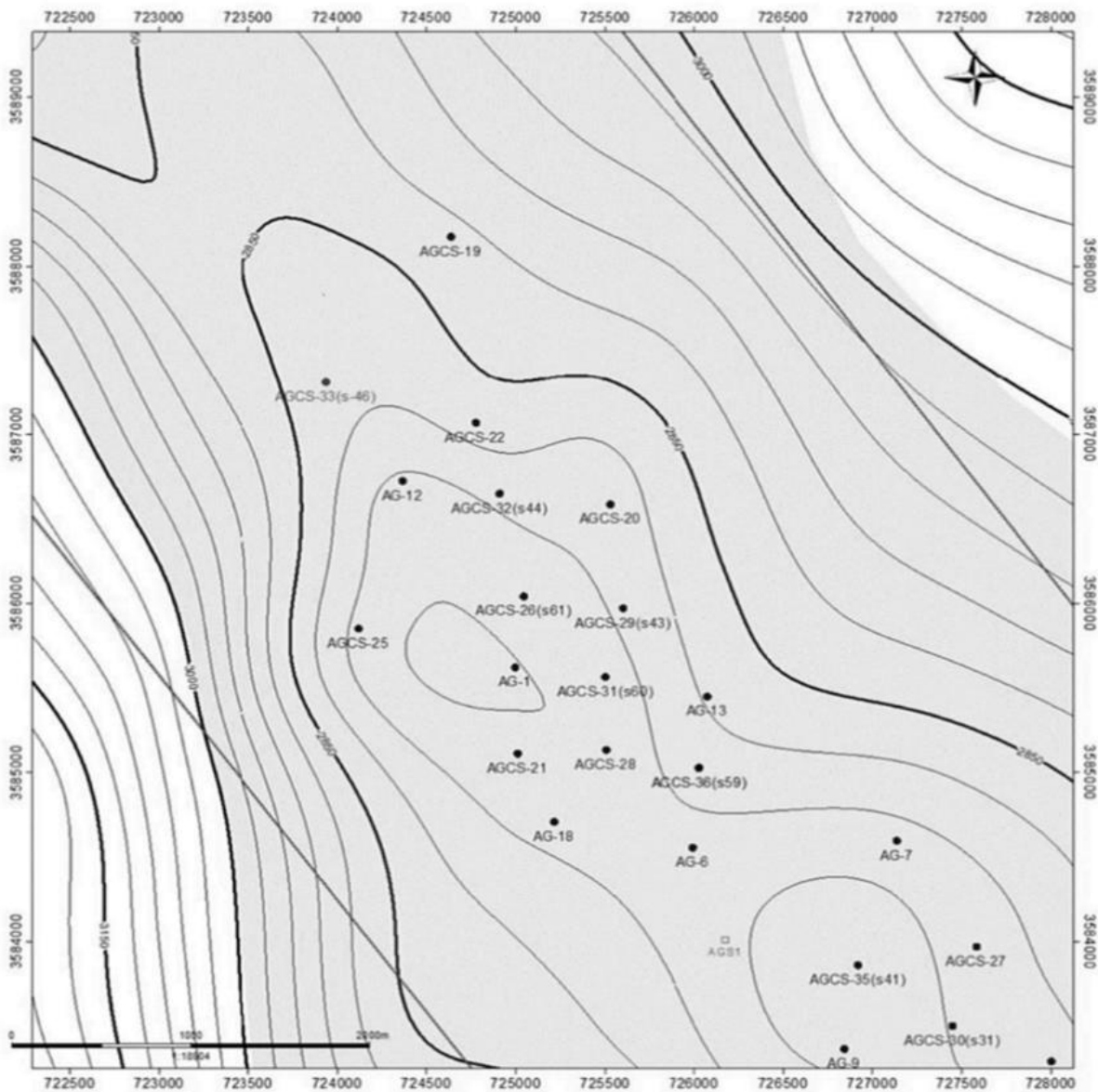


Figure 6—Location of wells in the Asmari formation within the Abu Ghirab field.

The study utilizes CMG™ commercial software to simulate well performance under miscible CO₂ injection. The primary objective is to estimate the optimal volume of CO₂ to be injected and assess the history of oil production. A key focus is determining the ideal depth for CO₂ injection and understanding how various factors, such as injection parameters, affect production rates. Additionally, the study examines the optimal injection conditions, especially in scenarios where water cut fluctuations are observed. Facies logs obtained from wireline logging data were used to construct a facies model in Petrel™ (**Figure 9**), which helped to best understand the reservoir heterogeneity. A simplified BLACKOIL model was developed using standard correlations, assuming a reservoir temperature of 150°F and a pressure range of up to 2600 psi. The model incorporates a bubble point pressure of 2600 psi, stock tank oil gravity of 40 API, and a gas density of 0.8, they were input into the simulation to ensure accurate modeling of fluid behavior under reservoir conditions. This integrated approach allows for a more precise evaluation of CO₂ injection strategies and their impact on enhanced oil recovery in the Asmari Formation.

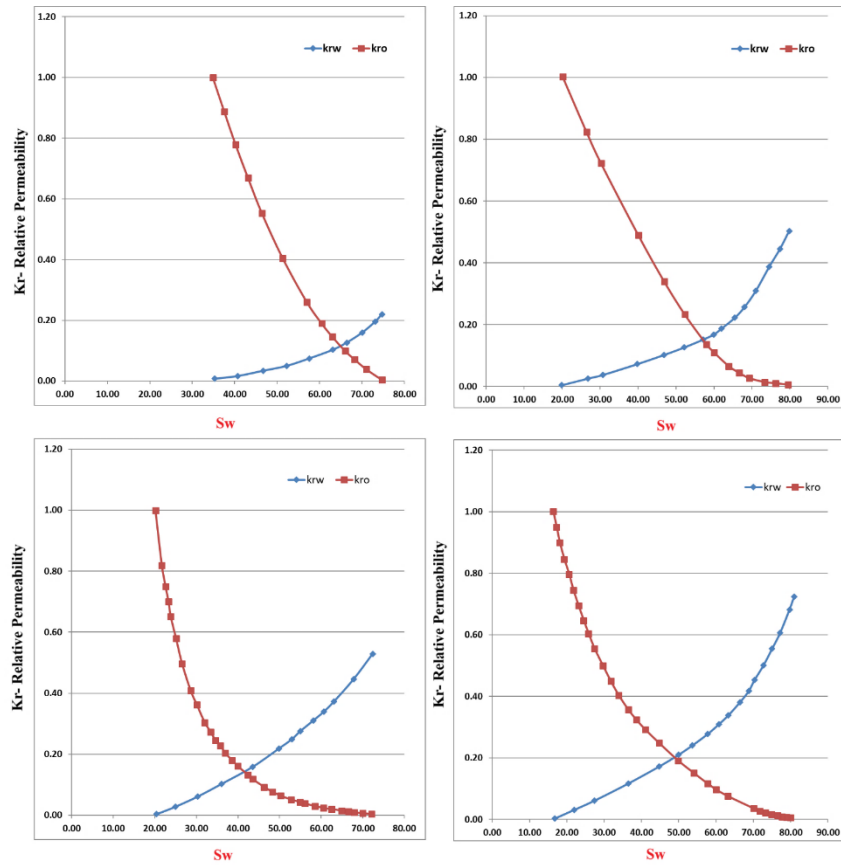


Figure 7—Oil and water relative permeability for different units of Asmari formation by core flooding.

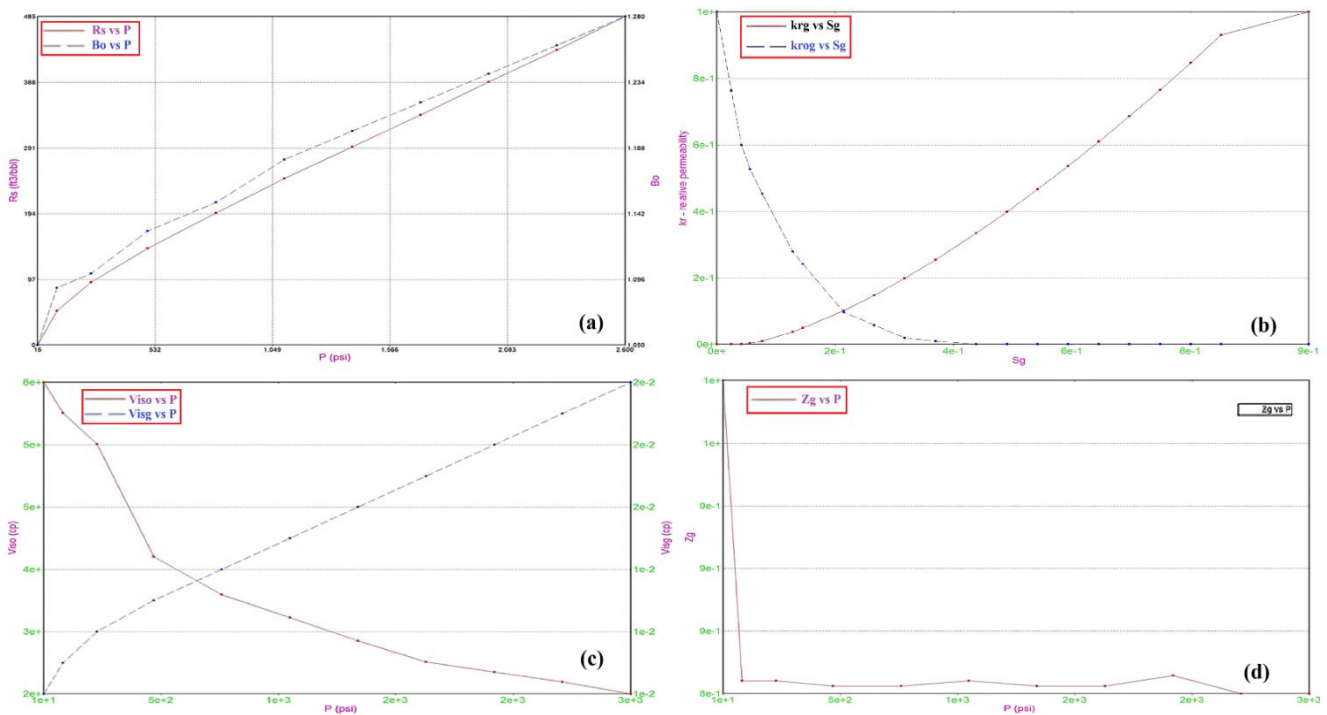


Figure 8—a) Pressure versus solution gas-oil ratio (R_s) and oil formation volume factor (B_o), b)Relative permeability of gas versus gas saturation (S_g), c)Pressure versus viscosity of oil and gas, and d)Pressure versus compressibility gas factor (Z_g).

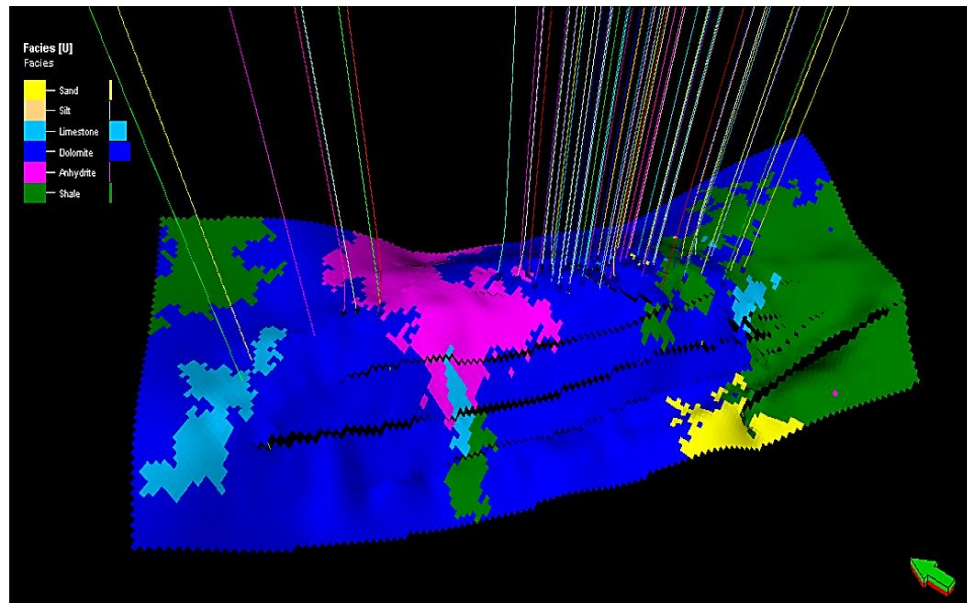


Figure 9—Facies model for Asmari formation in Abo Ghirab field (Asad and Hamd-Allah 2022).

The locations of the production wells were first marked on the map, and subsequently, the proposed injection well sites were also identified on the same map. To build the reservoir model, the lithofacies and petrophysical properties of the wells, including porosity, permeability, and water saturation, were entered based on their depth profiles. These properties were integrated into the model to represent the reservoir more accurately. The reservoir was subdivided into 29 distinct layers, each corresponding to a specific flow unit, as shown in **Figure 10**. The uppermost section of the reservoir consists of 4 layers, while the remaining sections were divided into 5 layers each. This stratification allows for a more detailed representation of reservoir heterogeneity and flow behavior, providing a better foundation for simulating fluid dynamics and optimizing both production and injection strategies.

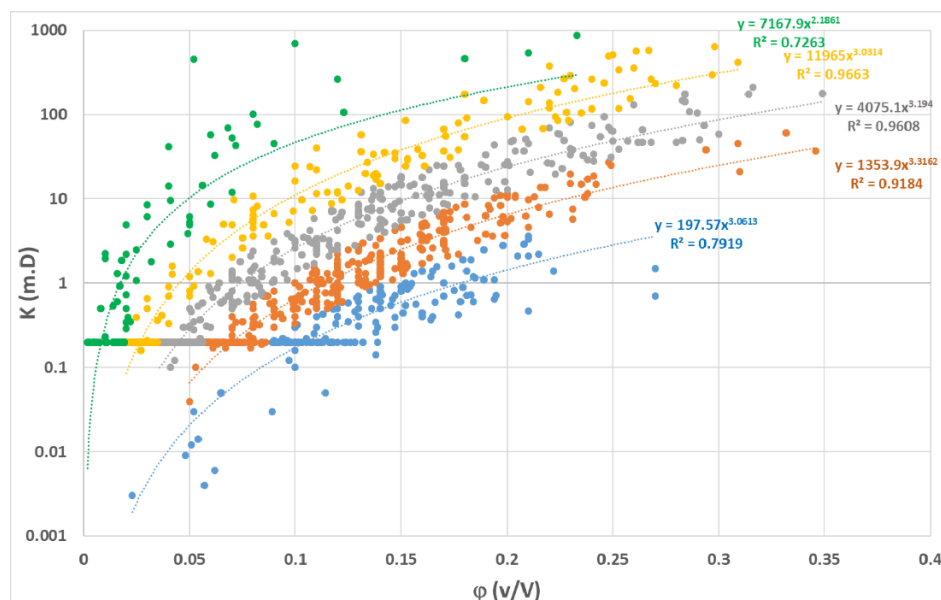


Figure 10—Flow units for lithofacies data.

Results and Discussion

Original Oil in Place (OOIP). The simulation was run to estimate the (OOIP) according to the equation,

$$OOIP = \frac{7758 \times A \times H \times \varphi \times S_{oi}}{B_{oi}} \dots\dots\dots(1)$$

where A is the reservoir area, acres; H is the average net reservoir thickness, ft; φ is the average porosity formation; S_{oi} is the initial oil saturation; and B_{oi} represents the oil formation volume factor at initial pressure, bbl/STB.

The results indicate that the estimated original oil in place (OOIP) for the southern dome of the Abu Ghirab Field is 89,331 MSTB. This represents a decrease in the reserve size for this specific portion of the field, highlighting a potential reduction in recoverable oil from this area. Given the presence of numerous faults within the Asmari Formation, which can both separate the reservoir and affect fluid flow, further exploration and appraisal of this region—along with other parts of the field—could prove valuable. Additional seismic surveys, well logging, and drilling activities may uncover untapped reserves or more accurate reservoir models, potentially increasing overall production from the Asmari Formation. Addressing the complexities introduced by faulting could also improve the understanding of fluid distribution and enhance recovery techniques, ultimately supporting long-term production in the Abu Ghirab Field.

Simulation for the Miscible CO₂ Injection. The simulation of miscible CO₂ injection from 2024 to 2030 shows no significant effect on the oil field between 2024 and the third quarter of 2026. During this time, cumulative oil production remains nearly identical, regardless of whether CO₂ injection is used. This indicates that CO₂ injection does not significantly change the field dynamics at this stage. Therefore, the simulation suggests that CO₂ injection should begin in September 2026 to initiate the miscible CO₂ flooding process, which is expected to improve oil recovery in the future (**Figure 11**). After the start of CO₂ injection in September 2026, oil production gradually increases. This increase continues steadily through 2029, with a more substantial rise in production anticipated in the latter part of that period. The gradual increase in production is attributed to CO₂ injection, which helps maintain or enhance reservoir pressure, enabling ongoing oil production through the primary recovery mechanism (i.e., natural reservoir pressure and gas drive). As long as the reservoir pressure remains sufficiently high, the primary recovery process can continue to support effective oil production, especially in the initial stages of CO₂ flooding. However, the effects of CO₂ injection become more pronounced after the onset of miscible flooding, as CO₂ aids in mobilizing additional oil that would not be recoverable through primary recovery alone.

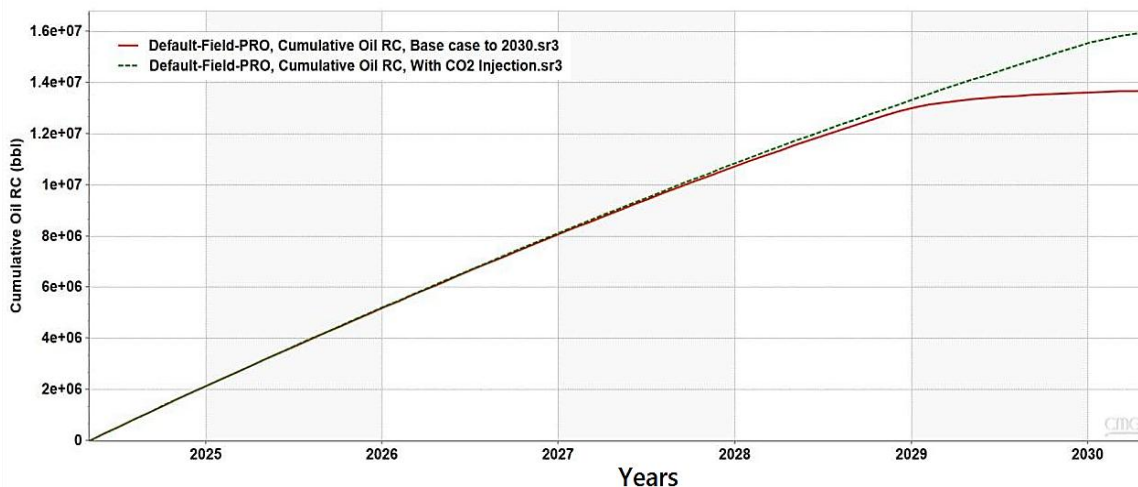


Figure 11—Cumulative oil production with and without CO₂ injection for the period from 2024 to 2030.

Figure 12 illustrates the oil production rate and cumulative oil production, both with and without CO₂ injection, from 2024 to 2030. The data indicates that, from 2024 until the third quarter of 2026, CO₂ injections have had minimal impact on the field, as oil production remains largely unchanged whether CO₂ is injected or not. However, starting from the fourth quarter of 2026, there is a noticeable increase in production linked to CO₂ injection, with production rates gradually rising as the miscible CO₂ flooding takes effect.

Despite this increase, the oil production rate declined from the end of 2028 through 2030. This decrease may be due to the gradual depletion of reservoir pressure and the dwindling effectiveness of the CO₂ injection in sustaining high production levels. This trend should be carefully considered when planning future production strategies for the wells, particularly concerning the oil prices during that period. If oil prices are lower from 2028 to 2030, the economic feasibility of continuing CO₂ injection and production may be affected, necessitating operational and financial planning adjustments.

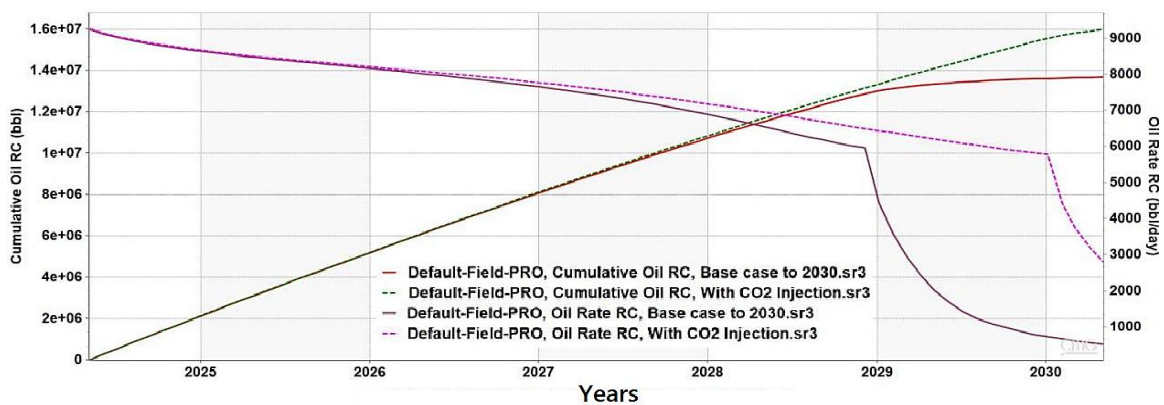


Figure 12—The oil production rate in addition to the Cumulative oil production with and without CO₂ injection from 2024 to 2030.

This study observed an increase in the gas-oil ratio starting in the third quarter of 2027. The rise in the gas-oil ratio is attributed to the injection of CO₂, which, while enhancing oil production initially, leads to a higher gas content in the produced fluids as the oil production rate begins to decline. This shift occurs because, over time, the miscible CO₂ injection primarily stimulates gas production rather than oil, particularly as the reservoir pressure stabilizes and the effectiveness of the miscible CO₂ injection diminishes.

As a result, the injection process could become less efficient in maintaining oil production, potentially reducing the overall recovery factor. This shift may make the CO₂ injection less economically viable unless oil prices during that period are high enough to offset the rising costs of CO₂ injection and the associated operational expenses. For the process to remain profitable, oil prices must be sufficiently high to cover both the capital and operational costs of injecting CO₂ and generate a reasonable return for the investor (**Figure 13**).

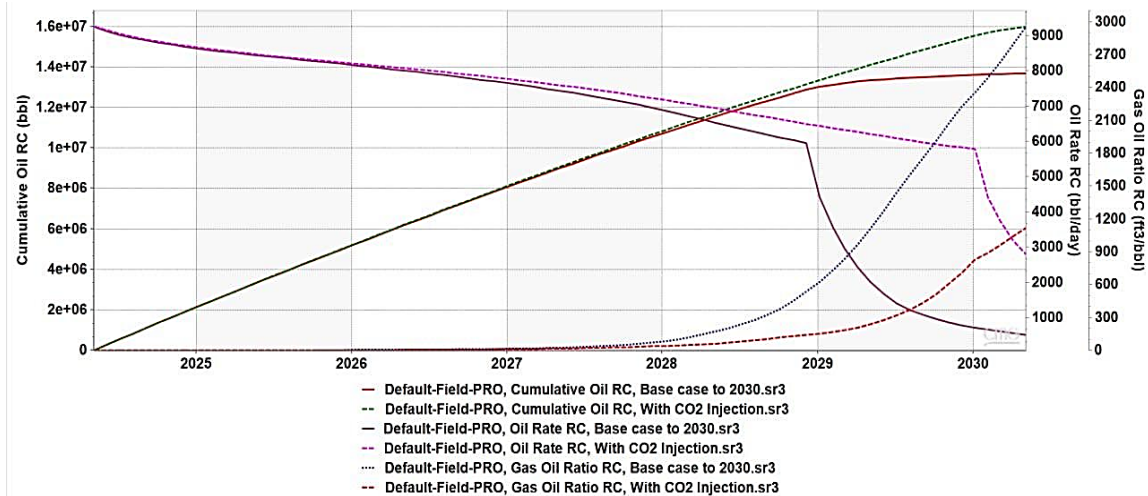


Figure 13—Gas oil ration with and without CO₂ injection for the period from 2024 to 2030.

Conclusions

The CMG™ simulator was used to model various scenarios and assess the effectiveness of miscible CO₂ injections for enhanced oil recovery (EOR) and its potential applications. Several factors, such as porosity, permeability, and formation thickness, were considered in evaluating the impact of CO₂ floods. The simulation results were compared between primary production and CO₂-enhanced production, showing an increase in oil recovery with CO₂ injection. Key findings of the study include:

1. The initial oil-in-place (OOIP) was determined to be 89331 MSTB, indicating a reduction in reserves in the southern dome of the field.
2. The simulation for CO₂ miscible injection between 2024 and 2030 revealed that CO₂ injection would have no significant impact on production through the third quarter of 2026. However, starting in the fourth quarter of 2026, a noticeable increase in production is expected because of CO₂ injection.
3. CO₂ injection should begin in September 2026 to initiate effective CO₂ flooding.
4. A rise in the gas-oil ratio (GOR) was observed starting from the third quarter of 2027, which indicates the changing dynamics of production.
5. From late 2028 to 2030, a decline in oil production rates is expected. This decline should be considered when selecting additional EOR methods to optimize the recovery of remaining oil.
6. Further exploration of the southern area of the field and other adjacent areas is recommended to enhance production from the Asmari Formation in the Abo Ghirab Field, as the formation contains numerous faults that could offer new opportunities for oil recovery.
7. The expected decline in production rates between late 2028 and 2030 should be carefully factored in production planning, particularly in relation to future oil prices.
8. In conclusion, while miscible CO₂ injection offers promising potential for enhancing oil recovery, careful attention must be paid to the timing of injection and the planning of subsequent EOR methods to manage declining production rates. Additional exploration and resource evaluation in the southern field area could further boost production in the long term.

Nomenclature

φ	=	porosity
A	=	reservoir area, acres
API	=	oil gravity

B_o	=	oil formation volume factor, bbl/STB
B_{oi}	=	oil formation volume factor at initial pressure, bbl/STB
CO_2	=	carbon dioxide
EOR	=	enhanced oil recovery
F	=	Fahrenheit
H	=	average net reservoir thickness, ft.
K	=	permeability, mD
K_{rg}	=	gas relative permeability
K_{ro}	=	oil relative permeability
K_{rog}	=	oil-gas relative permeability
K_{rw}	=	water relative permeability
MMP	=	minimum miscibility pressure, MPa
MSTB	=	million stock tank barrel
OIP	=	Oil in Place
OOIP	=	original oil in place
Pb	=	bubble point pressure, MPa
Psi	=	pound per square inch
PV	=	pore volume
PVT	=	Pressure-Volume-Temperature
R_c	=	recovery
R_s	=	solution gas-oil ratio
S_g	=	gas saturation
S_{oi}	=	initial oil saturation
S_w	=	water saturation
Z_g	=	compressibility gas factor

Conflicting Interests

The author(s) declare that they have no Conflicting interests.

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