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Results of a New CO_2 EOR Project in Colombia 18 Years after its Last Application

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Abstract

This study summarizes the results of a field pilot designed to evaluate CO_2 injection performance in permeable, depleted reservoirs through real-time pressure analysis. The pilot assessed injectivity, fluid–rock interactions, and early storage behavior by injecting CO_2 in both liquid and gaseous phases, supported by downhole pressure measurements for accurate reservoir diagnostics. Conducted in two tertiary-age formations previously validated for CO_2 compatibility, the pilot incorporated controlled injection within safe operating limits, specialized conditioning and transport procedures to ensure well integrity, and a structured monitoring program to capture reservoir response under an MMV framework.

Results confirm that both liquid- and gas-phase CO_2 injection are technically feasible, though they require distinct operational strategies and investment levels. The tested formations demonstrated adequate injectivity and containment capacity, reinforcing their potential for scalable CO_2 storage aligned with national decarbonization objectives. Overall, the pilot highlights the importance of intentional field experimentation to advance CCUS deployment in Colombia, supports the development of specialized CO_2 management protocols, and provides practical guidance for future storage projects aimed at enabling lower-carbon industrial operations and long-term climate resilience.

Introduction

Since the adoption of CO_2 in the oil and gas industry in the 1960s as an efficient solvent and a key fluid for enhanced oil recovery (EOR) Colombia has carried out several relevant projects, primarily in the Middle Magdalena Valley Basin (MMV). This basin hosts one of the country's most important refineries and surrounding mature fields with low recovery factors, making it a natural setting for CO_2-based recovery initiatives. The Putumayo Caguán Basin also undertook early applications, influenced by the natural presence of CO_2 in produced gas streams.

In the MMV Basin, Ecopetrol launched the first technical evaluations in 1978, including laboratory studies, numerical simulations, and reservoir modeling to assess the feasibility of CO_2 applications. These efforts supported the implementation of cyclic CO_2 stimulation (Huff & Puff) and carbonated water injection (CWI). Pilot tests demonstrated notable production increases, and the systematization of these efforts laid the technical foundation for proposing new initiatives (Castañeda, J., et al., 2025), (Gómez, R., & Flórez, A., 1990). The most recent pilot, executed in 2008, tested liquid-phase CO_2 injection to achieve incremental oil recovery (Sáchica, J., et al., 2009).

The Ecopetrol Group's renewed focus on CO_2 injection emerges at a critical moment, as the company simultaneously pursues emission reduction targets and improved recovery factors in mature fields, positioning CO_2 as a strategic asset rather than a liability. After an 18-year pause, the resumption of CO_2 injection supported by rigorous technical assurance has demonstrated both operational value and alignment with decarbonization objectives. This evolution underscores Colombia's longstanding expertise with CO_2 based technologies and establishes a solid foundation for advancing new CO_2 utilization and storage initiatives that support a lower-carbon future.

Theory and/or Methods

The global oil industry has long leveraged CO_2 technologies, initially driven by the challenge of producing highly viscous crude oils that proved unresponsive to early displacement methods such as waterflooding. Beginning with steam-based cyclic stimulation processes developed in the 1960s and progressing through evaluations of chemical additives, the field did not formally recognize CO_2's ability to significantly reduce in-situ oil viscosity until the late 1970s. Foundational laboratory work dating back to the 1930s, including the later introduction of the miscibility concept in the 1950s, laid the scientific basis for CO_2-EOR. These efforts culminated in early field pilots such as the 1964 Mead Strawn project, which demonstrated favorable recovery outcomes even under immiscible conditions, establishing CO_2 as a versatile and effective enhanced oil recovery agent.

By the 1970s and 1980s, CO_2-EOR expanded significantly as commercial projects demonstrated strong technical and economic performance. Today, these initiatives align closely with the global need to decarbonize industrial operations, integrating CO_2-EOR with subsurface retention strategies and positioning it as a key component within modern CCUS frameworks (Cubillos, H., et al., 2023).

Colombia has likewise advanced in the application of CO_2 across multiple contexts: in the Putumayo–Caguán Basin, where CO_2 naturally occurs in produced gas streams at variable concentrations; and in the Middle Magdalena Valley Basin, home to the Barrancabermeja Industrial Complex (CIB), a major evaluated source for CO_2 capture (Yañez, E. et al., 2020). Notably, this latter region hosts the first and only areal CO_2-EOR project in Colombia to date (carbonated-water flood in the Galán Field), as well as the highest number of CO_2 huff-and-puff applications (eight wells). These precedents underpin the renewed proposal to utilize CO_2 in enhanced recovery operations under a structured strategy designed to generate value while advancing decarbonization objectives.

Geological Framework

The area is characterized by a homocline that primarily dips towards the East, resulting in a low-relief structural anticline with a northeastward plunge. The structural features are influenced by a fault zone trending southwest to northeast, which represents the northern continuation of the major transtensional Fault. The stratigraphic sequence present in the area corresponds to a succession of clastic sedimentary rocks ranging from Tertiary to Quaternary age rocks, which rest unconformably over Paleocene cretaceous rocks (Ramos, H., et al., 2013). The stratigraphic sequence in the area begins at the surface with the Real Formation, followed by the Colorado Formation, the Mugrosa Formation, and the Esmeraldas Formation, all of which overlie the Eocene Unconformity.

Depending on location, northern wells terminate either in the Umir or La Luna formations. The depositional environment ranges from continental braided and meandering fluvial systems to transitional anastomosed and deltaic settings, resulting in a highly heterogeneous reservoir composed of thin sand bodies averaging 15 ft, interbedded with clay intervals. Reservoir properties include an average porosity of 18%, water saturation of 45%, and net pay thicknesses of 100–115 ft for Mugrosa B and 45–50 ft for Mugrosa C.

Production in the area is governed by solution gas drive and partial water drive mechanisms, primarily affecting the Colorado sands and the Mugrosa intervals. In contrast, the Esmeraldas sands are dominated exclusively by solution gas drive. These drive mechanisms, combined with the reservoir's stratigraphic and depositional heterogeneity, help explain why many of the sands remain only partially depleted, preserving potential for further recovery under enhanced oil recovery strategies.

Results

This pilot offers a valuable opportunity to evaluate CO_2 utilization under field conditions representative of Colombian reservoirs, generating operational, environmental, and productivity insights that inform future CO_2-EOR implementation in the region. The positive results ranging from measurable productivity improvements to achieving a net-negative carbon footprint provide the foundation for the technical discussion that follows. The following Figure 1, present the results aligned with the project objectives and the company's strategic direction.

Outcomes aligned with the project objectives and the Company's Strategic Direction

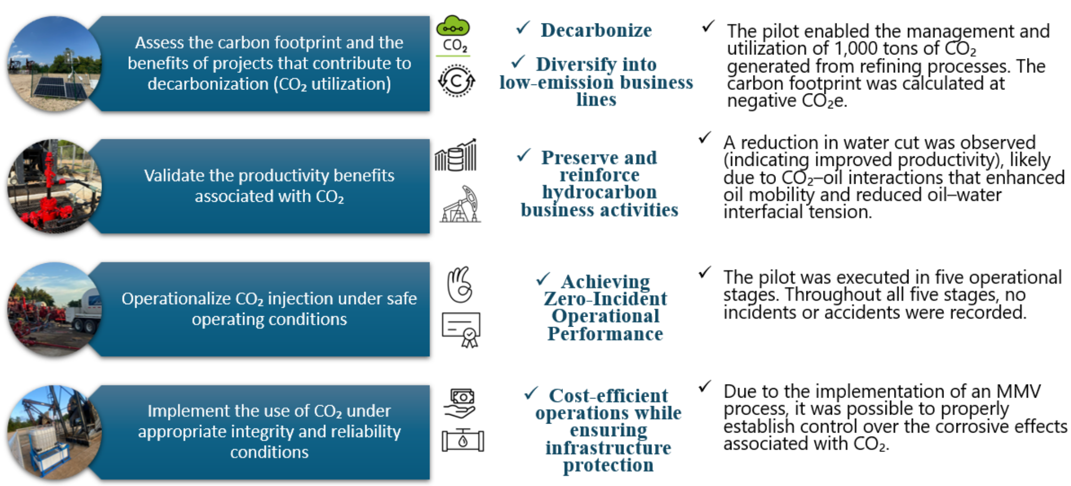

Figure 1. Outcomes aligned with the project objectives and the Company's Strategic Direction. Author's property

Measurement, Monitoring, and Verification (MMV)

This project implemented a MMV Plan as an innovative control methodology for CO_2-EOR operations in Colombia, despite such programs not being mandated for EOR applications as they are for geological CO_2 storage. The decision to adopt an MMV framework aimed to strengthen operational integrity, enhance facility safety, and ensure project continuity. Unlike MMV schemes designed for permanent storage, where CO_2 is treated as a waste stream requiring containment assurance, this pilot approached CO_2 as a process fluid, shifting the monitoring focus toward the early detection of operational deviations, equipment failures, and injection-production risks.

Accordingly, the MMV strategy was tailored to the specific operational conditions of the field, with monitored parameters, frequency, and duration selected based on the technical risks inherent to enhanced oil recovery processes. This fit-for-purpose design enabled the effective management of subsurface, operational, and facility-related uncertainties throughout the pilot, providing a robust framework aligned with the functional needs of CO_2-EOR rather than the regulatory requirements of carbon storage.

The MMV Plan was designed through an interdisciplinary methodology integrating environmental monitoring, operational surveillance, well integrity assessments, surface facility inspections, and reservoir performance evaluation. This structure enabled the establishment of a robust technical baseline and the definition of monitoring technologies and data-acquisition schemes suited to each stage of the WAG cycle—baseline, injection, and soak. Compliance results show high execution during the baseline phase (95%), followed by a slight decline during injection (92%) and a more significant reduction during soak (84%), yielding an overall consolidated compliance of 88.75%. The progressive decrease in compliance reflects increasing operational complexity, logistical dependencies, and cross-functional coordination needs, rather than technical limitations of CO_2 injection.

Performance across disciplines revealed near-perfect compliance in reservoir and well-related activities, attributed to stronger operational maturity and alignment between MMV requirements and routine surveillance practices. Overall, the MMV Plan proved essential for early deviation detection, identifying operational bottlenecks, strengthening decision-making, and providing governance and control throughout execution even in the absence of complete post-injection data. Its application in a non-regulated CO_2-EOR context highlights MMV as a key enabler for traceability, operational integrity, and the future scaling of CO_2-EOR initiatives in Colombia.

Discussion

Throughout the history of enhanced oil recovery, CO_2 injection has consistently demonstrated its technical effectiveness as an EOR mechanism. However, the central discussion in recent years has shifted from its technical feasibility to its overall business value. From an environmental standpoint, the pilot presented in this study provides clear evidence that CO_2-EOR can operate with a net-negative carbon footprint. Unlike many traditional EOR projects, the use of CO_2 in this case resulted not only in incremental oil recovery but also in measurable decarbonization, as the injected CO_2 remained effectively stored within the reservoir.

Conclusions

Overall, the pilot demonstrated highly satisfactory operational and technical outcomes. A consistent reduction in water production across both wells indicated measurable productivity gains, likely driven by favorable CO_2 oil interactions that enhanced fluid mobility.

The project was executed across five operational phases without any incidents or accidents, confirming strong adherence to safety and operational integrity standards. In addition, the implementation of an MMV framework enabled effective monitoring and mitigation of CO_2 related corrosion mechanisms, supporting the design of an optimized chemical-control strategy and the adoption of best practices. Collectively, these results validate the technical feasibility and safe deployment of CO_2 utilization within the field, reinforcing the potential for scaling up the initiative.

Implementing an MMV Plan despite not being a regulatory requirement for CO_2-EOR proved critical for establishing a robust technical baseline, strengthening governance, and reducing operational uncertainty.

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