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Research Article

OPTIMIZING CO_2 AND N_2 MISCIBLE GAS INJECTION FOR ENHANCED OIL RECOVERY IN THE LOWER INDUS BASIN, A SIMULATION STUDY

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ABSTRACT

The depletion of oil reservoirs worldwide has led to the increased importance of enhanced oil recovery (EOR) techniques to maximize production from mature fields. This study focuses on optimizing CO_2 (Carbon di oxide) and N_2 (Nitrogen) miscible gas injection strategies for enhanced oil recovery in the Lower Indus Basin of Pakistan. Using advanced reservoir simulation techniques, the study aims to determine the optimal injection rates for maximizing oil recovery. This study evaluates the potential of both CO_2 and N_2 injection at variable injection rates as methods of recovering oil from the same depleted reservoirs Both injection gases were injected at similar injections rate using the same injection patterns so that a fair comparison can be conducted. The results indicate that there is a considerable difference in the efficiencies of recovery between the injection of CO_2 and N_2. For low injection rates (LIRs) of CO_2, there is a consistent increase in the recovery factors, in which the miscibility of CO_2 with oil is better than others. The recovery factors for CO_2 at those rates trended increasingly better, thus establishing CO_2 as an efficient technology for EOR in depleted reservoirs. On the other hand, the injection of N_2 resulted in slight increases in oil recovery and having the advantage of pressure support, but it was observed immiscible with oil, which formed a very severe restriction to its displacement. More differences are revealed while comparing HIRs for both gases. The increase in rates of CO_2 injection were accompanied by the correlative increase in rates of oil displacement and in the recovery factors in all scenarios, which proved CO_2 to be one of the very effective EOR methods. Injecting N_2 at higher rates was also somewhat problematic concerning efficiency in oil recovery. Although higher N_2 rates improved maintenance of reservoir pressure, the resulting oil displacement was less than that from CO_2. High operational costs were another concern that high injection rates (HIRs) of N_2 brought forth, and the question that arose was whether it was economically feasible compared to the great benefits that CO_2 achieved. These results emphasize the fact that the right injection gas method should be chosen so as to recover maximum oil content, and in this regard, CO_2 has been proven to be a better one at HIRs in this region.

Keywords: Miscible Gas, CMG Simulation, N_2&CO_2 Injection, EOR in Depleted Oil reservoirs.

INTRODUCTION

The depleted oil reservoirs, by their nature, are characterized by low reservoir pressure and reduced oil saturation two characteristics that particularly present challenges to EOR applications. Recovery operations under such challenging conditions need an in-depth understanding of how injection parameters interact with reservoir properties. With the day by day demand for energy ever-increasing and conventional oil production constantly on the decline, methods of enhanced oil recovery become all the more significant. Out of these several EOR techniques, the efficiency of the injection operations has a far-reaching effect on overall oil recovery. EOR is the technology applied after using primary methods to extract more oil from the reservoirs, which is the increase in the recovery rate, typically up to 30-60%, which helps to maximize the oil produced from the reservoir(Torsæter 2021; Sircar *et al.,* 2022). Critical parameters of injection that go on to become key parameters of success for the EOR projects include injection rate, and pressure(Alfarge, Wei, and Bai 2017).

Enhanced oil recovery is the term used to describe a variety of methods applied to make extraction of more crude oil from a reservoir possible after primary and secondary methods are exhausted. There are three major EOR kinds: thermal, gas injection, and chemical all too complex and expensive but help prolong an oil field's life and increase production(Sikiru *et al.,* 2023). CO_2 injection for enhanced oil recovery has two-fold benefits: improvement in oil recovery and carbon dioxide sequestration(Alam *et al.,* 2022).Utilizing and storing CO_2 to minimize global warming(Awan and Kirmani 2024), with a focus on CO_2-enhanced oil recovery and its storage potential in oil reservoirs. Though CO_2 EOR is a mature technology applied in many reservoir types(Zhou *et al.,* 2023). CO_2injection in depleted oil reservoirs is the technique presents a very promising method of reducing greenhouse gas concentrations from the atmosphere. The most important challenge that the process addresses is the effective evacuation of these reservoirs through residual oil recovery*(Sang et al.,* 2024). A comprehensive review of EOR techniques has been discussed by (Tunio *et al.,* 2011), who has also pointed out that besides increasing the recovery rates, the injection of CO_2 offers an added advantage of CO_2 sequestration.

Application of CO_2 for enhancing oil recovery in the injection process is a well-proven technique. In the classification, it could either be miscible or immiscible depending on pressure injection. It is miscible when the pressure applied is more than minimum miscibility pressure MMP while it becomes immiscible below MMP. MMP is the lowest pressure at which CO_2 is fully miscible with the oil (Enab 2023).The determination MMP has been discussed by (Yellig and Metcalfe 1980)Miscible CO_2 flooding requires the reservoir to be brought back to a pressure level close to the original, to ensure that the CO_2 can thoroughly mix with oil for better recovery (Hill, Li, and Wei 2020).Enhanced oil recovery (EOR) techniques, particularly miscible gas injection, have become a vital tool for extracting additional hydrocarbons from these mature reservoirs. CO_2 and N_2 miscible gas

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injection are two of the most promising EOR methods, capable of improving recovery by reducing the oil's viscosity, increasing oil displacement efficiency, and enhancing sweep efficiency. The simulations carried out by (Alam *et al.,* 2022)for a period of 20 years have demonstrated that the highest recovery of oil, about 73% of the OOIP, would be received through the direct injection of CO_2 into the reservoir using vertical wells

The Lower Indus Basin, located in southern Pakistan, is part of the larger Indus Basin, which has been a significant producer of oil and gas for decades(Ahmad. 2018). The basin's geological complexity, coupled with its mature reservoir status, presents challenges for oil recovery. Pakistan is exploring several subsurface storage sites for CO_2, as a part of its efforts toward supporting global net-zero carbon ambition. Future benefit will be received by industries through utilization of the stored CO_2(Ahmed *et al.,* 2024). Depletion in these reservoirs has reduced reservoir pressure, making it more difficult to recover the remaining oil. Implementing CO_2 and N_2 miscible gas injection presents an opportunity to revitalize these reservoirs. The key characteristics of the Lower Indus Basin include: Complex stratigraphy with varying reservoir qualities, including sandstones and shales. Depleted pressure, moderate to high temperatures, and variable permeability and porosity. Mature reservoirs with declining production, requiring advanced EOR techniques for enhanced recovery. The Lower Indus Basin is one of the best-studied sedimentary basins in the country, with a distinctly high success rate of petroleum exploration. Two hundred and one wells have been drilled, out of which 35 have proved to be oil wells and 37 gas wells, which gives a success ratio of 36%.(Ahmad. 2018). The Lower Indus Basin of Pakistan is a key region for oil and gas exploration, but like many mature fields globally, its reservoirs are experiencing significant depletion (Ahmad. 2018). Based on the simulation, the optimal injection strategy involved using a high proportion of CO_2 at pressures above the minimum miscibility pressure (MMP). This strategy provided the highest oil recovery, with optimal injection rates balancing the need for rapid recovery and controlled gas breakthrough.

Implementing miscible gas injection in the Lower Indus Basin comes with several challenges like Availability of CO_2. CO_2 sourcing and transportation to the injection site can be costly and logistically challenging. Secondly Operational Costs: High injection pressures require robust infrastructure and energy consumption, increasing operational costs. And the Geological Complexity of the reservoir. The heterogeneous nature of the Lower Indus Basin's reservoirs complicate gas injection, requiring site-specific optimization for each reservoir. This study focuses on optimizing miscible gas injection techniques in the Lower Indus Basin, a region characterized by complex reservoir conditions, including varying permeability, porosity, and temperature gradients. The goal is to investigate the impact of different gas injection strategies on oil recovery, leveraging simulation tools to identify the best practices for maximizing recovery.

METHODOLOGY

The research methodology comprised reservoir simulation with CMG (Computer Modelling Group) GEM software, especially designed to model compositional and miscible gas injection processes. The simulation model includes information from the Lower Indus Basin so that it has enough field-specific data to represent reservoir conditions and predict the response of injected gases. Major aspects like reservoir geology, permeability ranging from 50 mD to 60 mD, and porosity from 15% to 20%, have also been mapped for realistic modeling. Pressure distribution was set based on historical production data with averages ranging from 2,500 psi to 3,500 psi typical for mature fields. Fluid properties including specific PVT analysis were critical to simulate the phase behavior of the oil and gases under reservoir conditions showing CO_2 to be far better in terms of solubility and displacement efficiency compared to N_2. Temperature of the reservoir was set between 150°F to 200°F, which greatly affected gas interactions. Injection rates were divided into low and high injection rates at 50,000 SCF/day and 20,000 MSCF/day, respectively. The injection rates had been designed keeping in consideration that there should not be a rise in the pressure of the reservoir during oil recovery processes. Miscibility was a necessity for efficient displacement of oil and thus was achieved in the pressure interval of 2,500 psi to 3,000 psi. A general grid size of 30x30x10 had been used for the model in order to take care of geological heterogeneities. The near injector and producer wells resolution was high. The model determined optimal gas injection strategies for CO_2 and N_2 that maximize oil recovery by tuning key parameters. It adds insight into the geological characteristics and gas injection challenges in the Lower Indus Basin, thereby underlining the roles of EOR techniques in maximizing recovery from depleted reservoirs. The results provide a robust framework for directing enhanced oil recovery operations under similar conditions.

RESULTS AND DISCUSSION

The simulation results provided insights into the performance of different gas injection strategies. The analysis was divided into two main parts: the impact of injection rate and pressure, and the comparison between CO_2 and N_2 miscible gas injections based on four cases of injection patterns represented by four cases as Case-1 for one injector at corner and one producer at Centre, Case-2 for two injector at corners and one producer at Centre, Cas-3 for three injector at corners and one producer at Centre and Case-4 represents the four Injector at Corners and one producer at Centre further as shown in fig 1. Left and right respectively for CO_2 and N_2 injection.

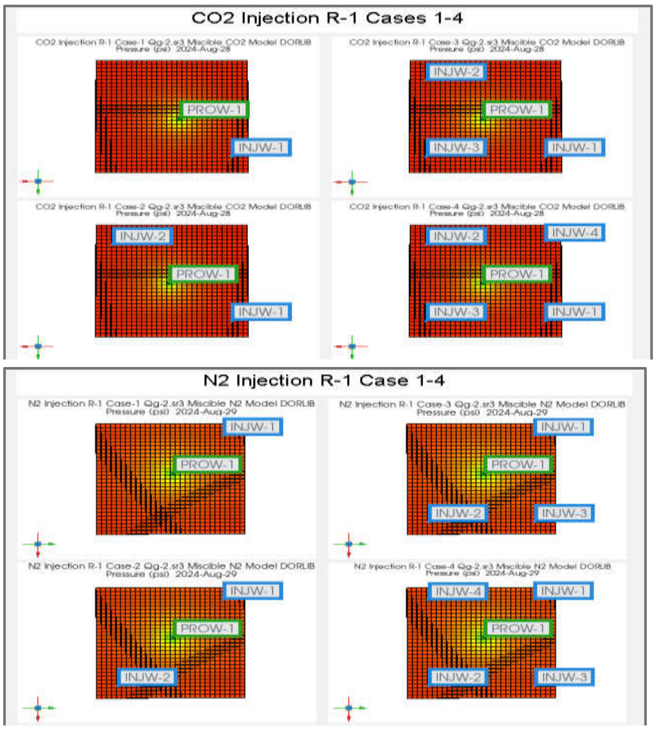


Fig 1. Four Case of CO_2& N_2Injection Patterns

Impact of CO_2 & N_2 Injection Rate on Oil Production Rate

The lower injection rates (LIRs) of 0.05, 0.1, 0.5 & 1.0 MMSCFD represented for Qg-1, Qg-2, Qg-3 and Qg-4 respectively for above

CO_2 Injection rates. Similarly, for the CO_2 injection at higher rates of 5, 10, 15 & 20 MMSCFD represented for Qg-8, Qg-9, Qg-10 and Qg-11 respectively for above CO_2 Injection rates were used for recovery of remaining or depleted reservoir. It was observed that the HIRs increased oil displacement, but excessive rates caused early gas breakthrough and reduced sweep efficiency, leading to lower overall recovery in some cases.

Oil Production Rate at LowerCO₂Injection Rates

Analysis of oil production rates obtained through CO_2 injection at different rates of 0.05, 0.1, 0.5, and 1.0 MMSCFD (Million Standard Cubic Feet per Day) for the recovery of remaining or depleted oil in the reservoir shed light on the correlation between injected gas volumes with the efficiency of recovery of oil in the field. Oil rate typically increases modestly at the lowest CO_2 injection rate of 0.05 MMSCFD; in any case, recovery is not much affected by this. This was also due to the fact that lesser gas volume injected into the reservoir was found not to be sufficient enough to mobilize any large quantity of oil, especially in a depleted reservoir where pressure support was too miniscule.

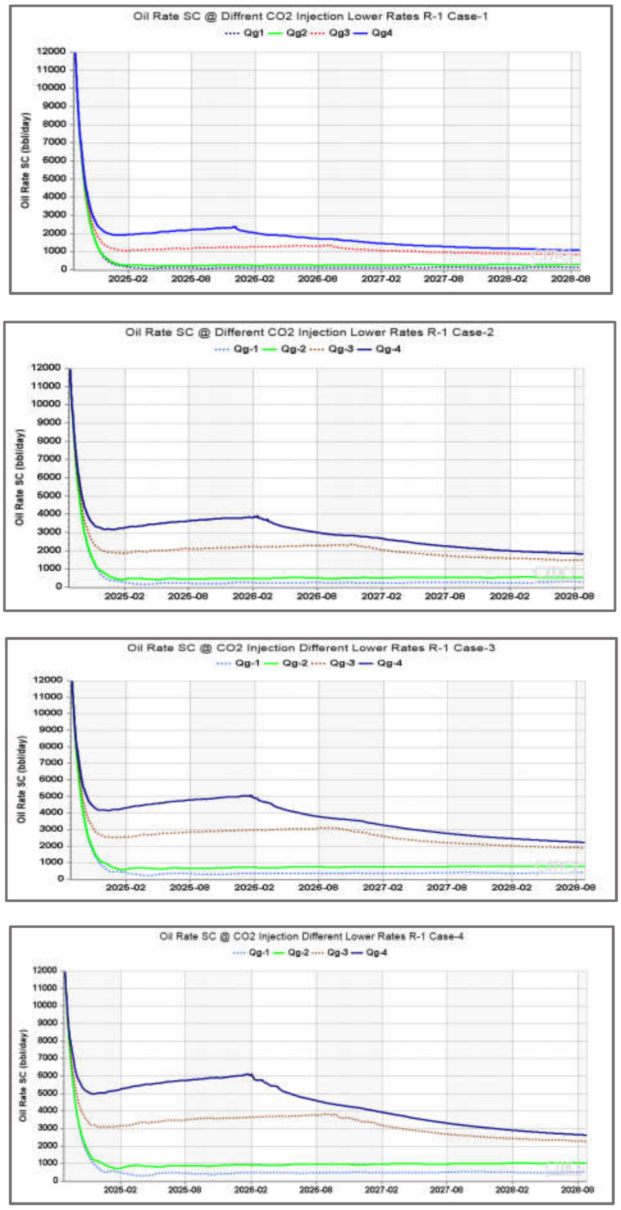


Fig 2. Oil Production Rate at Lower CO_2 Injection Rate for Case 1-4

Even at an injection rate of 0.1 MMSCFD, much higher than the lower rates, considerable improvements in oil production are observed in fig 2. The additional CO_2 now would act as better pressure support and enhancement in the efficiency of oil displacement.

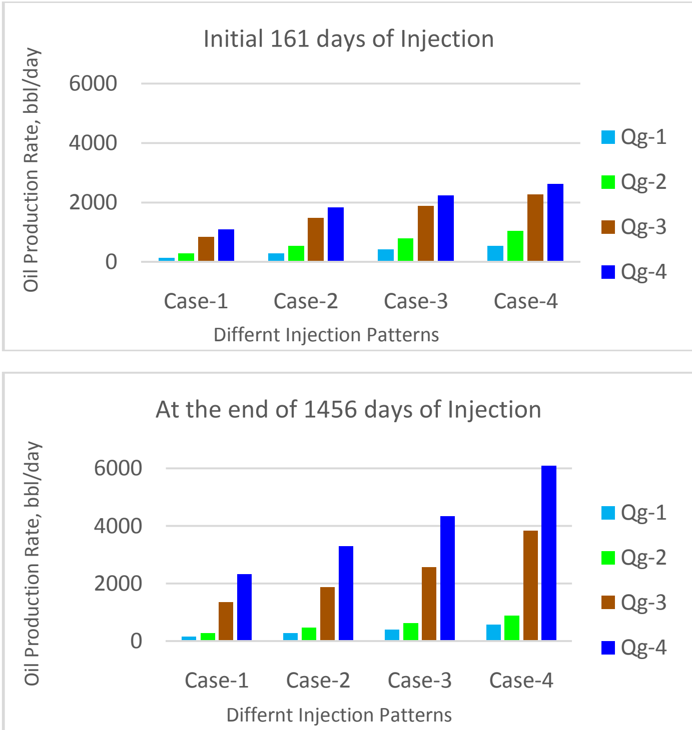
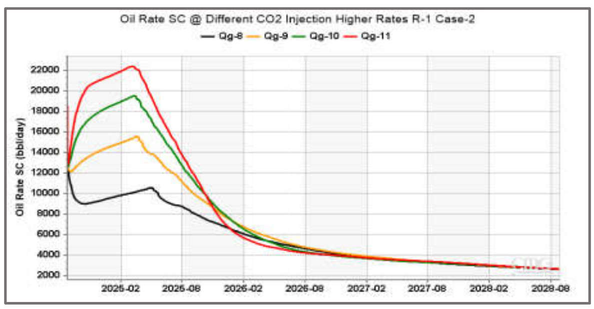


Fig 3. Oil Production Rates at Low CO_2Injection Rates during initial and final

At 0.5 MMSCFD, higher reservoir pressure and better oil displacement increases oil production. At this rate, injected CO_2 improves miscibility with oil for a more efficient recovery. In most depleted reservoirs, this rate is between the type of injection volume, and that of recovery effectiveness; thereby assuring the highest production in relation to large injection rates. At the maximum injection rate of 1.0 MMSCFD, oil production peaks at the highest possible injection rate as shown in fig 3. The huge volume of CO_2 assures good pressure maintenance and oil displacement for full miscibility with a significant reduction of oil viscosity so that high production rates are realized, making it very efficient for recovery.

Oil Production Rate at HIRs of CO₂

The resolution of the discussion on injection rates at higher rates for oil recovery from depleted reservoirs is to inject CO_2 into the reservoir at rates of 5, 10, 15, and 20 MMSCFD. In this regard, at a rate of 5 MMSCFD, crude oils recover significantly with improved pressure maintenance and better miscibility with oil, which improves displacement efficiency by reducing viscosity.



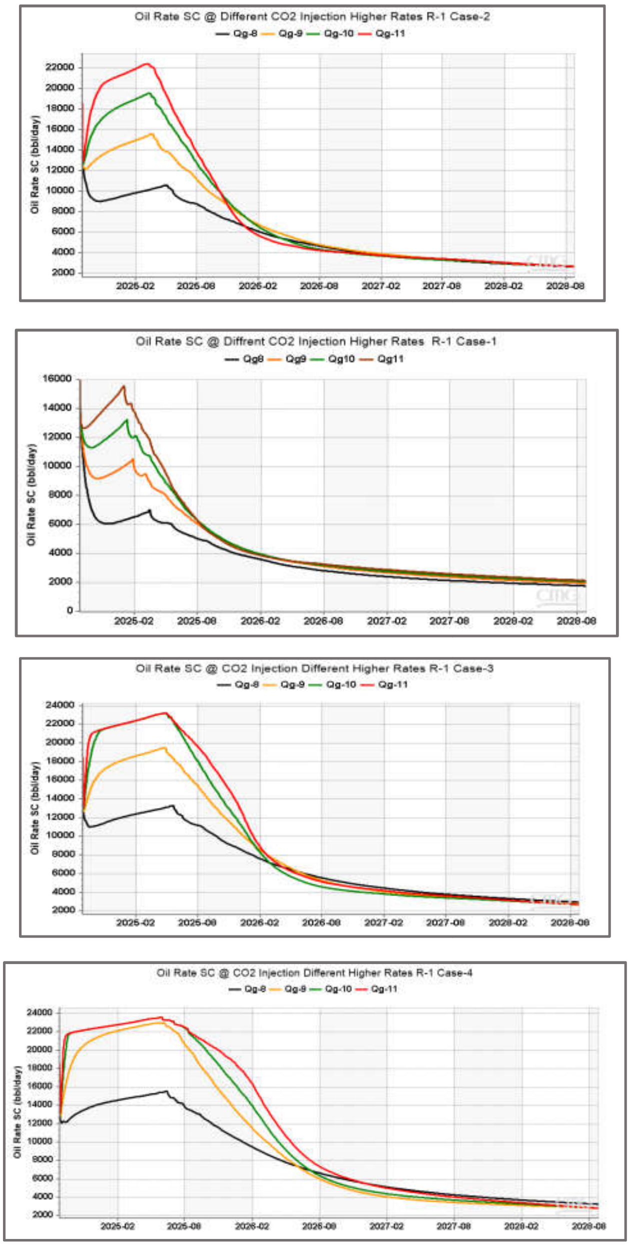


Fig 4. Oil Production Rate at Higher CO_2 Injection Rate for Case 1-4

The rate 10 MMSCFD referred as Qg-9 in this study is very effective in moderately heterogeneous reservoirs, and thus, for many field operations, it is the most appropriate rate. It gives more coverage and better miscibility and improves oil recovery by reducing viscosity and making flow toward production wells. The oil begins to rise further to much higher levels when the gas rate is at 15 MMSCFD as shown in fig 4. The greater volume of CO_2 will enable better sweep of the reservoir, especially in heterogeneous ones. However, the injection pressure is high and threatens channeling, especially in zones of higher permeability, hence there is danger of reservoir integrity at that rate.

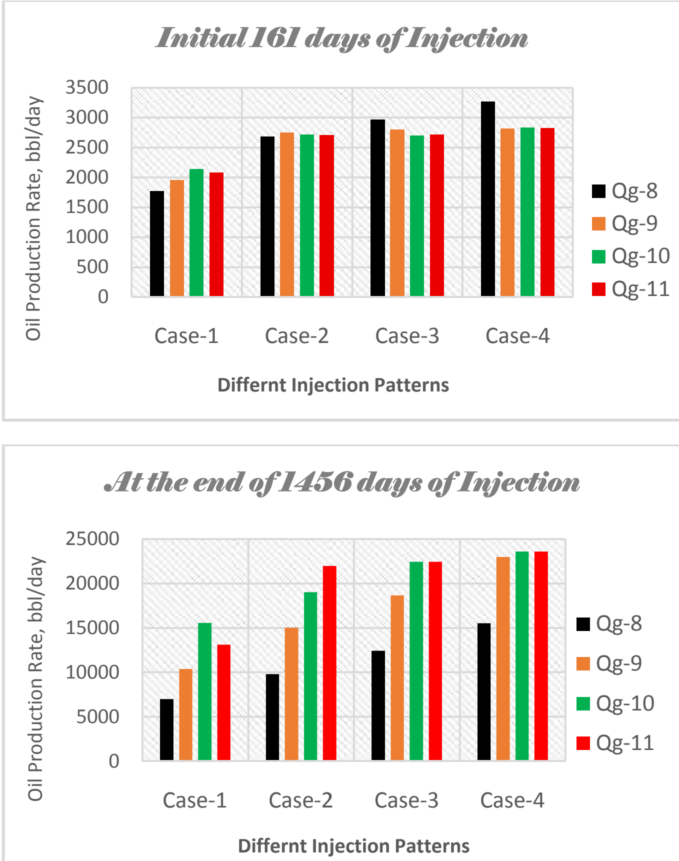
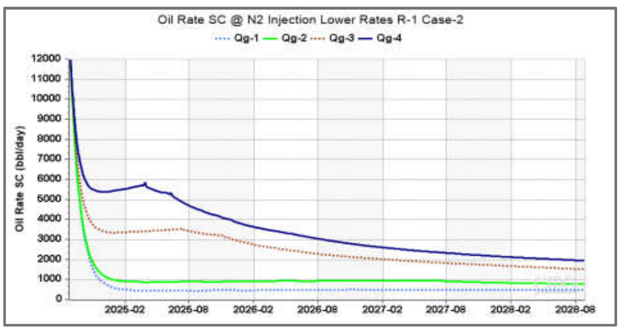


Fig 5. Oil Production Rates at HIRs of CO_2 during initial and final

From 10 MMSCFD, the CO_2injection shows better displacement and miscibility, hence resulting in better oil recovery due to viscosity reduction and flow encouragement into the production wells. The Qg-8 injection rate has delivered better result in cases 2, 3 & 4. This rate would be far better than other higher rates at initial period of injection later it become unstable recovery as shown in bar charts in fig 5. Pressure maintenance is much more improved but, at this operating rate, expenses will be higher, hence it does require careful economic consideration.

Oil Production Rate at Lower N_2 Injection Rates

N_2 injection rates of 0.05, 0.1, 0.5, and 1.0 MMSCFD were employed in oil recovery in a depleted reservoir. For 0.05 MMSCFD, pressure support and oil production were mainly insignificantly affected with very poor displacement efficiency and, hence, not much successful compared to CO_2.



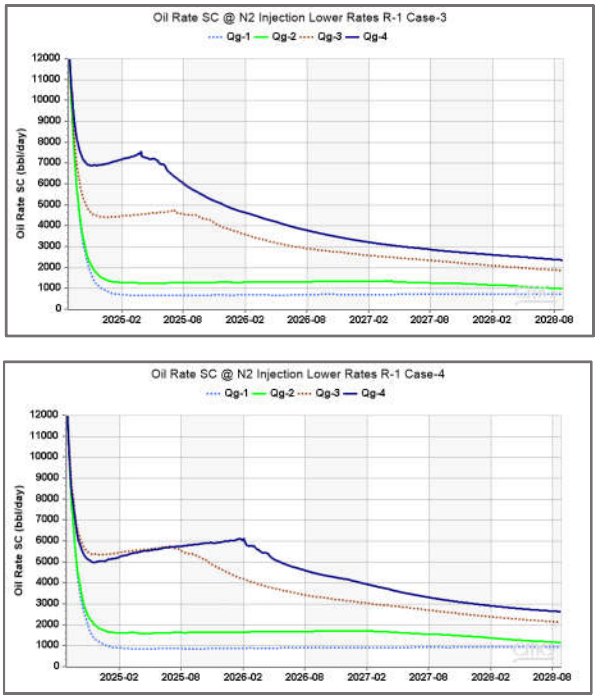


Fig 6. Oil Production Rate at Lower N_2 Injection Rate for Case 1-4

For 0.1 MMSCFD, the productions increased with improved pressure maintenance but N_2's immiscibility limited oil displacement compared to CO_2. Oil production increased dramatically at 0.5 MMSCFD while pressure support was greatly increased, even though N_2 was less effective overall as shown in fig 6. & 7. At 1.0 MMSCFD, N_2 generated the most oil production, as this supported the reservoir pressure over a greater volume though still less effective than CO_2 at comparable rates. Nitrogen injection is generally carried out with the purpose of pressure maintenance and should thus be used in those reservoirs where reservoir drive is to be held important, even if this immiscibility leads to somewhat lower efficiency than miscible gases like CO_2.

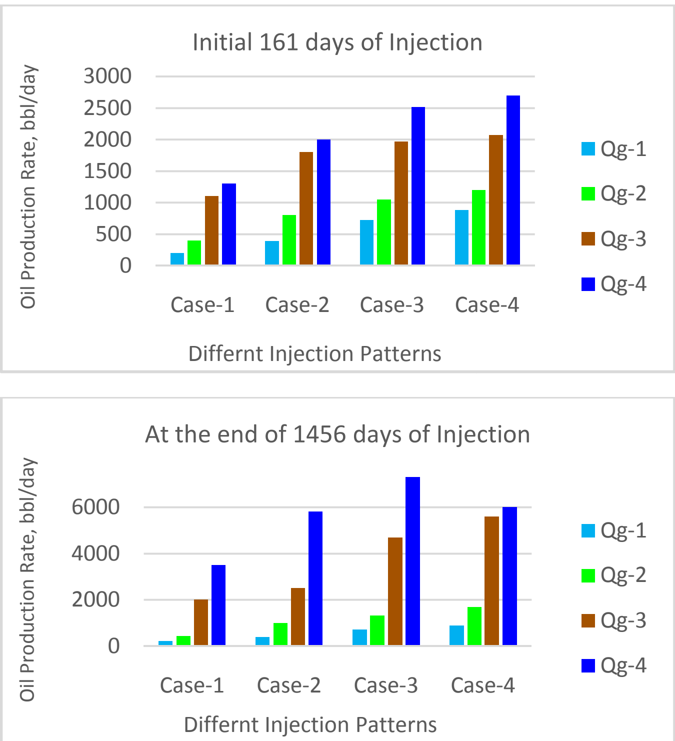


Fig 7. Oil Production Rates at Low N_2Injection Rates during initial and final injection period

Oil Production Rate at Higher N_2 Injection Rates

Similarly, the N_2 HIRs of 5, 10, 15, and 20 MMSCFD to monitor oil recoveries. The improvement in oil displacement efficiency is not gained with the rise in injection rates for N_2, but the fact is different from CO_2 injection. As it can be observed from fig 8 & 9. at 5 MMSCFD, N_2 provides supplementary pressure support, and its oil displacement efficiency is low compared to that of CO_2, hence providing production higher than lower rates but lower than that can be produced by CO_2.

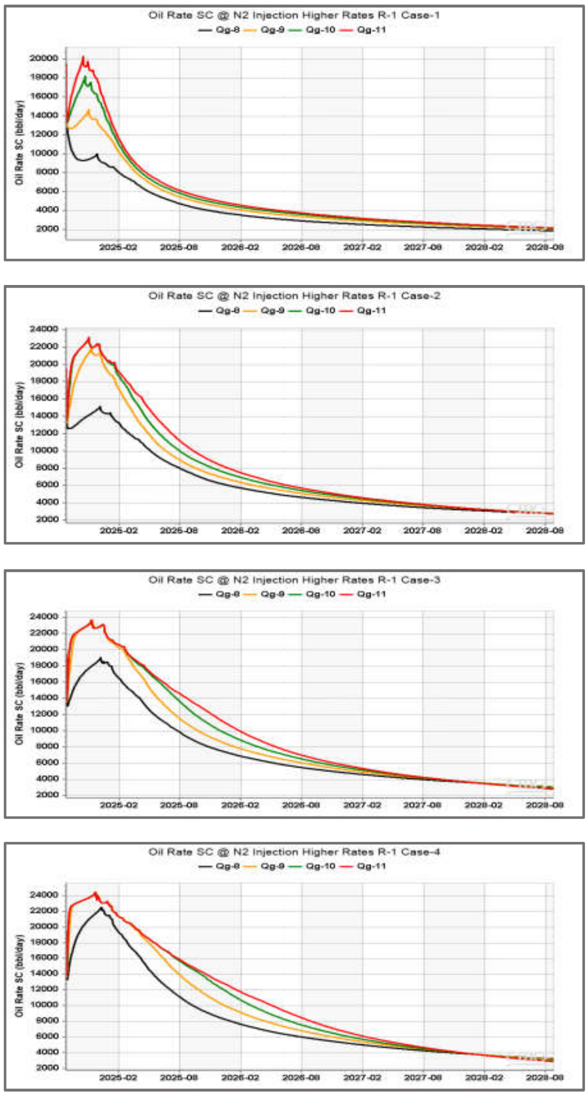
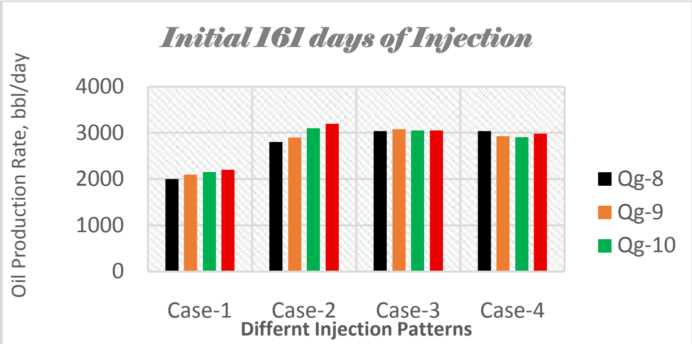


Fig 8. Oil Production Rate at Higher N_2 Injection Rate for Case 1-4

At 10 MMSCFD, N_2facilitates pressure maintenance but does not meet the maximum displacement of oil compared to CO_2. This rate may stabilize production but is less efficient, especially in those reservoirs in which miscibility is critical for the enhanced recovery. At 15 MMSCFD, the effectiveness of N_2 injection decreases further to gas channeling that affects less permeable areas having less effective displacement due to high-pressure zones produced by N_2. At maximum injection rate of 20 MMSCFD, while preserving the maximum pressure of N_2, it would provide the least effective oil displacement. Overall, such higher rate injections with N_2 provide little benefit to oil production because N_2has no miscibility with oil, thus causing inefficient displacement as most gas bypasses the oil-rich zones.



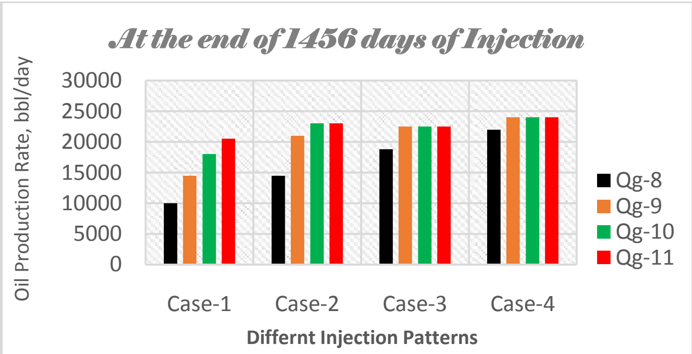


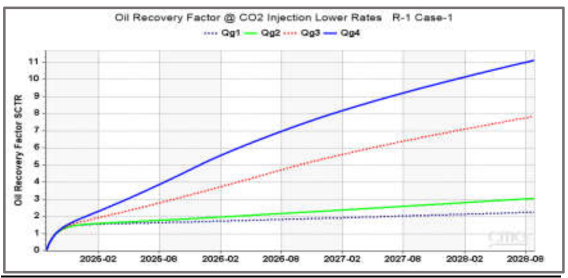
Fig 9. Oil Production Rates Obtained at N_2 High Injection Rates during initial and final

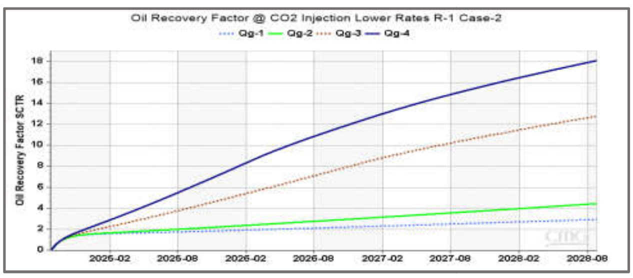
Impact of CO_2& N_2Injection Rate on Oil Recovery

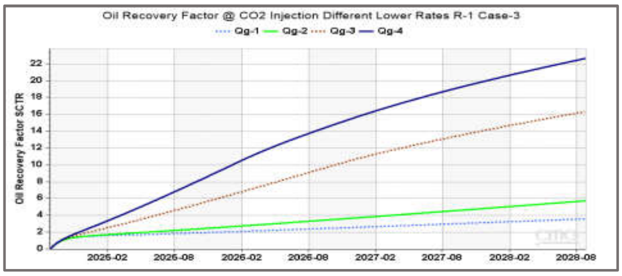
In this section, the analysis of The oil recovery factor of CO_2 injection and N_2 Injection carried out to study the effects of LIRs(Qg-1 to Qg-4) and high injection rates (Qg-8 to Qg-11) of CO_2 and N_2 on the oil recovery in a depleted reservoir within the Lower Indus Basin.

Oil Recovery at Lower CO_2 Injection Rates

At Qg-1 and Qg-2, at LIRs of CO_2, cases' differences in recovered improvements are pretty low. For example, at Qg-1, recovery factors vary between 2.25% Case 1 up to 4.24% Case 4, slightly up at Qg-2, now between 3.05 and 6.96%. This means, therefore, at such low levels of increases in the injection rates, the recovered quantities do not change much, especially in cases 1 and 2. As the injection rate progresses to Qg-3 and Qg-4, the effect on recovery becomes so pronounced.







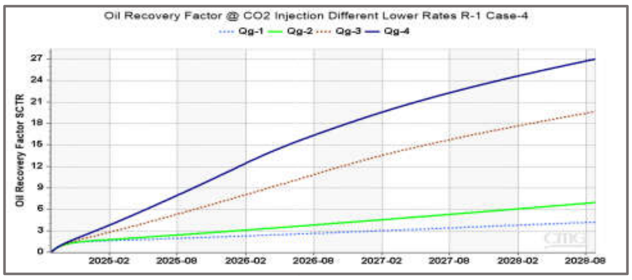
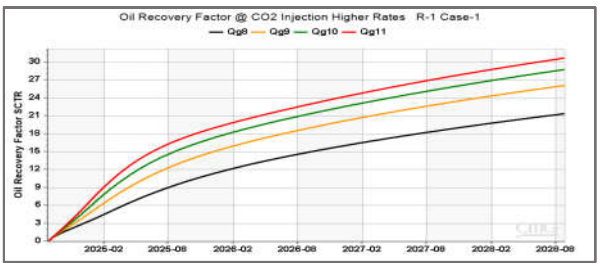


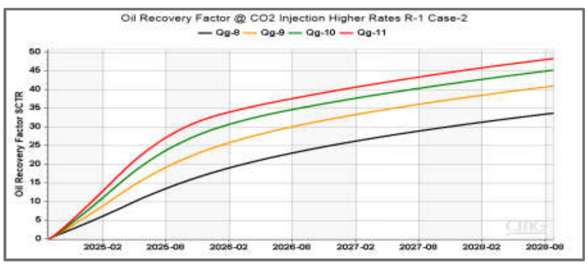
Fig 10. Oil Recovery Factor at Lower CO_2 Injection Rate of Case 1-4 for 4 Years

The recovery factor varies between 7.84% and 19.66%, which improves greatly, especially at later runs in Qg-3. The recovery factor is maximum at Qg-4, varying from 11.11% to 26.993%, indicating that recovery is highly consistent and reproducible in all cases with increased injection rates. For instance, Case 2, for example, makes a rise in recovery from 2.94% at Qg-1 to 18.085% at Qg-4 as of fig 10. This indicates that the highest injection rate made an difference towards oil recovery. Therefore, Qg-4 was the most effective injection rate that entailed the best results for all the cases presented, hence validating that the increase in the rate of CO_2 injection significantly enhances the oil recovery.

Oil Recovery at Higher CO_2 Injection Rates

Recovery factors for all four cases rise affectedly from Qg-8 to Qg-11 but higher injection rates (HIRs)also needs to balance it and it must be struck between recovery efficiency and economic feasibility. While Qg-8 is the lowest of the HIRs it does represent a significant gain in recovery over the LIRsso, it represents a cost-effective mechanism to gain moderate quantities of additional recovery at lower expense than the higher rates. Qg-9 has a recovery improvement level, which is significantly ranging from 26.074% in Case 1 to 59.53% in Case 4 while creating proper balance above performance.





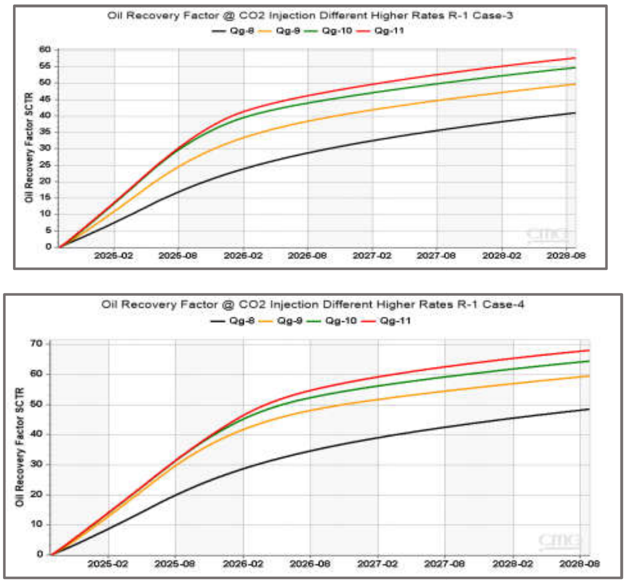


Fig11 Oil Recovery Factor at Higher CO_2 Injection Rate for Case 1-4

The recovery raised at Qg-10 to 28.74% to 64.48%, which gives a significant advantage above Qg-9, mainly during later cases as of fig 11 & 10.

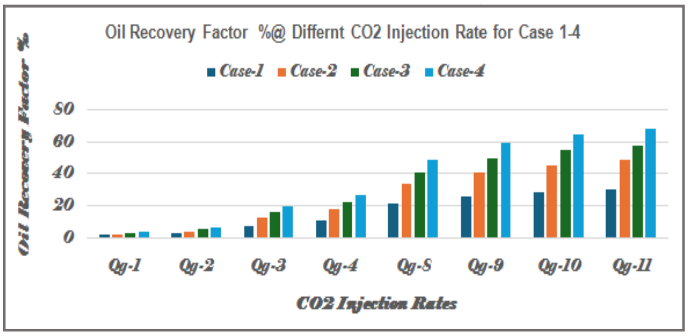


Fig 12 Oil Recovery Factor % at Different CO_2 Injection Rates of all cases 1-4

The increase from Qg-9 to Qg-10 appears higher than that between Qg-10 and Qg-11, and the conclusion is that Qg-10 is an optimal balance between performance and economic efficiency. Qg-11, whose recovery can rise up to a maximum extent of 30.66% to 68.06%, is the highest rate, but the cost rise is expensive and the marginal benefit above Qg-10 is only 3-4%. Qg-11 should be applied only where maximum recovery is a matter. Qg-8 provides a reasonable recovery enhancement, whereas Qg-9 provides a higher recovery as compared to Qg-8. Qg-10 is even having better recovery, especially in late cases. Qg-11 gives a greater recover and higher than all cases i.e. Qg-9 or Qg-8. Qg-11 should be considered only when full recovery is crucial from high residual or remaining oil.

Oil Recovery at Lower N_2 Injection Rates

As shown in fig 13 and 14, for LIRs of nitrogen ranging from Qg-1 to Qg-4, recovery factors increase. At Qg-1, the recovery factors are between 3.0% in Case 1 and 6.5% in Case 4, which is very inefficient for oil displacement. On the other hand, at Qg-2, recovery factors increase significantly and run from 4.25% in Case 1 to 10.5% in Case 4. For Case 4, recovery factors almost double at Qg-2 as compared to Qg-1. Qg-3 apparently follows through with much improved recovery factors, between 9.5% in Case 1 and 23.0% in Case 4, making it very effective especially in a later case. Qg-4 offers the highest recovery factors that lie between 12.5% for Case 1 and 27.0% for Case 4; however, the 4% gain from Qg-3 to Qg-4 indicates diminished returns. Overall, Qg-1 gives minimum recovery and Qg-2 offers moderate recovery but Qg-3 strikes a balance with stability.

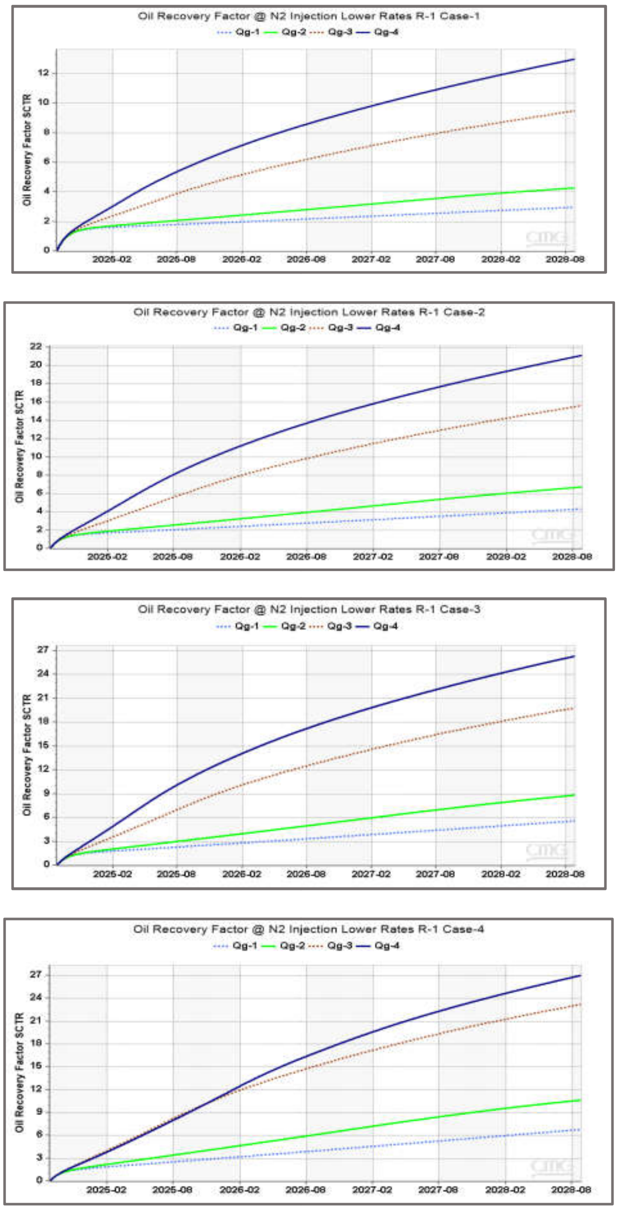


Fig13 Oil Recovery Factor at Lower N_2Injection Rate for Case 1-4

Oil Recovery at Higher N_2 Injection Rates

The improvement in the injection rate of N_2 at the high values leads to good improvements in the overall factor recovery for all four cases. Recovery is boosted up to as high as 23.5% for Case 1 and to 50% for Case 4. The comparative results show a dramatic improvement by values when compared with the LIRs. Qg-8 can be taken up for moderate to high recovery scenarios and also proved to be an effective alternative for high-rate injections. Recovery increases to 27.5% in Case 1 and 57.0% in Case 4 at Qg-9, indicating efficient sweep efficiency. Recovery factors for Qg-10 increase to 31.0% for Case 1 and to 60.0% for Case 4, which is modestly 3% better than Qg-9. Finally, Qg-11 gives the highest recoveries, from 33.0% in Case 1 to 62.5% in Case 4. However, the 2.5% increase from Case 4 compared to Qg-10 implies that increased injection cost may be a compromise.

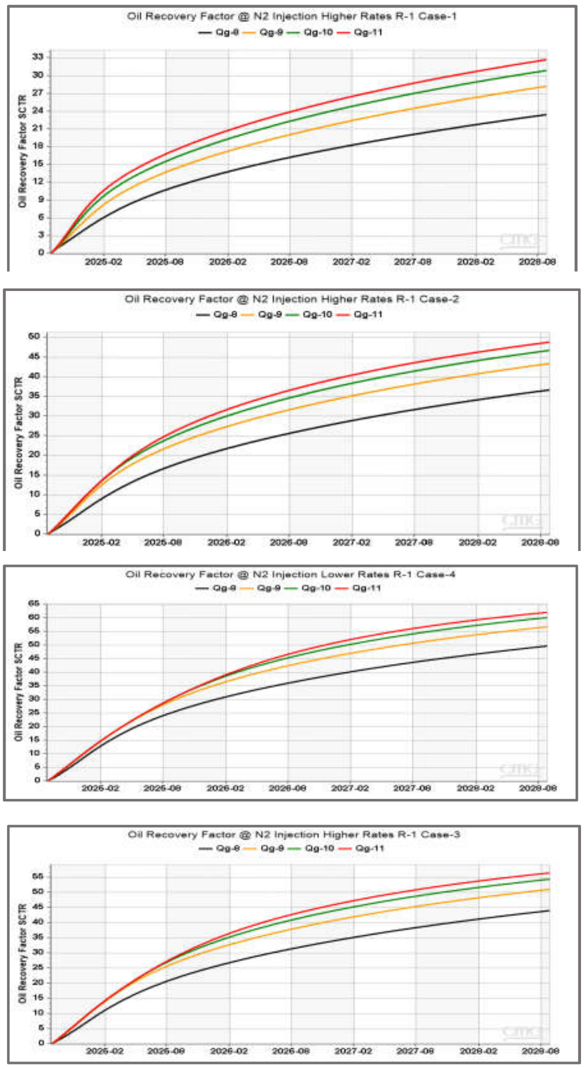


Fig 14 Oil Recovery Factor at Higher N_2Injection Rate for Case1-4

In theoretical concept, increasing injection rate will increase the efficiency of recovering efficiency, but the magnitude is reduced. Qg-8 is optimal in terms of recovery; Qg-9 provides better recovery compared with less recovery while Qg-10 gives even enhanced recovery at the expense of decreasing gain. Qg-11 provides the highest recovery but almost identical to Qg-10. In general, Qg-9 balances recovery; and Qg-10 and Qg-11 are best in increasing recovery but having increased injection volumes.

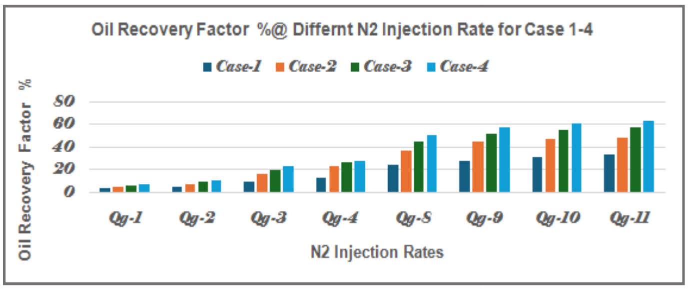


Fig 15. Oil Recovery Factor % at Different N_2Injection Rates of all cases 1-4

Comparison Between CO_2 and N_2 Injection

CO_2 and N_2 injection at low and high injection rates demonstrates significant differences in the recovery efficiency largely based on the premise that in EOR operations, one gas is used more effectively than the other. For LIRs, namely Qg-1 to Qg-4, N_2 tends to perform better than CO_2 especially in early stages. For example, recovery factors for N_2 range from 3.0% to 6.5% in Qg-1 for CO_2 they stand in the range of 2.25% to 4.24%. This trend continues with N_2 hitting 4.25% to 10.5% in Qg-2 than CO_2's 3.05% to 6.96%. However, as injection volumes rise in Qg-3 and Qg-4, this gap reduces. In Qg-4, N_2 recovers 12.5% to 27.00%, while CO_2 attains 11.11% to 26.993%, thus proving that CO_2 is just about touching N_2's performance for higher low rates. In HIRs (Qg-8 to Qg-11), CO_2 finally overtakes N_2 in the later cases. For Qg-8, recovery factors for N_2 are between 23.5% to 50%, whereas CO_2 recoveries were slightly lower at 22.0% to 50.0%. For Qg-9, CO_2 was greater than N_2 at the recovery factor of 26.074% to 59.53% as compared to N_2 recovery factor, 27.5% to 57.0%. The same continued that while CO_2 reached recovery factors of 28.74% to 64.48% for Qg-10, N_2 reached 31.0% to 60.0% and 33.0% to 62.5% for Qg-11, respectively.

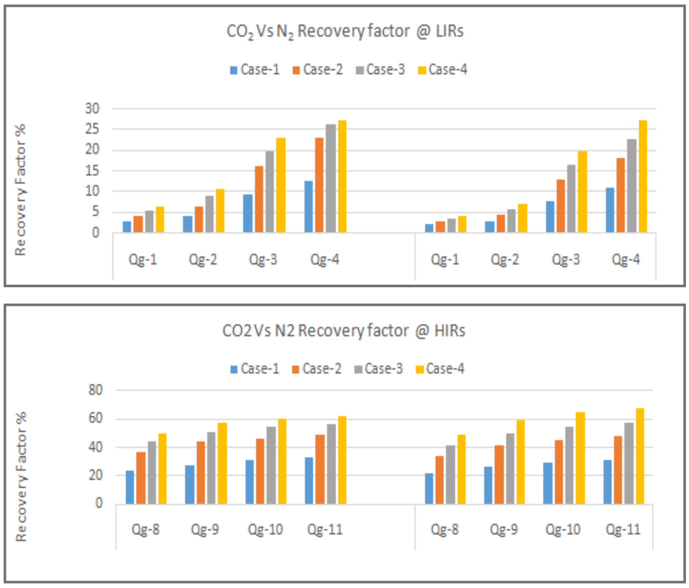


Fig16. CO_2 Vs N_2 Recovery factor of LIRs and HIRs

From fig 16. with these complex recovery cases (Case 4), CO_2 presents a high recovery efficiency that could even be up to 68.06% compared to N_2, at 62.5%, which suggests that it may be efficient in recoveries in complex reservoirs at high injection volumes. Incremental recoveries at such high rates may not be worthwhile to pay off for the added expense of injecting CO_2. Overall, N_2 has better efficiency compared to CO_2 in the early and intermediate recovery phases, particularly at relatively LIRs Qg-1 to Qg-3, whereas CO_2 performs better with HIRs, especially in more complex reservoirs. Hence, CO_2 is favored in situations where cost can be justified for optimal recovery.

CONCLUSION

This research presents the critical injection conditions during CO_2-injection as an EOR for depleted reservoirs. At HIRs, CO_2 injection is preferred over N_2due to its ability to enhance oil production by improving miscibility and sweep efficiency. N_2Injection gives pressure support but provides less mobility to displace additional oil.

- At LIRs (Qg-1 to Qg-4), N_2 is generally superior to CO_2, particularly in the earlier stages of recovery.
- As the injection volumes enhance in Qg-3 and Qg-4, the recovery performance gap between $N_2$and CO_2found to be narrow.

- For higher injection rates (Qg-8 to Qg-11), if $N_2$and CO_2 are compared, it is observed that the latter CO_2eventually overtakes the N_2, particularly in the later stages.
- In Case 4, CO_2 demonstrates a better recovery factor of 68.06% while N_2 only reaches up to 62.5%.
- Incremental recovery gains with CO_2 at high rates may not justify because the additional cost also will be included for injection higher volumes.
- N_2 is best applied in early and intermediate recovery phases, whereas CO_2 has application in more complicated reservoirs with a greater requirement for better recovery, particularly when the costs are justified.

It would be shown in this work that at a pressure more than MMP, the recovery of oil could be maximized by injection with CO_2 and N_2 be a fair replacement of CO_2 in case of unavailability or due to its high cost. The results of this investigation can be of value for the oil companies operating in the Lower Indus Basin because the injection parameters are to be optimized. Advanced simulation tools such as CMG GEM will be helpful in future field applications, while continuous research and field trials are needed to further focus the strategies of gas injection as applied into complex reservoirs.

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