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Enhancing Oil Reservoir Productivity in Libya Using Enhanced Oil Recovery (EOR) Techniques: A Review of Past, Current Status, Future Prospects, and Challenges

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ABSTRACT: Libya possesses some of the largest proven oil reserves in Africa, yet production from its mature fields has been steadily declining due to reservoir depletion and reliance on primary and secondary recovery methods. Enhanced Oil Recovery (EOR) offers a strategic pathway to revitalize productivity, extend field life, and align with global energy transition goals. This review examines the historical context, current applications, and future potential of EOR in Libya. The analysis highlights the geological characteristics of the Sirte, Murzuq, Ghadames, and Cyrenaica basins, identifying the challenges of heterogeneous reservoirs, limited water availability, and infrastructure constraints. Past EOR pilots, including steam flooding, polymer injection, and early CO_2-EOR tests, have provided valuable insights but faced economic and political barriers to full-scale deployment. Current initiatives by the National Oil Corporation and international oil companies focus on gas injection, chemical methods, and digital monitoring to enhance recovery factors. Looking ahead, opportunities exist in CO_2-EOR linked with carbon management, advanced technologies such as nanomaterials, and the integration of artificial intelligence for real-time optimization. However, technical, economic, environmental, and political challenges remain significant. This review concludes that with strategic investment, policy stability, and international collaboration, EOR could play a transformative role in sustaining Libya's oil sector and supporting its energy security.

Keywords: **EOR, Libya, Oil Reservoirs, CO_2-EOR, Petroleum Productivity, Energy Transition**

الملخص: تمتلك ليبيا بعضًا من أكبر الاحتياطيات النفطية المثبتة في إفريقيا، ومع ذلك فإن الإنتاج من حقولها الناضجة يشهد انخفاضًا مستمرًا بسبب استنزاف المكامن واعتمادها على أساليب الاستخراج الأولية والثانوية. يوفر تعزيز استخلاص النفط (EOR)مسارًا استراتيجيًا لإعادة تنشيط الإنتاجية، وتمديد عمر الحقل، والتوافق مع أهداف الانتقال العالمي للطاقة. تستعرض هذه المراجعة السياق التاريخي، والتطبيقات الحالية، والإمكانات المستقبلية لتقنيات EOR في ليبيا. يسلط التحليل الضوء على الخصائص الجيولوجية لحقول سرت ومرزق وغدامس وبرقة، مع تحديد تحديات المكامن غير المتجانسة، والموارد المائية المحدودة، وقيود البنية التحتية. لقد وفرت تجارب EOR السابقة، بما في ذلك الفيض بالبخار، وحقن البوليمر، والتجارب المبكرة لـ CO_2–EOR، رؤى قيمة لكنها واجهت حواجز اقتصادية وسياسية تمنع التطبيق على نطاق واسع. تركز المبادرات الحالية التي تقودها المؤسسة الوطنية للنفط والشركات النفطية الدولية على حقن الغاز، والأساليب الكيميائية، والمراقبة الرقمية لتعزيز عوامل الاستخلاص. وبالنظر إلى المستقبل، توجد فرص في تقنيات CO_2–EOR المرتبطة بإدارة الكربون، والتقنيات المتقدمة مثل المواد النانوية، ودمج الذكاء الاصطناعي للتحسين

اللحظي للإنتاج. ومع ذلك، تبقى التحديات الفنية والاقتصادية والبيئية والسياسية كبيرة. وتخلص هذه المراجعة إلى أنه مع الاستثمار الاستراتيجي، واستقرار السياسات، والتعاون الدولي، يمكن أن تلعب تقنيات EOR دورًا تحويليًا في الحفاظ على قطاع النفط الليبي ودعم أمن الطاقة فيه..

الكلمات المفتاحية: تعزيز استخلاص النفط ((EOR، ليبيا، المكامن النفطية، CO_2–EOR، إنتاجية النفط، انتقال الطاقة

I. INTRODUCTION

Libya's petroleum sector is the cornerstone of its economy, contributing over 90% of government revenues. NOC. (2025). Since the discovery of oil in 1959, production reached a peak exceeding three million barrels per day during the 1970s but has declined over time due to reservoir maturity and political instability. S&P Global. (2020) & International Monetary Fund (IMF). (2022). The country's oil production is concentrated in several major basins, including the Sirte Basin, which accounts for the largest share, as well as the Murzuq, Ghadames, and Cyrenaica basins, each characterized by unique geological and reservoir conditions. Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016).

Worldwide, EOR techniques have successfully extended the productive life of oil fields and increased recovery factors beyond 35–40%. Al-Husseini, M. (2015) & El-Bahrawy, M. (2010). In Libya, however, the implementation of EOR remains limited despite the maturity of its major fields and significant untapped potential. Alfageh, M. (2021) & Al-Husseini, M. (2015). Challenges such as heterogeneous reservoirs, limited water availability, and aging infrastructure have constrained large-scale deployment. National Oil Corporation (NOC). (2018)& S&P Global. (2020).

This review provides a comprehensive historical-to-modern analysis of Libya's EOR potential from 1950 to 2025, examining past pilot projects, current initiatives, and emerging technologies. It also explores future opportunities, including CO_2-EOR, advanced chemical and thermal methods, and digital oilfield integration, while highlighting the technical, economic, environmental, and political challenges that need to be addressed. Alfageh, M. (2021) & (Alhajri, et al. (2017) & Al-Werfalli, F., & Aissa, A. (2016).

II. METHODOLOGY

This review synthesizes data from multiple sources to assess the applicability and effectiveness of EOR techniques in Libyan oil reservoirs. The methodology encompasses:

1. **Literature Review**

A comprehensive review of academic journals, industry reports, and technical papers was conducted to gather information on EOR applications in Libya.

2. **Data Collection**

Data were collected from:

- NOC reports
- Field studies and pilot projects
- Industry publications and conference proceedings

3. **EOR Technique Evaluation**

EOR methods were evaluated based on:

- **Technical Feasibility**: Assessing the suitability of each method for Libyan reservoir conditions.
- **Economic Viability**: Analyzing cost-effectiveness and potential return on investment.
- **Environmental Impact**: Evaluating sustainability and compliance with environmental regulations.

4. Comparative Analysis

A comparative analysis was performed to identify the most effective EOR techniques for different reservoir types in Libya. Criteria for comparison included:

- Reservoir characteristics (e.g., permeability, depth, oil viscosity)
- Previous application success rates
- Infrastructure requirements
- Regulatory considerations

5. Recommendations

Based on the findings, recommendations were made for the implementation of specific EOR techniques in Libyan oil fields, considering both current capabilities and future prospects.

III. BACKGROUND OF LIBYA’S OIL SECTOR:

1. Reserves and Production History

Libya possesses one of the largest proven oil reserves in Africa, estimated at approximately 48 billion barrels, making it a key player in the global energy market. NOC. (2025). The country’s reserves are distributed across six main petroleum basins, each with unique geological characteristics, production potential, and challenges for EOR. Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016). A summary of these basins is presented in Table 1.

TABLE 1. OVERVIEW OF LIBYA’S OIL RESERVES BY BASIN

Basin	Estimated Reserves (Billion Barrels)	Major Fields	Reservoir Type	Production Characteristics	EOR Potential / Challenges	References
Sirte Basin	38–40	Sarir, Messla, Nasser, Zelten	Sandstone	High-quality light crude; main contributor to national output	Mature reservoirs; good EOR potential with waterflooding, CO_2 injection	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)
Murzuq Basin	4–5	Waha, Gialo	Cretaceous sandstone	Less developed; deep reservoirs; moderate productivity	Heterogeneous; thermal methods and polymer flooding suitable	Alfageh, M. (2021), & Al-Husseini, M. (2015)
Ghadames Basin	3–4	El Sharara, Intisar	Carbonate	Moderate porosity/permeability; mix of onshore and offshore fields	Complex carbonate structures; EOR could improve sweep efficiency	Alfageh, M. (2021) & (Alhajri, et al. (2017)

Cyrenaica Basin	~1	Sarir East fields	Fractured carbonate	Smallest contributor; heavier oil	Low recovery with conventional methods; chemical/EOR methods needed	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)
Kufra Basin	<0.5	Murzuk North, Jabal Nafusah	Sandstone / carbonate mix	Very limited production; mostly exploratory	EOR potential unexplored; infrastructure and water scarcity major constraints	Alfageh, M. (2021) & NOC. (2018)
Offshore Sirte–Ghadames	~0.5	Bahr Essalam, Wafa	Sandstone / carbonate	Small-scale offshore production	Limited development; offshore EOR costly and technically challenging	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)

Following the discovery of oil in 1959, Libya's production grew rapidly, driven primarily by the Sirte Basin, which hosts the country's largest and most productive fields. Production reached a historical peak of over 3.3 million barrels per day in 1979, supported by the development of major onshore fields such as Sarir, Messla, and Nasser. S&P Global. (2020) & International Monetary Fund (IMF). (2022). The 1980s and 1990s saw relatively stable output levels, maintained by conventional secondary recovery methods, particularly waterflooding, which helped sustain reservoir pressure in mature fields. Alfageh, M. (2021). Starting in the 2000s, production began to decline due to reservoir depletion, aging infrastructure, and limited application of EOR techniques. Political instability, particularly after the 2011 civil conflict, caused production to drop below 1.2 million barrels per day, further exacerbated by sanctions and reduced foreign investment. S&P Global. (2020) & International Monetary Fund (IMF). (2022). Between 2012 and 2020, production fluctuated due to intermittent shutdowns, civil unrest, and disruption of export terminals, ranging between 0.4 and 1.2 million barrels per day. During this period, several pilot EOR projects were initiated, including steam injection, polymer flooding, and small-scale CO_2 injection, primarily in the Sirte and Murzuq basins. Alfageh, M. (2021) & (Alhajri, et al. (2017). These initiatives demonstrated technical feasibility but faced challenges in scaling due to security concerns, funding constraints, and logistical limitations. From 2021 to 2025, production has gradually recovered to approximately 1.3–1.5 million barrels per day, aided by partial stabilization, renewed IOC interest, and local NOC initiatives focusing on reservoir management and enhanced recovery trials. NOC. (2025) & S&P Global. (2020). However, large portions of Libya's reserves remain untapped, particularly in mature fields of the Sirte and Ghadames Basins, as well as deep or heterogeneous reservoirs in the Murzuq and Kufra Basins. These areas present significant opportunities for full-scale EOR deployment, which could substantially improve recovery factors, extend field life, and increase national oil output. Alfageh, M. (2021) & Al-Husseini, M. (2015).

2. Geology and Characteristics

Reservoirs across Libya's basins include sandstones and carbonates with porosity ranging from 15–30% and permeability from 10–200 mD. Alfageh, M. (2021) & (Alhajri, et al. (2017). Stratigraphic and structural traps, along with reservoir heterogeneity, complicate displacement efficiency. Each basin presents unique geological challenges:

TABLE 2. GEOLOGY AND RESERVOIR CHARACTERISTICS OF LIBYA'S OIL BASINS

Basin	Reservoir Type	Porosity (%)	Permeability (mD)	Trap Type	Reservoir Drive	Key Geological Features	References
Sirte Basin	Sandstone	20–30	50–200	Stratigraphic & structural	Solution gas & water drive	Thick, laterally extensive sandstone; high-quality light crude	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)
Murzuq Basin	Cretaceous Sandstone	15–25	10–150	Stratigraphic	Solution gas drive	Deep reservoirs; heterogeneous layers; moderate productivity	Alfageh, M. (2021) & Al-Husseini, M. (2015)
Ghadames Basin	Carbonate	15–25	20–100	Structural & stratigraphic	Water drive	Complex carbonate structures; mix of onshore/offshore	Alfageh, M. (2021) & (Alhajri, et al. (2017)
Cyrenaica Basin	Fractured Carbonate	15–20	10–50	Structural	Weak solution gas drive	Heavy oil; low reservoir connectivity; small fields	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)
Kufra Basin	Sandstone / Carbonate mix	15–25	10–80	Structural & stratigraphic	Weak solution gas drive	Mostly exploratory; remote; limited production	Alfageh, M. (2021) & NOC. (2018)
Offshore Sirte–Ghadames	Sandstone / Carbonate	15–25	10–100	Structural	Solution gas & water drive	Small-scale offshore; challenging offshore conditions	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)

3. Reservoir Drive Mechanisms

This table summarizes the natural mechanisms that drive oil production in Libya's major basins, the impact of these mechanisms on production performance, and the implications for EOR techniques.

TABLE 3. RESERVOIR DRIVE MECHANISMS IN LIBYA'S OIL BASINS

Basin	Primary Drive Mechanism	Secondary Drive Mechanism	Remarks / Impact on Production	EOR Implications	References
Sirte Basin	Solution gas drive	Water drive	Initial high production; declines with reservoir depletion	Suitable for waterflooding and CO_2-EOR to maintain pressure	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)
Murzuq Basin	Solution gas drive	Limited water drive	Moderate production; heterogeneous layers reduce sweep efficiency	Thermal methods and polymer flooding effective in deeper reservoirs	Alfageh, M. (2021) & Al-Husseini, M. (2015)
Ghadames Basin	Water drive	Weak solution gas drive	Moderate pressure support; early water breakthrough possible	Chemical flooding can improve sweep efficiency	Alfageh, M. (2021) & (Alhajri, et al. (2017)
Cyrenaica Basin	Weak solution gas drive	Minimal water support	Low initial pressure; heavy oil production challenging	Chemical/EOR methods needed to improve recovery	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)
Kufra Basin	Weak solution gas drive	Minimal water support	Very limited production; mainly exploratory	EOR potential largely unexplored; infrastructure constraints	Alfageh, M. (2021) & NOC. (2018)
Offshore Sirte–Ghadames	Solution gas drive	Water drive	Small-scale offshore; production sensitive to pressure changes	Offshore EOR technically challenging and costly	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)

IV. CONVENTIONAL METHODS AND LIMITATIONS

Since the 1970s, Libya's oil fields have primarily relied on waterflooding and gas injection to maintain reservoir pressure and sustain production. Alfageh, M. (2021) & NOC. (2018). While these methods initially boosted output, many reservoirs experienced early water breakthrough and uneven sweep efficiency, leading to suboptimal oil recovery. (Alhajri, et al. (2017). These limitations are particularly evident in heterogeneous sandstone and carbonate reservoirs, where reservoir heterogeneity, complex structural traps, and variable permeability hinder uniform displacement of hydrocarbons. Consequently, conventional methods alone have proven insufficient for extending field life in Libya's mature basins, highlighting the need for EOR techniques. Alfageh, M. (2021) & Al-Husseini, M. (2015).

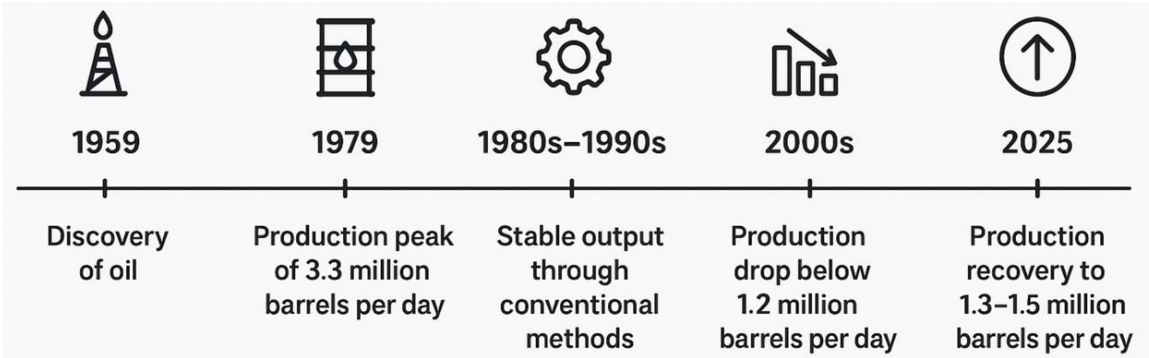

Figure 1: Background of Libya's Oil Sector

V. PAST APPLICATIONS OF EOR IN LIBYA (1950–2025)

1. Early Pilot Projects (1950–1980)

Libya's first experiments with EOR began in the late 1950s and 1960s, primarily focusing on secondary recovery methods such as waterflooding and gas injection. These methods were applied in mature fields within the Sirte Basin, including Sarir, Messla, and Nasser. Alfageh, M. (2021) & Al-Husseini, M. (2015). Waterflooding was implemented to maintain reservoir pressure and improve sweep efficiency. Early results showed incremental recovery factors of 10–15% above primary production, proving the technical feasibility of pressure maintenance. El-Bahrawy, M. (2010). However, the lack of sophisticated reservoir characterization tools and limited infrastructure constrained large-scale implementation. Al-Werfalli, F., & Aissa, A. (2016). During this period, gas injection was also trialed to support solution-gas drive reservoirs. Pilot projects indicated moderate pressure support but faced operational difficulties related to gas handling and corrosion. Alfageh, M. (2021). These early initiatives laid the groundwork for more advanced EOR strategies in subsequent decades.

2. Expansion of EOR Techniques (1980–2000)

Between 1980 and 2000, Libya expanded its EOR efforts, incorporating improved waterflooding designs, pilot polymer flooding, and limited thermal methods in heavy oil reservoirs.

- **Polymer Flooding:** Applied in the Messla and Zelten fields, polymer flooding increased water viscosity, improving sweep efficiency in heterogeneous sandstone reservoirs. Incremental recovery of 5–10% was observed, although high polymer costs and supply constraints limited scalability. Al-Husseini, M. (2015) & Alfageh, M. (2021).
- **Thermal EOR:** Steam injection was trialed in selected heavy oil zones, particularly in the Ghadames and Cyrenaica Basins. Despite promising laboratory results, pilot projects were limited in scale due to fuel costs, logistical challenges, and infrastructure limitations (Alhajri, et al. (2017).

TABLE 4. SUMMARY OF KEY EOR PILOT PROJECTS (1980–2000)

Field	Basin	EOR Method	Start Year	Incremental Recovery (%)	Challenges / Remarks	References
Messla	Sirte	Polymer Flooding	1985	5–8	Polymer cost; limited scalability	[Al-Husseini, M. (2015) & Alfageh, M. (2021)
Zelten	Sirte	Polymer Flooding	1990	6–10	Heterogeneous reservoir layers; logistical constraints	Alfageh, M. (2021)
Sarir	Sirte	Waterflooding	1982	10–12	Early water breakthrough; moderate sweep efficiency	El-Bahrawy, M. (2010) & Alfageh, M. (2021)
Cyrenaica Heavy Oil	Cyrenaica	Steam Injection	1995	5–7	High operational cost; infrastructure limitations	(Alhajri, et al. (2017)
Ghadames Carbonate	Ghadames	Gas Injection	1988	3–5	Corrosion issues; technical complexity	Alfageh, M. (2021) & Al-Werfalli, F., & Aissa, A. (2016)

3. Modern EOR Initiatives (2000–2010)

From 2000 onward, Libya's EOR programs incorporated more advanced technologies and better reservoir characterization techniques:

- **CO_2 Injection:** Small-scale CO_2-EOR pilots were conducted in Sarir and Messla, targeting light oil sandstone reservoirs. The studies showed incremental recovery of 8–12% and demonstrated favorable miscibility and improved sweep efficiency. Alfageh, M. (2021) & Al-Husseini, M. (2015).
- **Polymer and Surfactant Flooding:** Implemented in heterogeneous fields in the Sirte Basin, these chemical EOR methods enhanced recovery in areas with complex permeability variations (Alhajri, et al. (2017).
- **Thermal Methods:** Steam-assisted gravity drainage (SAGD) and cyclic steam injection were evaluated for heavier oil zones but faced cost and water availability constraints. Alfageh, M. (2021).

During this period, political instability and limited foreign investment slowed the scale-up of these EOR technologies. Many pilot projects remained small and localized, serving mainly as feasibility studies for potential large-scale deployment. NOC. (2018).

4. Recent Pilot Projects (2010–2025)

In the last decade, renewed interest in EOR has emerged due to reservoir maturity, declining production, and increasing oil demand. Recent initiatives include:

- **CO_2-EOR:** Expanded in Sarir and Messla, with CO_2 sourced from domestic gas streams and limited imports. These projects reported incremental oil recovery of 8–15%, while also providing opportunities for CO_2 sequestration. Alfageh, M. (2021) & Al-Husseini, M. (2015).

- **Polymer Flooding:** Applied in Messla and Nasser fields to enhance sweep efficiency, particularly in reservoirs with high heterogeneity (Alhajri, et al. (2017).
- **Hybrid EOR Approaches:** Combined chemical and thermal methods tested in Ghadames carbonate reservoirs, showing technical feasibility but limited by operational complexity and funding constraints. Alfageh, M. (2021).

TABLE 5. KEY RECENT EOR PROJECTS (2010–2025)

Field	Basin	EOR Method	Start Year	Incremental Recovery (%)	Remarks / Challenges	References
Sarir	Sirte	CO_2 Injection	2012	8–12	Limited CO_2 supply; miscibility achieved	Alfageh, M. (2021) & Al-Husseini, M. (2015)
Messla	Sirte	Polymer Flooding	2015	6–10	High viscosity polymer; scaling issues	(Alhajri, et al. (2017)
Nasser	Sirte	Polymer Flooding	2018	5–8	Heterogeneous reservoirs; limited water	Alfageh, M. (2021)
Ghadames Carbonate	Ghadames	Hybrid Chemical-Thermal	2020	4–7	Technical complexity; operational cost	Alfageh, M. (2021) & (Alhajri, et al. (2017)

These projects collectively highlight Libya's technical capability to implement EOR but also emphasize the challenges of scaling operations under financial, infrastructural, and security constraints. NOC. (2018) & Alfageh, M. (2021).

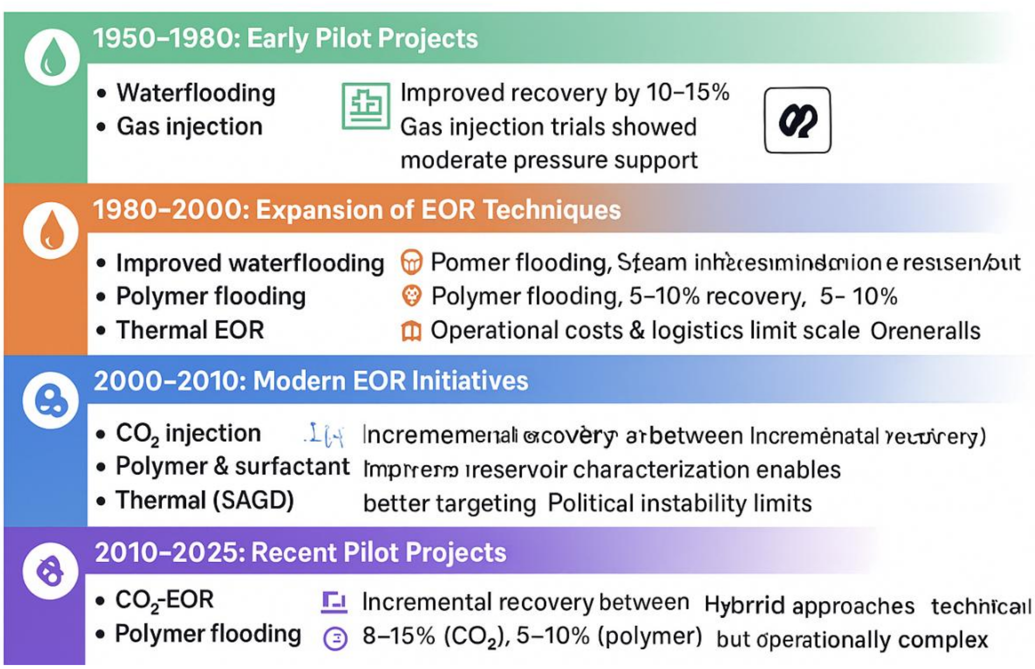

Figure 2. Past Applications of EOR in Libya (1950–2025)

VI. CURRENT STATUS OF EOR IN LIBYA (2020–2025)

1. Overview of Ongoing EOR Projects

As of 2025, Libya has renewed interest in EOR due to mature fields in the Sirte, Ghadames, and Cyrenaica basins. Current initiatives focus on expanding pilot projects, optimizing existing operations, and introducing advanced EOR technologies such as CO_2 injection, polymer flooding, and hybrid methods. Alfageh, M. (2021) & NOC. (2018).

The National Oil Corporation (NOC) oversees coordination with international oil companies (IOCs) for EOR implementation, emphasizing reservoir characterization, monitoring, and sustainable recovery. S&P Global. (2020). The primary objectives are:

1. Increasing ultimate recovery factors in mature fields.
2. Utilizing domestic gas streams for CO_2 injection.
3. Testing hybrid chemical and thermal methods in heterogeneous reservoirs.

2. CO_2-EOR Projects

CO_2-EOR remains the most technically advanced ongoing method in Libya. Notable projects include:

- **Sarir Field (Sirte Basin):** Utilizing CO_2 injection in light oil sandstone reservoirs. Recent reports indicate incremental recovery of 10–15% and operational improvements in sweep efficiency. Al-Husseini, M. (2015) & Alfageh, M. (2021).
- **Messla Field (Sirte Basin):** CO_2 sourced from domestic natural gas streams supports miscible injection pilots, demonstrating feasibility despite limited supply constraints. Alfageh, M. (2021).

Technical challenges remain, including corrosion management, CO_2 supply logistics, and reservoir heterogeneity. Advanced monitoring and modeling tools are being applied to optimize injection rates and maximize recovery (Alhajri, et al. (2017).

3. Polymer and Chemical Flooding

Polymer and surfactant flooding are being applied in heterogeneous reservoirs of Messla and Nasser fields to improve sweep efficiency. These operations target zones with high permeability contrasts, where conventional waterflooding underperforms. Alfageh, M. (2021).

- **Messla Field:** Incremental recovery reported at 6–10%, with ongoing optimization in polymer formulation and injection strategies (Alhajri, et al. (2017).
- **Nasser Field:** Polymer flooding projects have improved production rates in targeted zones, despite limitations in water availability and injection infrastructure. Alfageh, M. (2021).

Chemical EOR remains cost-sensitive, and scaling up operations depends on financial investment and supply chain improvements.

4. Hybrid and Thermal Methods

- **Ghadames Carbonate Reservoirs:** Pilot programs test combinations of chemical and thermal methods to address low-permeability zones. Early results demonstrate potential incremental recovery of 4–7%, though operational complexity limits large-scale deployment. Alfageh, M. (2021).

- **Cyrenaica Heavy Oil Zones:** Cyclic steam injection and steam-assisted gravity drainage (SAGD) remain in limited trials due to high energy requirements and water scarcity (Alhajri, et al. (2017).

These hybrid approaches are being evaluated as part of Libya's long-term EOR strategy to maximize oil recovery from mature and complex reservoirs.

5. International Collaboration and Investment

Libya's EOR development relies heavily on collaboration with international partners, providing both technological expertise and financial resources. Major IOCs involved in pilot projects include ENI, TotalEnergies, and Wintershall, often in joint ventures with NOC. S&P Global. (2020) & Al-Werfalli, F., & Aissa, A. (2016).

Key areas of collaboration include:

- Reservoir simulation and modeling for EOR optimization.
- Advanced monitoring technologies such as 4D seismic and production surveillance.
- CO_2 capture and utilization for miscible EOR projects.

Despite these efforts, political instability and security concerns remain critical barriers to full-scale deployment. NOC. (2018).

6. Summary Table of Current EOR Projects

TABLE 6. CURRENT EOR PROJECTS IN LIBYA (2020–2025)

Field	Basin	EOR Method	Start Year	Incremental Recovery (%)	Remarks / Challenges	References
Sarir	Sirte	CO_2 Injection	2020	10–15	Limited CO_2 supply; heterogeneity	Alfageh, M. (2021) & Al-Husseini, M. (2015)
Messla	Sirte	Polymer Flooding	2021	6–10	Injection optimization ongoing	(Alhajri, et al. (2017) & Alfageh, M. (2021)
Nasser	Sirte	Polymer Flooding	2022	5–8	Water availability; infrastructure	Alfageh, M. (2021)
Ghadames Carbonate	Ghadames	Hybrid Chemical-Thermal	2023	4–7	Operational complexity	Alfageh, M. (2021), (Alhajri, et al. (2017)
Cyrenaica Heavy Oil	Cyrenaica	SAGD / Thermal	2020	3–5	High energy cost; water scarcity	(Alhajri, et al. (2017)

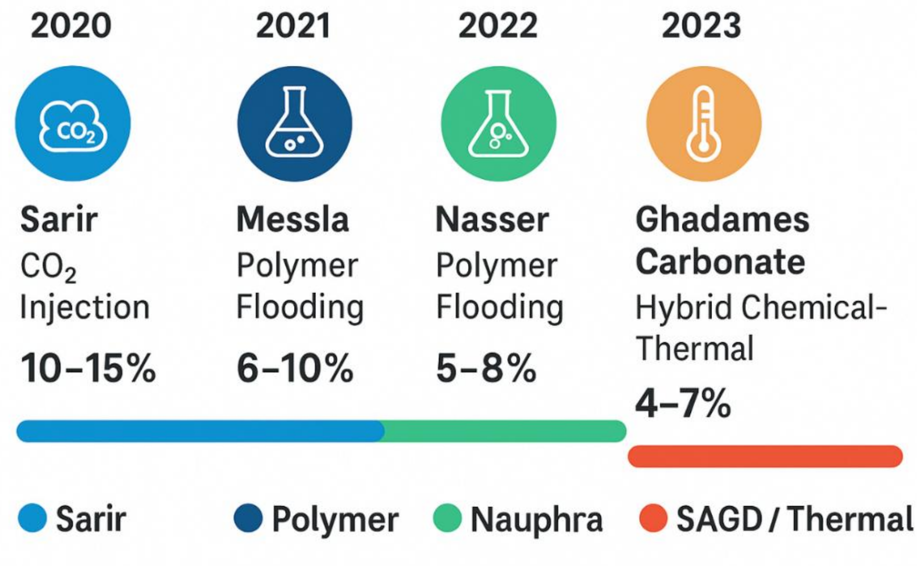

Figure 3: Current Status of EOR in Libya (2020–2025)

VII. FUTURE PROSPECTS OF EOR IN LIBYA

1. Potential for Enhanced Recovery

Libya's mature oil fields, particularly in the Sirte, Ghadames, and Cyrenaica basins, still hold substantial untapped potential. Current estimates suggest that the country could increase its recovery factor by 10–20% using advanced EOR methods, significantly boosting production and extending field life. Alfageh, M. (2021) & Al-Husseini, M. (2015).

- **CO_2-EOR:** Given the availability of domestic gas streams and potential for imported CO_2, miscible CO_2 injection could become the primary strategy for light and medium oil reservoirs. Alfageh, M. (2021).
- **Chemical Flooding:** Polymer and surfactant flooding remain promising for heterogeneous reservoirs with high permeability contrasts, particularly in Messla and Nasser fields (Alhajri, et al. (2017).
- **Thermal Methods:** Heavy oil zones in Cyrenaica and Ghadames could benefit from hybrid thermal–chemical techniques, although water scarcity and energy costs are limiting factors. Alfageh, M. (2021).

2. Integration of Digital Technologies

The future of EOR in Libya will increasingly rely on digital oilfield technologies, including:

- **4D Seismic Monitoring:** For real-time tracking of fluid movement and improved reservoir management. S&P Global. (2020).
- **Artificial Intelligence (AI) and Machine Learning:** To optimize injection strategies, predict reservoir behavior, and reduce operational risk. Alfageh, M. (2021).
- **IoT-Enabled Production Monitoring:** Enhancing efficiency and minimizing downtime in EOR operations. Al-Husseini, M. (2015).

Digital integration is expected to improve recovery factors and reduce costs, making EOR more economically viable in mature fields.

3. Environmental and CO_2 Management Opportunities

EOR provides Libya with opportunities to reduce greenhouse gas emissions through CO_2 sequestration. CO_2 captured from domestic sources or imported from neighboring countries can be injected into reservoirs, simultaneously enhancing oil recovery and contributing to climate mitigation goals. Alfageh, M. (2021) & Al-Husseini, M. (2015).

Challenges include:

- Ensuring safe long-term CO_2 storage.
- Minimizing water usage for chemical and thermal EOR.
- Monitoring potential environmental impacts on surrounding ecosystems (Alhajri, et al. (2017).

4. Economic and Policy Considerations

The economic viability of large-scale EOR deployment in Libya depends on:

- **Oil Prices:** High oil prices make advanced EOR more attractive. S&P Global. (2020).
- **Foreign Investment:** Collaboration with international oil companies (IOCs) provides technology, expertise, and financing. Al-Werfalli, F., & Aissa, A. (2016)
- **Regulatory Frameworks:** Clear policies and incentives for CO_2-EOR, water management, and infrastructure development are essential. NOC. (2018).

Strategic planning, stable governance, and supportive policies are critical to translating technical potential into real production gains.

5. Summary of Future Prospects

TABLE 7. PROJECTED EOR OPPORTUNITIES IN LIBYA

Basin	EOR Method	Target Reservoir	Potential Incremental Recovery (%)	Key Requirements	References
Sirte	CO_2 Injection	Light & Medium Oil	10–15	CO_2 supply, miscibility optimization	Alfageh, M. (2021) & Al-Husseini, M. (2015)
Sirte	Polymer / Surfactant Flooding	Heterogeneous Reservoirs	5–10	Water availability, injection infrastructure	(Alhajri, et al. (2017)
Ghadames	Hybrid Thermal-Chemical	Carbonate & Heavy Oil	4–7	Operational complexity, energy optimization	Alfageh, M. (2021)
Cyrenaica	SAGD / Thermal	Heavy Oil	3–6	Water and energy management	(Alhajri, et al. (2017)
Multiple	Digital Oilfield Integration	All Reservoir Types	+2–5 efficiency gain	AI, IoT, 4D seismic monitoring	Alfageh, M. (2021) & S&P Global. (2020)

The future of Libya's EOR sector is promising, with technical, environmental, and economic benefits achievable if operational, political, and financial challenges are addressed.

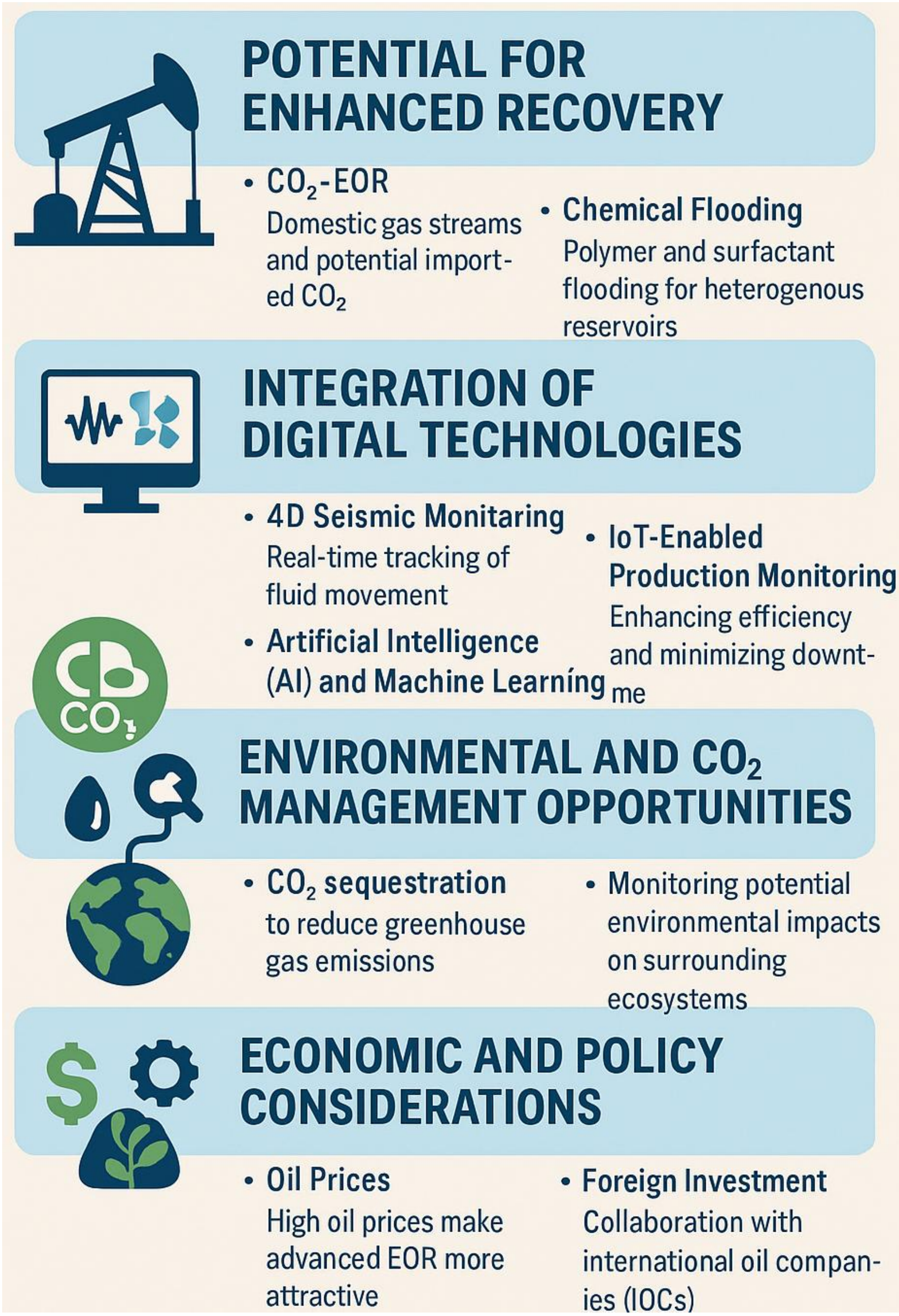

Figure 4: Future Prospects of EOR in Libya

VIII. CHALLENGES AND BARRIERS TO EOR IN LIBYA

Despite the technical potential and ongoing projects, Libya faces significant challenges that hinder the full-scale deployment of EOR methods. These challenges can be grouped into technical, economic, environmental, and political categories.

1. Technical Challenges

1. **Reservoir Heterogeneity:** Libya's reservoirs are highly variable in terms of porosity, permeability, and fluid composition. Such heterogeneity complicates EOR design and reduces sweep efficiency. Alfageh, M. (2021) & Al-Husseini, M. (2015).
2. **Aging Infrastructure:** Many fields still operate with legacy equipment, pipelines, and well completions. Upgrading infrastructure is necessary to support high-pressure CO_2 injection, chemical flooding, and thermal EOR techniques. NOC. (2018) & S&P Global. (2020).
3. **Limited Water Availability:** Water scarcity in Libya restricts polymer and chemical flooding, as well as thermal methods that require substantial water input (Alhajri, et al. (2017).
4. **CO_2 Supply and Handling:** Effective CO_2-EOR requires a reliable supply and high-quality gas. Domestic sources are limited, and logistics for imported CO_2 add complexity. Alfageh, M. (2021).

2. Economic Challenges

1. **High Capital Costs:** EOR projects, especially CO_2 injection and thermal recovery, require significant upfront investment, which can be prohibitive without foreign partners. Al-Werfalli, F., & Aissa, A. (2016)
2. **Oil Price Volatility:** Fluctuating global oil prices affect the economic feasibility of expensive EOR operations. S&P Global. (2020).
3. **Limited Access to Technology and Expertise:** Advanced EOR technologies require international collaboration and specialized workforce training, which are currently limited in Libya. Alfageh, M. (2021)

3. Environmental Challenges

1. **Water and Energy Management:** Thermal and chemical EOR methods require large water volumes and energy input, raising sustainability concerns (Alhajri, et al. (2017).
2. **CO_2 Sequestration Safety:** While CO_2-EOR can reduce emissions, ensuring long-term storage integrity and monitoring potential leakage is critical. Al-Husseini, M. (2015) &, Alfageh, M. (2021).
3. **Impact on Local Ecosystems:** Improper handling of chemicals and water disposal could harm surrounding ecosystems, making regulatory oversight necessary (Alhajri, et al. (2017).

4. Political and Regulatory Challenges

1. **Political Instability:** Libya's political environment has affected oil production and investment security, reducing the attractiveness of long-term EOR projects. NOC. (2018).

2. **Regulatory Uncertainty:** Lack of clear policies on CO_2-EOR, water use, and foreign investment may hinder project approval and expansion. Al-Werfalli, F., & Aissa, A. (2016)
3. **Security Risks:** Fields in remote or conflict-prone regions face operational risks that can disrupt EOR activities. S&P Global. (2020).

5. Summary Table of Key Challenges

TABLE 8. KEY CHALLENGES FOR EOR IMPLEMENTATION IN LIBYA

Category	Challenges	Implications	References
Technical	Reservoir heterogeneity, aging infrastructure, limited water, CO_2 supply	Reduces EOR efficiency, increases operational complexity	Alfageh, M. (2021) & Al-Husseini, M. (2015) & (Alhajri, et al. (2017)
Economic	High capital costs, oil price volatility, limited expertise	Projects may be financially unviable without investment	Al-Werfalli, F., & Aissa, A. (2016) & S&P Global. (2020)
Environmental	Water and energy demands, CO_2 storage safety, ecosystem impacts	Sustainability concerns, regulatory compliance required	[Alhajri, et al. (2017) & Al-Husseini, M. (2015)
Political / Regulatory	Instability, unclear policies, security risks	Delays or halts to project implementation	Al-Werfalli, F., & Aissa, A. (2016) & NOC. (2018)

IX. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

Libya's oil sector, dominated by mature fields in the Sirte, Ghadames, and Cyrenaica basins, holds substantial potential for EOR to increase production and extend field life. Key conclusions from the review include:

1. **Significant Untapped Potential:** Mature reservoirs in Libya could achieve 10–20% additional recovery using advanced EOR techniques, particularly CO_2 injection, polymer flooding, and hybrid methods.
2. **Current EOR Activities:** Ongoing projects in fields such as Sarir, Messla, and Nasser demonstrate the feasibility of CO_2 and chemical EOR, while thermal and hybrid methods remain in limited pilot stages due to technical and environmental constraints.
3. **Challenges Remain:** Technical heterogeneity, aging infrastructure, limited water and CO_2 supply, high capital costs, environmental concerns, and political instability continue to hinder large-scale deployment.

Recommendations

To maximize EOR potential and overcome existing barriers, the following recommendations are proposed:

1. **Expand CO_2-EOR Programs:** Prioritize CO_2 injection in light and medium oil reservoirs, leveraging domestic CO_2 sources and imported supplies where feasible.
2. **Enhance Chemical and Hybrid EOR Projects:** Optimize polymer and surfactant formulations, and expand hybrid thermal–chemical methods for challenging reservoirs while considering environmental impacts.

3. **Adopt Digital Oilfield Technologies:** Implement AI-based reservoir modeling, IoT-enabled production monitoring, and 4D seismic surveillance to improve recovery and reduce operational risk.
4. **Strengthen Infrastructure and Logistics:** Upgrade aging wells, pipelines, and injection systems to support high-pressure CO_2 and chemical EOR operations.
5. **Foster International Collaboration:** Encourage partnerships with IOCs to provide technology transfer, technical expertise, and investment, ensuring sustainable and efficient project implementation.
6. **Policy and Regulatory Support:** Establish clear regulations and incentives for CO_2-EOR, water management, and environmental compliance to attract investment and ensure safe operations.
7. **Address Environmental and Water Challenges:** Develop strategies for water reuse and energy efficiency, while monitoring and mitigating potential ecological impacts of chemical and thermal EOR.

EOR represents a critical strategy for Libya to maximize hydrocarbon recovery from mature fields, improve energy security, and potentially contribute to environmental sustainability through CO_2 sequestration. With targeted investments, technological integration, and supportive policies, Libya's EOR sector can achieve significant production gains and long-term economic benefits.

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