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ADVANCING CO_2-ENHANCED OIL RECOVERY INTO A NATIONAL CCUS FRAMEWORK FOR UZBEKISTAN: CHALLENGES, OPPORTUNITIES, AND IMPLEMENTATION PATHWAYS

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Abstract. *Uzbekistan faces the dual challenge of meeting Paris Agreement commitments while sustaining production from aging oil fields. CO_2-enhanced oil recovery (CO_2-EOR)—particularly Water-Alternating-Gas (WAG), cyclic Huff-and-Puff, and hybrid chemical-assisted flooding—offers a pathway to increase oil recovery and permanently store CO_2. This review systematically evaluates these methods for Uzbekistan's Amu Darya and Fergana basins. WAG is well-suited to conventional waterflooded reservoirs; Huff-and-Puff fits tighter formations; hybrid methods require local validation. Major barriers remain—no CO_2 transport network, no legal pore-space framework, and lacking rock-fluid data. The paper provides a practical roadmap for pilots, policy, and research, helping Uzbekistan turn CO_2-EOR into a realistic decarbonization tool.*

Keywords: *CO_2-enhanced oil recovery (CO_2-EOR); carbon capture, utilization and storage (CCUS); enhanced oil recovery; carbon sequestration; water-alternating-gas (WAG) injection; CO_2 huff-and-puff; cyclic CO_2 injection; hybrid CO_2 flooding; mobility control; sweep efficiency; gas channeling control; foam-assisted WAG (FAWAG); chemical-assisted CO_2 flooding; heterogeneous reservoirs; tight oil reservoirs; unconventional reservoirs; reservoir engineering; reservoir simulation; sustainable oil recovery; Amu Darya Basin; Fergana Basin; Ustyurt blocks; Uzbekistan.*

1. Introduction

Conventional primary and secondary recovery methods typically produce only approximately 20–30% of the original oil in place (OOIP), leaving the majority of hydrocarbons trapped within reservoir formations due to capillary forces, reservoir heterogeneity, and unfavorable mobility conditions [1]. Consequently, the recovery of residual oil requires the implementation of advanced enhanced oil recovery (EOR) technologies to improve displacement efficiency and maximize hydrocarbon production from mature reservoirs. Among tertiary recovery methods, carbon dioxide (CO_2) injection has emerged as one of the most attractive and cost-effective EOR techniques because of its technical, economic, and environmental advantages.

Compared with many other injection agents, CO_2 is relatively inexpensive and widely available from industrial emission sources, making it economically favorable for large-scale field applications. Injected CO_2 enhances oil recovery by reducing oil viscosity, promoting oil swelling, lowering interfacial tension, and improving miscibility between reservoir fluids and injected gas, thereby mobilizing previously unrecoverable hydrocarbons.

Previous field applications and experimental studies have demonstrated that CO_2 flooding can provide an additional recovery of approximately 15–25% of the original oil in place (OOIP), significantly increasing the ultimate recovery factor of oil reservoirs [2]. To maximize the effectiveness of CO_2 injection, various deployment strategies have been developed to suit different reservoir conditions. The following sections examine three major approaches: Water-Alternating-Gas (WAG) injection, the Huff-and-Puff technique, and Hybrid CO_2 flooding methods.

2. Methods

This study conducts a systematic synthesis of global CO_2-EOR deployment strategies. The methodological framework comprises three stages:

1. Literature Collection: Peer-reviewed experimental, simulation, and field studies on CO_2WAG, Huff-and-Puff, and hybrid CO_2 flooding were identified using keyword searches in major scientific databases, prioritizing studies published within the last decade.

2. Data Extraction: Key performance indicators—including incremental oil recovery (% OOIP), wettability alteration (contact angle change), soaking period, injection cycles, and storage efficacy—were extracted from selected studies (e.g., [3–11]).

3. Multi-Criteria Screening for Uzbekistan: A screening framework was constructed to assess reservoir compatibility, mobility control requirements, and operational feasibility specifically for the Amu Darya and Fergana basins, drawing on regional CO_2 source and storage assessments [12,13]. This synthesis adapts global knowledge to the geological and infrastructural context of Uzbekistan's mature petroleum basins.

3. Results

3.1 CO_2 Water-Alternating-Gas (WAG) Injection

CO_2-WAG injection is a field-scale EOR technology commonly utilized in conventional oil reservoirs with moderate to high permeability and sufficient inter-well communication. The process involves injecting alternating slugs of CO_2 and water. While CO_2 enhances oil swelling and achieves miscibility, the injected water reduces gas mobility, controls channeling, and improves sweep efficiency to delay early gas breakthrough. This technique is particularly effective in mature sandstone and carbonate reservoirs with heterogeneity where continuous gas injection would suffer from gravity override and poor areal sweep. Figure 1 shows alternating slugs of water and CO_2 injected through the injection well, creating an oil bank ahead of the displacement front.

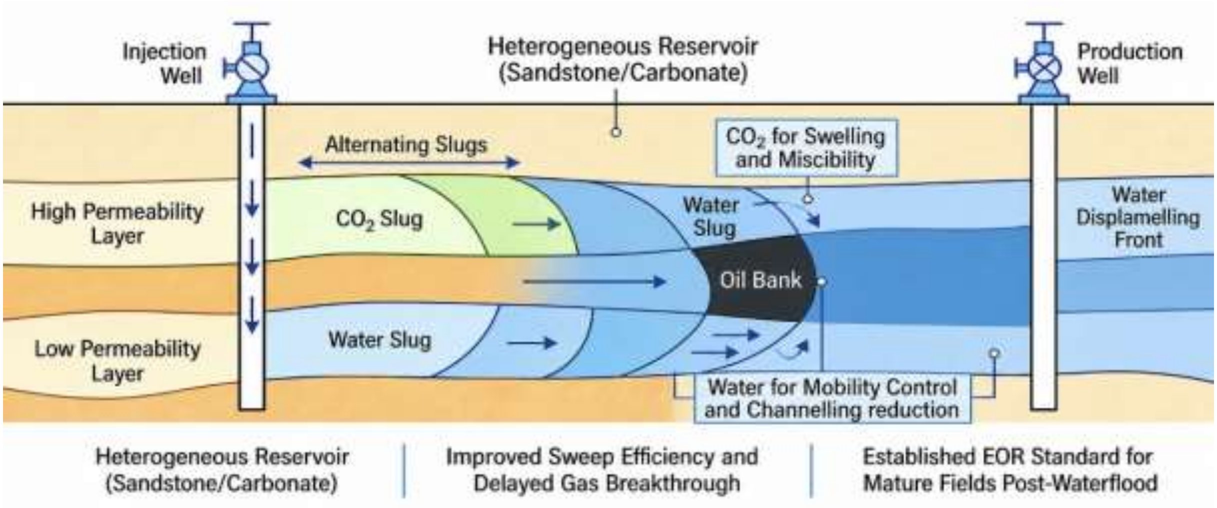

Figure 1. Schematic of CO_2 Water-Alternating-Gas (WAG) injection in a heterogeneous reservoir.

Recent research comparing WAG to continuous injection strategies shows:

· Hussain et al. [3] found that continuous CO_2 flooding achieved 27.2% recovery (water-wet) and 17.2% (mixed-wet), while WAG achieved 26% and 16.1%, respectively.

· Eyitayo et al. [4] reported that all strategies shifted wettability toward CO_2-wet (contact angle increases of 9–77%). WAG showed the least alteration in sandstone (29.6% change), making it most favorable for CO_2 storage security.

· Sun et al. [5] developed a hybrid numerical-machine-learning workflow for CO_2-WAG optimization, achieving NPV of $205M and 92.9% storage efficacy vs. $183M and 81.2% in the base case.

3.2 CO_2 Huff-and-Puff Technique

The Huff-and-Puff process is primarily applied in tight and unconventional oil reservoirs where ultra-low permeability limits traditional flooding. This single-well technique injects CO_2, allows a soaking period, then returns the well to production. Figure 2 illustrates the three-phase cyclic injection process in an ultra-low permeability unconventional reservoir.

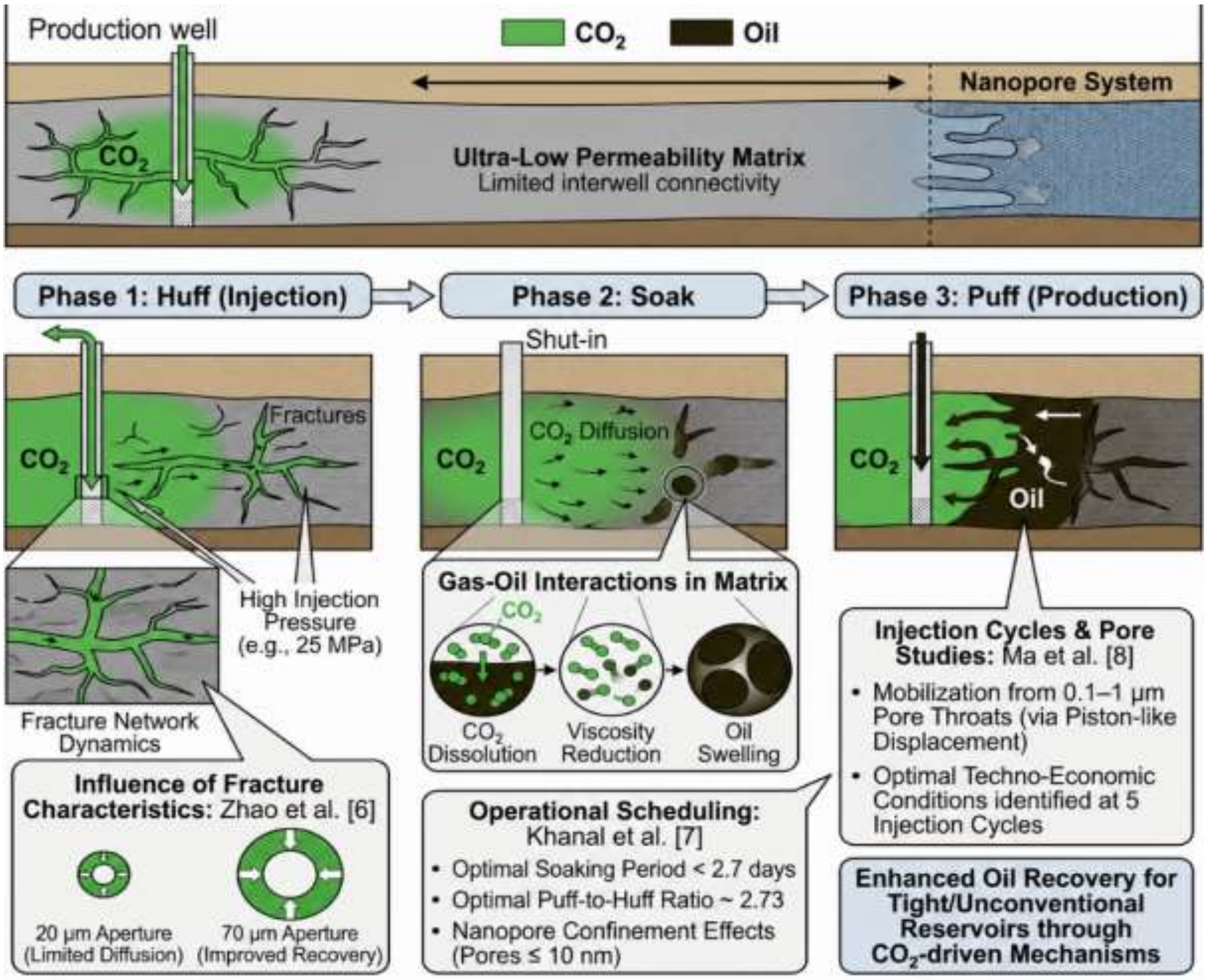

Figure 2. Schematic of CO_2 huff-and-puff (cyclic injection) in an ultra-low permeability unconventional reservoir.

Key quantitative findings:

· Zhao et al. [6]: Enlarging fracture apertures (20 µm → 70 µm) significantly improved recovery during early cycles.

· Khanal et al. [7]: Identified optimal puff-to-huff ratio ≈ 2.73 and soaking period < 2.7 days; nanopore confinement (pores ≤ 10 nm) improved recovery by >3%.

· Ma et al. [8]: Both fractured and unfractured samples achieved ultimate recovery factors of ~37% under optimal conditions (five cycles, 25 MPa injection pressure).

3.3 Hybrid CO_2 Flooding

Hybrid CO_2 flooding integrates conventional injection with mobility-control agents (foam, polymers, surfactants) to minimize gas channeling.

Figure 3 compares conventional flooding (35–45% OOIP recovery with gas channeling) vs. hybrid flooding (55–65%+ OOIP recovery).

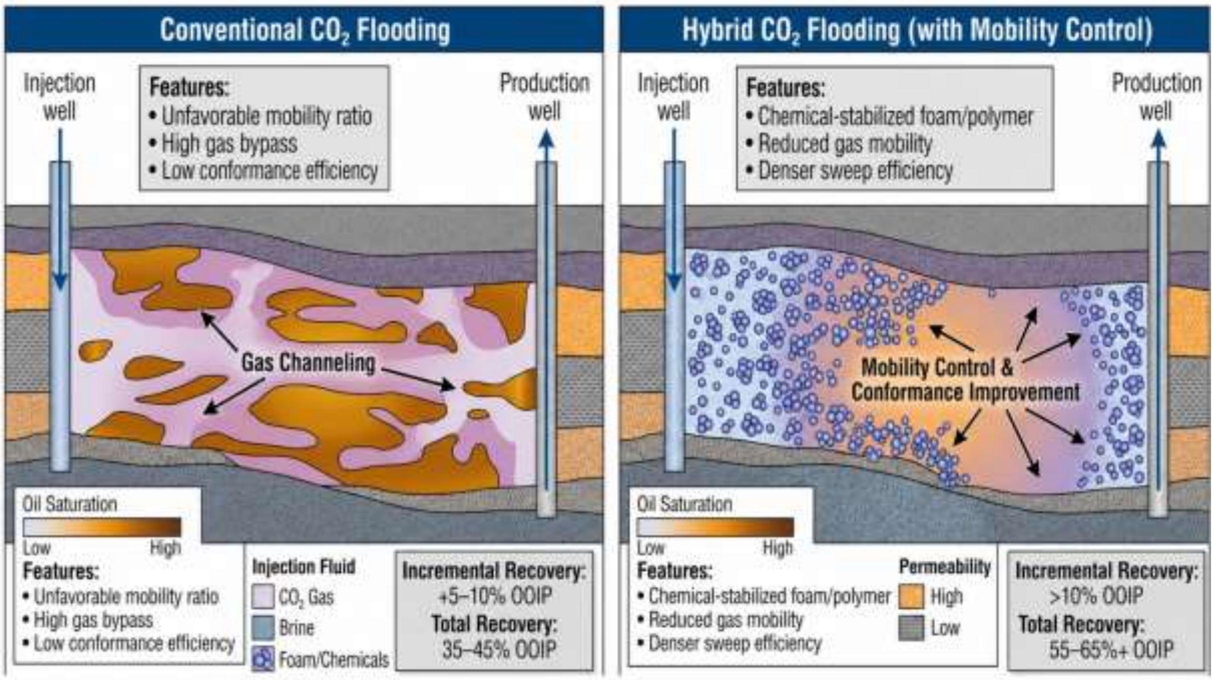

Figure 3. Comparison of conventional and hybrid CO_2 flooding with mobility control.

Laboratory findings include:

· Fang et al. [9]: Foam-, polymer-, gel-, and nanoparticle-assisted WAG improve mobility control and increase oil recovery by >5% over conventional WAG.

· Ratanpara et al. [10]: Hybrid huff-and-puff with SDS surfactant achieved 37% OOIP cumulative recovery (~10% improvement over waterflooding).

· Koyanbayev et al. [11]: AOS-stabilized CO_2 foam achieved an additional 6–10% OOIP recovery following waterflooding and CO_2 flooding.

Table 1 and Figure 4 provide a broader quantitative comparison, summarizing the recovery ranges and key controlling parameters for these CO_2-based techniques.

Method	Recovery/increment (%)	Key notes
CO_2-WAG	16-26% total	Lower wettability alteration; ML-optimized storage efficacy up to 92.9%
CO_2 Huff-and-Puff	~37% total	Optimal at 5 cycles, <2,7 days soaking, 25MPa
Chemical-assisted WAG	+5% over WAG	Foam, polymer, gel, nanoparticle assisted
Surfactant + CO_2 hybrid	37% total (+10%over waterflood)	SDS surfactant at 2% w/v
CO_2 foam	+6-10%overwaterflood+CO_2	AOS-stabilized foam

Table 1. Comparison of CO_2-based enhanced recovery methods with reported recovery ranges and key characteristics.

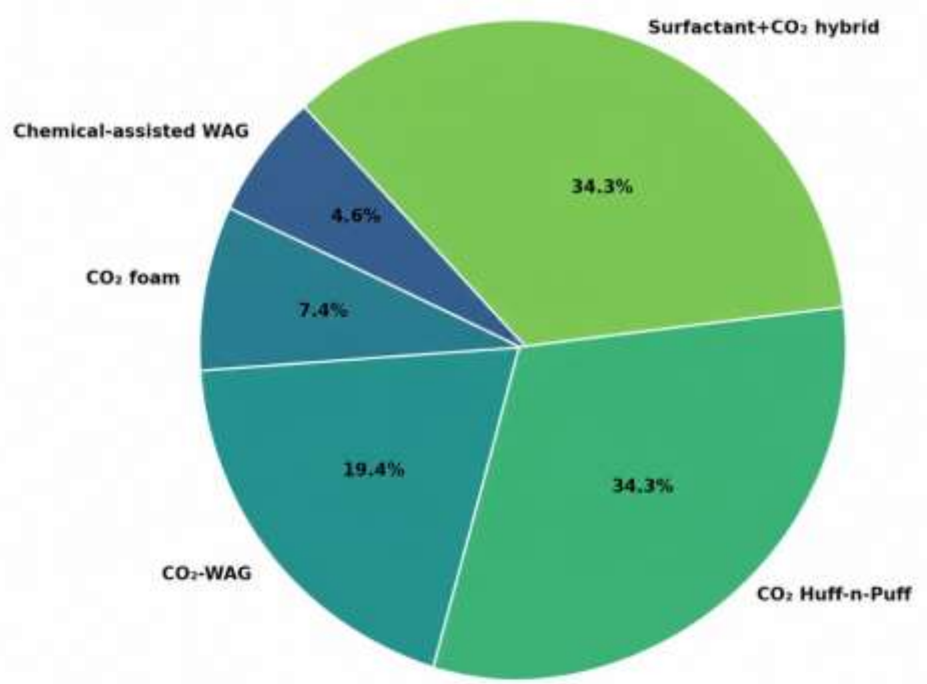

Figure 4. Reported recovery percentages for different CO_2-based

enhanced recovery methods presented as a pie chart.

3.4 Uzbekistan-Specific CO_2 Supply and Cost Assessment

Kamolov et al. [12] evaluated Uzbekistan's CO_2 storage and utilization potential:

· Total annual CSU capacity: 1,171 million tons (exceeding annual emissions)
· Saline aquifers: ~35,000 Mt
· EGR: 372 Mt · EOR: 72 Mt
· Methanol production: 2.4 Mt/year; urea: 0.72 Mt/year

Kamolov et al. [13] conducted a techno-economic analysis of post-combustion carbon capture using MEA absorption integrated with a 450 MW NGCC power plant in Uzbekistan:

· 45% exhaust gas recirculation (EGR) reduces column size by 35%
· 90% CO_2 capture rate (1.05 Mt/year)
· Plant efficiency decreases from 55.8% to 46.8%
· CO_2 capture cost: 61.22 USD/ton
· LCOE increase of 45% to 77.97 USD/MWh

4. Discussion

4.1 Interpretation of Findings and Applicability to Uzbekistan

The results confirm that each CO_2-EOR deployment strategy addresses distinct reservoir challenges, with varying applicability to Uzbekistan's geological settings. WAG injection emerges as the most immediately transferable technology for Uzbekistan's conventional reservoirs—particularly in the Amu Darya, Fergana, Ustyurt blocks (Figure 5) and potentially Caspian basins—where extensive waterflooding history has established the well patterns, injection infrastructure, and reservoir knowledge base necessary for field-scale implementation.

Figure 5. CO_2 storage potential and utilization pathways in Uzbekistan.

The demonstrated capability of machine learning-assisted optimization to simultaneously improve both economic returns and CO_2 storage efficacy offers a practical pathway for Uzbekistan.

Huff-and-Puff represents a strategically important entry point for Uzbekistan's tighter, low permeability formations. Its single-well operational model, lower upfront capital requirements, and effectiveness in reservoirs with limited inter-well connectivity make it particularly suited for pilot-scale deployment.

Chemically assisted hybrid flooding methods, while showing the highest recovery enhancements in laboratory studies, require a phased development approach. The absence of site-specific experimental data on foam stability, surfactant compatibility, and polymer performance under Uzbek reservoir conditions constitutes a critical knowledge gap.

4.2 Binding Constraints for Uzbekistan

Three binding constraints consistently identified across the reviewed literature must be addressed:

1. Absence of a dedicated CO_2 capture and transport network
2. Lack of regulatory frameworks governing pore-space ownership and long-term liability
3. Insufficient localized rock-fluid interaction data for reservoir-specific feasibility assessment

4.3 Economic Barrier and Path Forward

The techno-economic assessment by Kamolov et al. [13] confirms technical feasibility of MEA-based post-combustion capture but reveals a critical economic barrier: a capture cost of 61.22 USD/ton and 45% LCOE increase renders large-scale deployment financially prohibitive for commoditized products and erodes EOR profitability. This reality necessitates a shift from conventional amine scrubbing toward next-generation capture technologies—advanced solvents, membranes, or solid sorbents—which have demonstrated significantly lower energy penalties and costs in global pilot projects.

Identifying an optimal, cost-effective capture solution is the single most decisive factor in unlocking Uzbekistan's 72 Mt EOR storage potential [12] and realizing a commercially viable CCUS value chain.

4.4 Proposed Sequential Implementation Strategy

The findings support a phased approach:

1. Phase 1: Initiate Huff-and-Puff pilots in tight formations to demonstrate technical viability.
2. Phase 2: Concurrently conduct laboratory studies (core-flood experiments under reservoir conditions) to validate hybrid methods locally.
3. Phase 3: Progress toward integrated WAG-CCUS operations in mature waterflooded fields as CO_2 infrastructure and regulatory mechanisms mature.

5. Conclusion

This systematic synthesis confirms the substantial technical potential for CO_2-based enhanced oil recovery in Uzbekistan's mature petroleum basins.

Uzbekistan's geological portfolio, infrastructure inheritance, and emerging industrial CO_2 sources constitute a favorable foundation for CCUS-EOR development.

This review contributes a structured, evidence-based framework that translates global CCUS-EOR knowledge into the Uzbek context, providing reservoir engineers, policymakers, and research institutions with a screening methodology for candidate field selection and a prioritized research agenda. Such a phased approach positions CO_2-EOR as a practical bridge connecting Uzbekistan's energy security objectives with its emerging decarbonization commitments, offering a replicable model for other Central Asian hydrocarbon economies navigating the global energy transition.

List of abbreviation

· AOS — Alpha Olefin Sulfonate
· Caspian — Caspian region (geological region)
· CCS — Carbon Capture and Storage
· CCUS — Carbon Capture, Utilization, and Storage
· CO_2 — Carbon Dioxide
· CO_2-EOR — Carbon Dioxide-Enhanced Oil Recovery
· CSU — Carbon Storage and Utilization
· EGR — Enhanced Gas Recovery (or Exhaust Gas Recirculation, depending on context)
· EOR — Enhanced Oil Recovery
· FAWAG — Foam-Assisted Water-Alternating-Gas
· LCOE — Levelized Cost of Electricity
· MEA — Monoethanolamine
· ML — Machine Learning
· Mt — Million tons
· NGCC — Natural Gas Combined Cycle
· NPV — Net Present Value
· OOIP — Original Oil in Place
· SDS — Sodium Dodecyl Sulfate
· WAG — Water-Alternating-Gas

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