



FROM DISPLACEMENT PHYSICS TO INTELLIGENT AND SUSTAINABLE EOR: MULTISCALE EVOLUTION OF ENHANCED OIL RECOVERY MECHANISMS, TECHNOLOGIES, AND STRATEGIES ALIGNED WITH THE SUSTAINABLE DEVELOPMENT GOALS (2000–2026)

DA FÍSICA DO DESLOCAMENTO À EOR INTELIGENTE E SUSTENTÁVEL: EVOLUÇÃO MULTIESCALAR DOS MECANISMOS, TECNOLOGIAS E ESTRATÉGIAS DE RECUPERAÇÃO AVANÇADA DE PETRÓLEO ALINHADA AOS OBJETIVOS DE DESENVOLVIMENTO SUSTENTÁVEL (2000–2026)

DOI: 10.5281/zenodo.23377477



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ABSTRACT

Enhanced Oil Recovery (EOR) is a fundamental approach for increasing oil production from mature reservoirs, in which a significant fraction of the oil remains trapped due to capillary forces, unfavorable mobility ratios, heterogeneity, and preferential flow. This review analyzes the evolution of physics applied to EOR between 2000 and 2026, highlighting the transition from methods based on the

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optimization of isolated properties toward integrated, multiscale, and reservoir-specific strategies. The main mechanisms associated with low-salinity water and *smart water*, polymers, surfactants, ASP processes, miscible CO₂ and CO₂-foam, nanotechnology, microfluidics, and *digital rock physics* are discussed. The analysis demonstrates that mobility, capillarity, wettability, interfacial tension, miscibility, rheology, and transport act in a coupled manner, making it inadequate to evaluate any technology based on a single performance parameter. The development of microfluidics, computed tomography, and digital rock reconstructions has expanded the ability to directly observe pore-scale phenomena and relate them to macroscopic responses. More recently, *physics-informed machine learning*, Physics-Informed Neural Networks (PINNs), neural networks, and neural operators have been used to integrate experimental data and physical laws for the prediction and optimization of recovery processes. Parallely, it is demonstrated that the evolution of contemporary EOR extends beyond production maximization by directly aligning with the United Nations Sustainable Development Goals (SDGs) of the 2030 Agenda, highlighting resource optimization in mature fields (SDG 12 - Responsible Consumption and Production), digitalization and AI innovation (SDG 9 - Industry, Innovation, and Infrastructure), permanent geological carbon storage via CCUS (SDG 13 - Climate Action), and transitional energy efficiency (SDG 7 - Affordable and Clean Energy). It is concluded that the main frontier of contemporary EOR does not lie in the search for a universal technology, but rather in the combination of physical mechanisms, experimental characterization, computational modeling, artificial intelligence, and global sustainability guidelines. This integration establishes the foundations for intelligent, adaptive, multiscale, sustainable EOR guided by the characteristics and uncertainties of each reservoir. It is concluded that the main frontier of contemporary EOR does not lie in the search for a universal technology, but rather in the combination of physical mechanisms, experimental characterization, computational modeling, and artificial intelligence. This integration establishes the foundations for intelligent, adaptive, multiscale EOR guided by the characteristics and uncertainties of each reservoir.

Keywords: Enhanced Oil Recovery. Sustainable Development Goals (SDGs). Energy Sustainability. Flow in Porous Media. Enhanced Oil Recovery (EOR). Artificial Intelligence.

RESUMO

A recuperação avançada de petróleo (Enhanced Oil Recovery - EOR) constitui uma abordagem fundamental para aumentar a produção em reservatórios maduros, nos quais parcela significativa do óleo permanece aprisionada devido a forças capilares, razões de mobilidade desfavoráveis, heterogeneidade e escoamento preferencial. Esta revisão analisa a evolução da física aplicada à EOR entre 2000 e 2026, destacando a transição de métodos baseados na otimização de propriedades isoladas para estratégias integradas, multiescalares e específicas para cada reservatório. São discutidos os principais mecanismos associados à água de baixa salinidade e *smart water*, polímeros, surfactantes, processos ASP, CO₂ miscível e CO₂-FOAM, nanotecnologia, microfluídica e *digital rock physics*. A análise evidencia que mobilidade, capilaridade, molhabilidade, tensão interfacial, miscibilidade, reologia e transporte atuam de maneira acoplada, tornando inadequada a avaliação de qualquer tecnologia por um único parâmetro de desempenho. O desenvolvimento de microfluídica, microtomografia computadorizada e reconstruções digitais da rocha ampliou a capacidade de observar diretamente fenômenos na escala dos poros e relacioná-los às respostas macroscópicas. Mais recentemente, *physics-informed machine learning*, PINNs, redes neurais e operadores neurais





passaram a integrar dados experimentais e leis físicas para previsão e otimização dos processos de recuperação. Paralelamente, evidencia-se que a evolução da EOR contemporânea transcende a maximização da produção ao alinhar-se diretamente aos Objetivos de Desenvolvimento Sustentável (ODS) da Agenda 2030 da ONU, destacando-se a otimização de recursos em campos maduros (ODS 12 - Consumo e Produção Responsáveis), a digitalização e inovação com inteligência artificial (ODS 9 - Indústria, Inovação e Infraestrutura), o sequestro geológico permanente de CO₂ via CCUS (ODS 13 - Ação Contra a Mudança Global do Clima) e a eficiência energética transicional (ODS 7 - Energia Limpa e Acessível). Conclui-se que a principal fronteira da EOR contemporânea não está na busca por uma tecnologia universal, mas na combinação de mecanismos físicos, caracterização experimental, modelagem computacional, inteligência artificial e diretrizes globais de sustentabilidade. Essa integração estabelece as bases para uma EOR inteligente, adaptativa, multiescalar, sustentável e orientada pelas características e incertezas de cada reservatório.

Palavras-chave: Recuperação Avançada de Petróleo. Objetivos de Desenvolvimento Sustentável (ODS). Sustentabilidade Energética. Escoamento em Meios Porosos. Enhanced Oil Recovery (EOR). Inteligência Artificial.

1. INTRODUCTION

The evolution of EOR between 2000 and 2026 represents more than the emergence of new technologies; it reflects the progressive expansion of our capacity to understand, represent, and control the physical phenomena governing oil recovery. Throughout this process, physics has evolved from serving merely as a tool for interpreting experimental results to becoming the integrating element connecting displacement mechanisms, rock-fluid interactions, porous-medium characterization, computational modeling, and artificial intelligence. The current frontier therefore lies not in the pursuit of a single universal method, but rather in the ability to combine physical mechanisms according to the specific characteristics of each reservoir.

Within this context, the concept of multiscale intelligent EOR emerges as an approach grounded in the integration of physical phenomena operating from the nanoscale and pore scale to the core and reservoir scales, connecting experimentation, digital rock physics (DRP), multiscale modeling, artificial intelligence, and advanced optimization strategies. In this review, Multiscale Intelligent EOR is formally defined as an integrative framework in which physical mechanisms operating from the molecular and pore scales to the core and reservoir





scales are interconnected through experimental characterization, digital rock physics, multiscale modeling, physics-informed artificial intelligence, monitoring, and optimization tailored to reservoir-specific conditions.

The term is therefore employed in this work as a conceptual synthesis proposed by the authors to organize and integrate advances that, although present across different research directions in the literature, have frequently been addressed in a fragmented manner. From this perspective, recovery efficiency is not interpreted as the outcome of the isolated application of a particular technology, but rather as the consequence of the dynamic interaction among capillarity, wettability, mobility, miscibility, rheology, transport, and heterogeneity, all of which constitute the physical basis of displacement in porous media.

Operationally, the multiscale perspective adopted in this review encompasses: (i) molecular- and nanoscale phenomena associated with adsorption, surface forces, intermolecular and ionic interactions, and wettability alteration; (ii) pore-scale phenomena related to capillary trapping, interfacial dynamics, snap-off, and local displacement mechanisms; (iii) core-scale responses, including pressure drop, relative permeability, fluid mobility, and recovery efficiency; and (iv) reservoir- and field-scale phenomena associated with heterogeneity, sweep efficiency, injectivity, breakthrough, monitoring, and optimization. This framework enables an explicit physical connection to be established between fundamental mechanisms observed at the smallest scales and the macroscopic performance of EOR processes.

The consolidation of this approach has been driven by the simultaneous advancement of experimental techniques, computational methods, and digital tools capable of establishing connections across different physical scales. Phenomena observed at the nanoscale and pore scale have increasingly been linked to responses measured at the core and reservoir scales, reducing reliance on interpretations based exclusively on macroscopic observations. In parallel, advances in microfluidics, X-ray micro-computed tomography (micro-CT), digital rock physics, and physics-guided modeling have significantly expanded the ability to characterize, represent, and predict the behavior of rock-fluid systems.



More recently, the incorporation of artificial intelligence, physics-informed machine learning (PIML), physics-informed neural networks (PINNs), and neural operators has enabled the integration of experimental data, numerical simulation, and physical laws, providing new opportunities for prediction, optimization, and decision-making. In these models, physics does not merely serve as prior knowledge; rather, it acts as a fundamental constraint on the learning process, ensuring consistency between the patterns identified by algorithms and the principles governing transport phenomena, multiphase flow, and oil recovery.

Accordingly, the concept of multiscale intelligent EOR does not represent a specific technology, nor does it imply the existence of a universal recovery method. Instead, it represents a new way of understanding and designing enhanced oil recovery processes, in which physics occupies a central role by connecting microscopic mechanisms, experimental observations, digital rock representations, computational modeling, and artificial intelligence. Its conceptual contribution lies precisely in organizing these dimensions into an integrated, physics-oriented architecture capable of connecting mechanisms, data, and decisions across different spatial and operational scales. Within this framework, this critical review examines how advances in physics between 2000 and 2026 have transformed the understanding and application of EOR by critically comparing mechanisms, experimental results, and scale-related limitations, with particular emphasis on the transition from conventional processes toward multiscale, hybrid, and data-driven strategies.

In parallel with scientific and technological advances, it has become imperative to contextualize the evolution of EOR within global frameworks for sustainability, energy efficiency, and environmental impact reduction. In this regard, the transition from the physics of conventional displacement toward multiscale intelligent EOR is connected to the Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda.

Optimizing the recovery factor of mature reservoirs may reduce the overall environmental footprint of extractive activities when implemented under appropriate operational and life-cycle conditions and may contribute to avoiding or delaying the



development of new exploration frontiers in environmentally sensitive areas (SDG 12, Responsible Consumption and Production), while digitalization, advanced sensing technologies, and physics-based artificial intelligence models promote technological modernization and resilient industrial infrastructure (SDG 9, Industry, Innovation and Infrastructure).

Furthermore, advances in CO₂-EOR and CO₂-foam processes establish a direct link with Carbon Capture, Utilization, and Storage (CCUS), transforming one of the major greenhouse gases into a recovery agent while potentially enabling its permanent sequestration within the porous medium when these processes are integrated with appropriate site characterization, containment-capacity assessment, monitoring, verification, and long-term storage-management practices. This establishes a direct interface with SDG 13, Climate Action, and SDG 7, Affordable and Clean Energy, particularly within the broader context of the energy transition.

2. METHODOLOGY OF THE STRUCTURED CRITICAL LITERATURE REVIEW

This research was conducted as a structured, critical, and multiscale review of the literature, encompassing studies published between January 2000 and July 2026, with the aim of analyzing the evolution of Enhanced Oil Recovery (EOR) technologies, their underlying physicochemical mechanisms, and the experimental and computational methods employed to investigate them.

The literature search was conducted across Scopus, Web of Science, ScienceDirect, SpringerLink, OnePetro, Wiley Online Library, and ACS Publications, using combinations of search terms organized into three main categories: (i) EOR technologies, including low-salinity water, smart water, polymers, surfactants/alkali-surfactant-polymer (ASP) systems, CO₂, foams, and nanofluids; (ii) physical and physicochemical mechanisms, such as wettability alteration, interfacial tension, capillarity, miscibility, adsorption, rheology, mobility control, and rock-fluid interactions; and (iii) investigation methods, including microfluidics,





micro-computed tomography (micro-CT), digital rock physics, pore-network modeling, molecular dynamics, reservoir simulation, and physics-informed artificial intelligence. The search strategies were adapted to the specific characteristics of each database and supplemented by screening the reference lists of the selected studies.

The eligibility criteria included peer-reviewed articles published in English, with a verifiable DOI and an explicit contribution to the understanding of mechanisms associated with EOR. Experimental, computational, and field studies were considered, along with critical reviews relevant to conceptual consolidation. Patents, editorials, gray literature, theses, dissertations, documents without a DOI, duplicate records, and studies focused exclusively on economic or operational aspects without mechanistic interpretation were excluded.

The retrieved records were consolidated and subjected to duplicate removal based on DOI, title, authorship, journal, and year of publication. Study selection was performed sequentially through title, abstract, and full-text screening. Eligible studies were subsequently assessed for methodological quality, considering the appropriateness of the experimental or computational design, description of boundary conditions, reproducibility, quantification of physical variables, treatment of uncertainties, and consistency between the reported evidence and the proposed mechanisms.

Data were extracted using a standardized matrix containing information on the EOR technology, rock-fluid system properties, experimental conditions, investigation method, physical mechanism, response variables, quantitative results, and study limitations. The studies were classified according to their predominant scale of investigation, encompassing molecular/interfacial, pore, microfluidic, core, pilot, and reservoir/field scales, thereby enabling an assessment of whether the identified mechanisms persist or change during upscaling.

Owing to the heterogeneity of experimental conditions, rock-fluid systems, and methodological approaches, a quantitative meta-analysis was not performed. Instead, a comparative, mechanistic, and critical synthesis was undertaken based on the convergence of evidence across different methods and scales. The interpretation followed a hierarchical





framework spanning the molecular/interfacial, pore, core, and reservoir scales, distinguishing mechanisms that were directly demonstrated from those supported by indirect evidence or only proposed.

Finally, the analysis was structured according to the relationships among EOR technology, physical mechanism, scale of action, observation method, experimental/computational evidence, effect on displacement behavior, scale-related limitations, and reservoir applicability. This approach enabled the integration of experimental, computational, and field-scale findings and provided a critical assessment of how fundamental EOR mechanisms propagate from the molecular and pore scales to reservoir conditions.

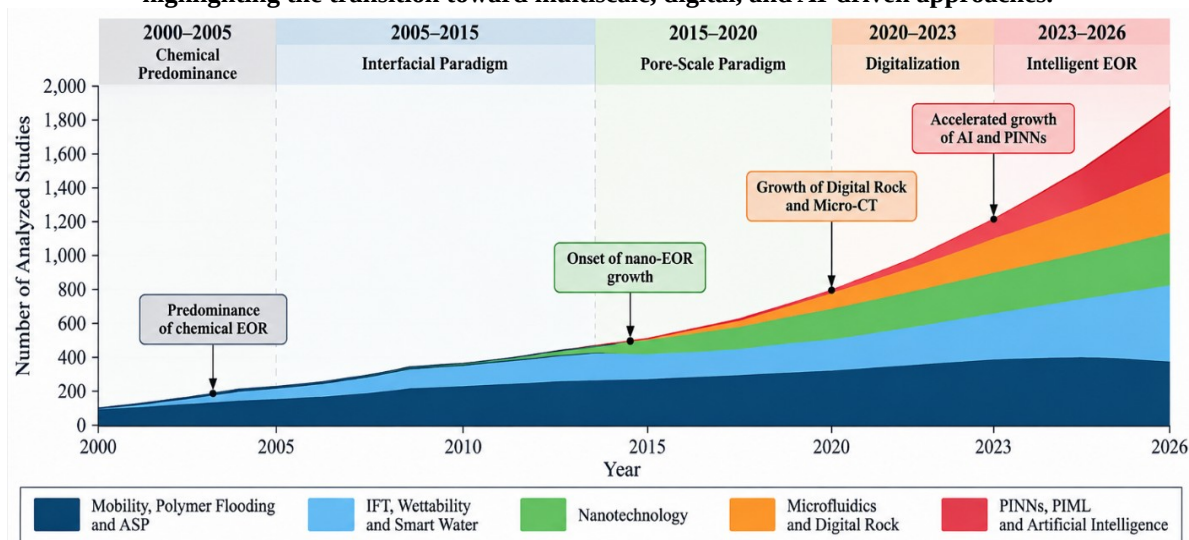
3. TEMPORAL EVOLUTION AND TRANSFORMATION OF THE PHYSICAL PARADIGMS OF EOR

The analysis of the literature published between 2000 and 2026 reveals a progressive transformation in the scientific themes and paradigms associated with the physics applied to enhanced oil recovery. Figure 1 summarizes this temporal evolution based on the bibliographic corpus analyzed in this review, highlighting the shift in research focus from predominantly macroscopic approaches centered on mobility, miscibility, and displacement efficiency toward strategies grounded in interfacial phenomena, multiscale characterization, digital representation of porous media, and artificial intelligence.





Figure 1. Temporal evolution of the dominant themes in physics applied to EOR (2000 - 2026), highlighting the transition toward multiscale, digital, and AI-driven approaches.



This trajectory reflects advances in the scientific capacity to understand, visualize, model, and optimize the physical mechanisms that control oil recovery across different scales. As presented in Figure 1, the early years of the period analyzed were characterized by a predominance of studies focused on mobility control, polymer flooding, surfactants, and sweep efficiency. From the 2010s onward, a significant increase in research interest in interfacial and physicochemical phenomena became evident, including wettability, interfacial tension (IFT), adsorption, and rock-oil-water interactions. This shift is particularly evident in chemical EOR methods, in which the optimization of a single property has progressively given way to approaches that account for the simultaneous interaction of multiple recovery mechanisms. In low-salinity waterflooding, for example, mechanisms such as wettability alteration, multicomponent ion exchange, electrical double-layer expansion, mineral dissolution, and pH variations may act simultaneously and are strongly dependent on mineralogy, brine composition, crude-oil properties, and saturation history (Lyu, Zhong, Ning, 2022; Mwakipunda *et al.*, 2023).

The evolution of CO₂-EOR further reinforces this trend, as favorable miscibility conditions do not necessarily translate into improved reservoir-scale performance. Challenges



associated with the high mobility of CO₂, including viscous fingering, channeling, and premature breakthrough, have driven the development of complementary strategies such as WAG (water-alternating-gas) and mobility-control methods. In parallel, the increasing use of high-resolution experimental techniques, such as microfluidics and X-ray microcomputed tomography (micro-CT), has expanded the ability to directly investigate mechanisms that were previously inferred primarily from macroscopic responses, bringing experimental analysis closer to the pore scale.

The most recent stage of this evolution is characterized by the integration of experimental approaches, Digital Rock Physics (DRP), multiscale modeling, and artificial intelligence, including physics-informed machine learning (PIML) and physics-informed neural networks (PINNs). As evidenced in Figure 2, the evolution of EOR has not occurred through the simple replacement of technologies, but rather through the progressive incorporation of new levels of physical description and analytical capability. Consequently, phenomena traditionally investigated in isolation—such as mobility, capillarity, wettability, miscibility, transport, and heterogeneity—are increasingly interpreted within an integrated, multiscale, and data-driven framework that provides the conceptual basis for contemporary intelligent EOR. Beyond comparing technologies and their maturity levels, it is therefore important to establish a direct relationship between the main reservoir limitations, the physical mechanisms responsible for these limitations, and the EOR strategies developed to mitigate them.

Table 1 integrates these relationships by showing how challenges such as capillary trapping, unfavorable mobility ratios, reservoir heterogeneity, poor sweep efficiency, and high gas mobility can be associated with specific physical mechanisms and, consequently, guide the selection of appropriate recovery strategies. This perspective emphasizes that EOR technology selection should begin with the identification of the dominant reservoir mechanisms rather than being driven solely by the availability of a particular technology. Table 1 further demonstrates that different reservoir limitations can be addressed through distinct physical mechanisms and, in many cases, through more than one EOR strategy. This





relationship also illustrates the nonlinear nature of technological evolution: although a strategy may be developed to control a specific mechanism, its effectiveness ultimately depends on its interaction with other phenomena within the system. For example, reducing IFT may promote oil mobilization without necessarily overcoming mobility-control or heterogeneity-related limitations; similarly, increasing the viscosity of the injected aqueous phase may improve mobility control while adversely affecting injectivity. EOR selection should therefore account for the combined effects of the dominant mechanisms and their interactions across scales.

Table 1. Integrated relationship between displacement challenges, dominant physical mechanisms, and enhanced oil recovery (EOR) strategies.

Reservoir Limitation	Physical Mechanism	EOR Strategy
Capillary trapping	High capillary pressure / low capillary number	Surfactant flooding, smart water, nanoparticles
Unfavorable mobility ratio	Viscosity contrast between phases	Polymer flooding
Viscous fingering	Mobility instability	Polymer flooding, WAG, CO ₂ foam
Heterogeneity / channeling	Preferential flow distribution	Polymer flooding, CO ₂ foam, WAG
High residual oil saturation	Capillary forces and low oil mobility	Surfactants, ASP, smart water
Unfavorable wettability	Rock-oil-water interactions	Smart water, surfactants, nanoparticles
High CO ₂ mobility	Low gas viscosity / displacement instability	CO ₂ foam, WAG
Low injectivity	Retention, adsorption, and increased viscosity	Optimization of polymers, surfactants, and nanoparticles
High chemical retention / adsorption	Fluid-rock interactions	Tailored chemical formulations / nanomaterials
Poor pore-network connectivity	Restrictions on transport and fluid flow	Nanoparticles, smart water, hybrid strategies

Table 2 summarizes, from a multiscale perspective, the relationships among the main EOR technologies, their dominant and secondary recovery mechanisms, experimental evidence at the pore, core, and field scales, and the main barriers associated with their



implementation. This organization enables comparison not only of the physical and chemical foundations of each approach but also of their technological maturity and the challenges involved in transitioning across scales, from understanding displacement mechanisms to reservoir-scale application.

Table 2. Multiscale framework of EOR mechanisms, technologies, and technological maturity

Technology	Dominant Mechanism	Secondary Mechanisms	Pore-Scale Evidence	Core-Scale Evidence	Field-Scale Evidence	Main Barrier
Smart water	Wettability alteration	Surface chemistry	High	High	Moderate	Mineralogical dependence
Polymer flooding	Mobility control	Rheology	High	High	High	Stability / injectivity
Surfactant flooding	IFT reduction	Wettability alteration	High	High	Moderate	Adsorption / cost
CO ₂ -EOR	Miscibility	Mass transfer	High	High	High	Mobility control
CO ₂ foam	Gas mobility control	Capillarity	High	High	Moderate	Stability
Nanoparticles	Surface interactions	IFT / transport	High	Moderate	Low–moderate	Retention
Microfluidics	Direct observation	Mechanistic characterization	Very high	—	—	Representativeness
DRP	Pore structure	Transport	Very high	High	Moderate	Upscaling
PINNs	Physics-informed modeling	Data assimilation	—	—	Emerging	Generalization
Neural operators	Physical-field prediction	Upscaling	—	—	Emerging	Extrapolation

As shown in Table 2, EOR technologies exhibit different levels of maturity and supporting evidence across the pore, core, and field scales. Established methods, such as





polymer flooding, surfactant flooding, and CO₂-EOR, are supported by extensive experimental evidence, although limitations related to stability, injectivity, mobility control, and cost remain.

Emerging approaches, including nanoparticles, PINNs, and neural operators, show considerable potential but still face challenges related to retention, representativeness, generalization, and field-scale implementation. Thus, the framework highlights that EOR evolves through an integrated and nonlinear process, combining physical and chemical mechanisms, mobility-control technologies, and advanced modeling tools to address the major challenges associated with upscaling.

The following sections examine these technologies in greater depth by comparing their mechanisms, reported performance, and limitations, with particular emphasis on the physical principles governing oil recovery. This perspective highlights the transition toward hybrid and multiscale strategies tailored to the specific characteristics of each reservoir.

4. LOW-SALINITY WATERFLOODING AND SMART WATER

Low-salinity waterflooding (LSW) and smart water are EOR strategies based on modifying brine composition to alter wettability, electrostatic interactions, capillary pressure, and chemical equilibrium at the rock–oil–water interface (Tetteh, Brady, Ghahfarokhi, 2020; Nande, Patwardhan, 2022). Several mechanisms have been proposed, including multicomponent ion exchange, electrical double-layer expansion, mineral dissolution, fines migration, and pH variations. However, there is no consensus regarding the predominance of a single mechanism, as their relative contributions depend on rock type and system conditions (Tetteh, Brady, Ghahfarokhi, 2020; Lyu *et al.*, 2022).

Wettability remains one of the key parameters governing the process, although wettability alteration does not always correlate directly with increased oil recovery, highlighting the complexity of the relationship between interfacial properties and reservoir performance (Katende; Sagala, 2019). Recent studies further indicate that brine ionic





composition may be more important than total salinity, particularly in systems involving calcium, magnesium, and sulfate ions, with the response being strongly influenced by mineralogy, crude-oil composition, temperature, and saturation history (Lyu *et al.*, 2022).

Differences between sandstone and carbonate reservoirs, together with the challenges associated with extrapolating laboratory results to the field scale, reinforce the absence of a universal brine composition or a single mechanism responsible for enhanced recovery. Smart water therefore represents progression toward engineered-brine approaches that integrate surface chemistry, mineralogy, electrochemistry, and flow physics, with performance ultimately governed by the specific characteristics of each reservoir (Tetteh; Brady; Ghahfarokhi, 2020; Nande; Patwardhan, 2022; Mwakipunda *et al.*, 2023).

5. POLYMERS AND RHEOLOGY

Polymers are widely used in EOR to improve the mobility ratio between the injected water and oil by increasing the viscosity of the aqueous phase and mitigating phenomena such as *viscous fingering*, channeling, and premature water breakthrough.

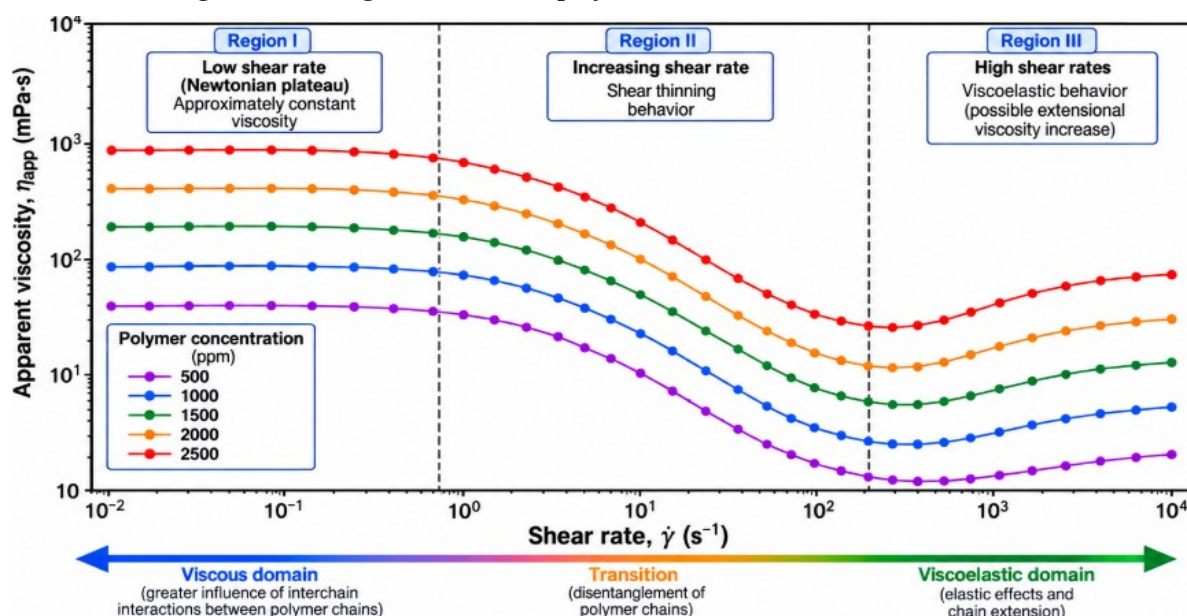
Their primary purpose is therefore to improve sweep efficiency and divert the injected fluid toward regions that still contain mobile oil (Standnes; Skjevrak, 2014; Jouenne, 2020). In porous media, polymer solutions generally exhibit non-Newtonian behavior, with viscosity depending on shear rate and flow conditions. Moreover, mechanical and thermal degradation, adsorption, retention, permeability reduction, and viscoelastic effects can significantly affect polymer performance under reservoir conditions.

Consequently, the effectiveness of polymer flooding depends not only on increasing aqueous-phase viscosity but also on preserving the polymer's rheological and transport properties during propagation through the porous medium (Jouenne, 2020). Figure 2 conceptually illustrates this dependence of apparent viscosity on shear rate, highlighting the transition among different rheological regimes.





Figure 2. Rheological behavior of polymer solutions as a function of shear rate



Source: Conceptually adapted from Rock *et al.* (2020) and Zeynali *et al.* (2023)

The rheological behavior of polymers in porous media is more complex than a simple increase in water viscosity. Increasing polymer concentration tends to increase apparent viscosity, whereas higher shear rates may induce shear-thinning behavior and viscoelastic effects, causing the properties measured under laboratory conditions to change during flow through the reservoir. In addition, factors such as mechanical and thermal degradation, adsorption, retention, and polymer–rock interactions can significantly reduce process efficiency, making initial viscosity alone insufficient to predict field performance (Jouenne, 2020).

In this context, the main challenge in polymer flooding has shifted toward achieving an appropriate balance among mobility control, chemical stability, and injectivity preservation. Analyses of field projects have shown that reservoir characteristics, including permeability, the volume of polymer injected, and the ability to maintain injectivity, are critical determinants of successful implementation (Standnes, Skjevrak, 2014).



More recent developments have focused on polymers capable of operating under high-temperature and high-salinity conditions and in the presence of divalent ions, as well as on the development of copolymers, functionalized polymers, and hybrid systems combining polymers, surfactants, nanoparticles, and smart water. Thus, polymers are no longer regarded solely as viscosifying agents but have become components of multifunctional recovery strategies. Consequently, the most suitable polymer is not necessarily the one that provides the highest viscosity, but rather the one that offers the most favorable balance among mobility control, stability, injectivity, and sweep efficiency under actual reservoir conditions (Jouenne, 2020).

Between 2000 and 2026, polymer flooding evolved from a technology primarily focused on increasing water viscosity into an approach based on the rheological control of flow through porous media and the integration of transport and interfacial interaction mechanisms. This trend reflects the broader evolution of EOR toward hybrid, multi-mechanistic, and reservoir-specific systems (Jouenne, 2020; Lyu *et al.*, 2022).

6. SURFACTANTS AND ALKALINE–SURFACTANT–POLYMER (ASP) PROCESSES

Surfactants are widely used in EOR because of their ability to reduce interfacial tension (IFT) and alter wettability, thereby promoting the mobilization of residual oil. However, their effectiveness depends not only on IFT reduction but also on factors such as adsorption, retention, emulsification, stability, and transport through porous media (Yang *et al.*, 2020). Advances in the understanding of these processes have demonstrated that salinity, adsorption, diffusion, and other transport mechanisms play decisive roles in the performance of chemical flooding systems (Liu *et al.*, 2007; Zhao *et al.*, 2007; Yin *et al.*, 2008).

These limitations have driven the development of SP (surfactant–polymer flooding) and ASP processes, in which surfactants promote microscopic oil mobilization, while polymers improve mobility control and sweep efficiency. The performance of these systems results from the interplay among IFT, capillarity, rheology, and transport and may be





adversely affected by adsorption, precipitation, emulsification, and loss of injectivity. Raffa, Broekhuis, and Picchioni (2016) highlighted this convergence through multifunctional polymeric surfactants, whereas Sun, Guo, and Li (2020) reported an average incremental recovery of approximately 12% of OOIP in field applications, highlighting the challenges associated with translating laboratory-scale performance to reservoir conditions.

More recently, techniques such as micromodels and pore-scale experiments have enabled direct investigation of residual oil displacement, demonstrating that EOR performance depends on the evolution of fluid interfaces, capillary forces, and flow patterns within the pore network (Yang *et al.*, 2021; Jing *et al.*, 2021). Thus, between 2000 and 2026, surfactant flooding evolved from an approach primarily focused on IFT reduction into a multiscale strategy integrating wettability, capillarity, mobility, and transport, thereby establishing a more comprehensive understanding of recovery mechanisms (Liu *et al.*, 2007; Zhao *et al.*, 2007; Yin *et al.*, 2008; Raffa, Broekhuis, Picchioni, 2016; Sun, Guo, Li, 2020; Yang *et al.*, 2021; Jing *et al.*, 2021).

As summarized in Table 3, the evolution of surfactants in EOR has extended beyond the development of more efficient formulations to encompass an enhanced ability to simultaneously control mechanisms such as capillarity, wettability, mobility, and transport across different scales.

Accordingly, the main contribution of these systems lies in the integrated modification of the balance among capillary, viscous, and interfacial forces, shifting the focus from simple IFT reduction toward the development of strategies capable of mobilizing residual oil, controlling its displacement pathways, and maintaining effective transport through porous media. This transition represents one of the most important developments in the physics underlying EOR, marking a shift from approaches based on isolated properties toward integrated control of multiphase flow in porous media.





Table 3. Evolution of physical mechanisms and technological strategies associated with surfactant flooding between 2000 and 2026

Period	Predominant technological evolution	Physical/chemical mechanisms emphasized	Representative studies analyzed
2000–2005	Consolidation of surfactant flooding as an EOR method	IFT reduction, capillary mobilization, wettability alteration, and phase behavior	Hirasaki <i>et al.</i> (2002); Pitts, Wyatt, Surkalo (2004)
2006–2010	Increased focus on surfactant–rock–fluid interactions	Dynamic IFT, adsorption, retention, salinity, and transport through porous media	Liu <i>et al.</i> (2007); Zhao <i>et al.</i> (2007); Yin <i>et al.</i> (2008); Barnes <i>et al.</i> (2008)
2011–2015	Integration of surfactants, polymers, and mobility control	IFT + mobility + emulsification + chemical transport	Rai, Bera, Mandal (2014); Son <i>et al.</i> (2014); Wu <i>et al.</i> (2015)
2016–2020	Multifunctional systems and field-scale validation	SP/ASP, ultralow IFT, mobility control, emulsification, and stability	Raffa, Broekhuis, Picchioni (2016); Hussein <i>et al.</i> (2017); Sun <i>et al.</i> (2020)
2021–2023	Direct investigation of pore-scale mechanisms	Residual oil displacement, snap-off, film flow, emulsification, and wettability alteration	Yang <i>et al.</i> (2021); Jing <i>et al.</i> (2021); Chen <i>et al.</i> (2021)
2024–2026	Smart surfactants and multiscale integration	Switchable surfactants, SP systems, and integration of experimental studies with reservoir simulation	Kamaludin, Suhaidi, Ismail (2024); recent studies on switchable surfactants (2024–2026)

7. MISCIBLE CO₂ AND CO₂ FOAM

Miscible CO₂ injection is one of the major EOR strategies because it combines oil-viscosity reduction, oil swelling, extraction of light components, and interphase mass transfer. When the minimum miscibility pressure (MMP) is reached, miscibility promotes oil mobilization; however, process efficiency depends on the balance among miscibility, diffusion, mass transfer, and mobility ratio. Thus, achieving miscibility alone does not





guarantee high recovery performance, particularly in heterogeneous reservoirs, where the high mobility of CO₂ can promote channeling and displacement instabilities (Kumar *et al.*, 2022).

This complexity becomes even more relevant in low-permeability reservoirs, particularly tight-oil systems, where diffusion, adsorption, and transport limitations play significant roles. To address limitations associated with high gas mobility, CO₂-foam processes have been developed, in which foam reduces the effective mobility of CO₂ and improves sweep efficiency by redirecting flow toward less-swept regions of the reservoir.

Foam performance depends on lamella stability and on factors such as the presence of oil, surfactant adsorption, salinity, temperature, and rock properties (Talebian *et al.*, 2014). Recent advances include the development of more stable surfactants, improvements in foam transport, and the use of nanoparticles to enhance foam stability, although the resulting gains remain strongly dependent on system-specific conditions (Jian *et al.*, 2021).

Therefore, the evolution of CO₂-EOR between 2000 and 2026 does not represent the replacement of miscible CO₂ flooding by CO₂-foam processes, but rather the progressive integration of complementary mechanisms involving mass transfer, miscibility, mobility control, capillarity, and reservoir heterogeneity. This convergence reinforces the broader trend in modern EOR toward combining multiple physical phenomena to maximize oil recovery and optimize the spatial distribution of the displacing agent within the reservoir (Ibrahim *et al.*, 2026).

8. NANOTECHNOLOGY

The application of nanotechnology to EOR has progressively expanded the ability to control physical phenomena across multiple scales. Owing to their high surface-area-to-volume ratio, nanoparticles can modify wettability, interfacial tension (IFT), disjoining pressure, and transport properties, thereby directly influencing oil trapping and mobilization mechanisms (Cheraghian, Hendraningrat, 2016a; Sun *et al.*, 2017).





Early studies focused primarily on interfacial engineering, emphasizing wettability alteration, IFT reduction, and stabilization of aqueous films (Cheraghian, Hendraningrat, 2016a, 2016b). Subsequent studies demonstrated that Nano-EOR performance also depends on transport, mobility, colloidal stability, and rock–nanoparticle interactions, which are influenced by nanoparticle type, size, and concentration, as well as by mineralogy and fluid properties (Sun *et al.*, 2017; Agista, Guo, Yu, 2018).

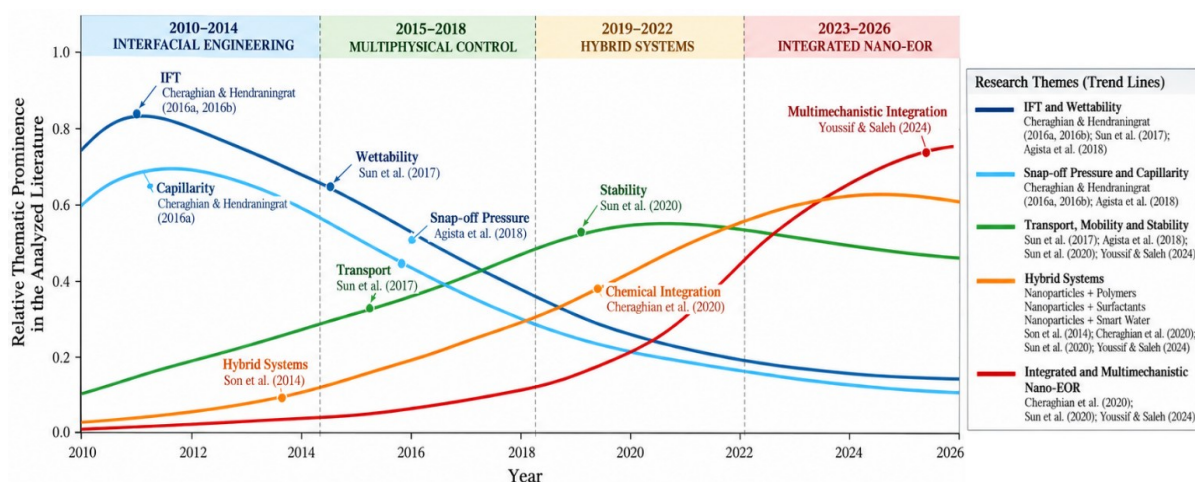
As illustrated in Figure 3, the evolution of Nano-EOR has involved the progressive incorporation of additional physical mechanisms. Between 2017 and 2020, nanotechnology increasingly came to be regarded as a multiphysics strategy simultaneously involving transport, mobility, and interfacial stability, while also revealing limitations associated with nanoparticle aggregation, adsorption, and retention within porous media (Sun *et al.*, 2020). From 2020 onward, research increasingly shifted toward hybrid systems combining nanoparticles with polymers, surfactants, and smart water, together with the integration of nanoscale, pore-scale, and macroscopic phenomena (Cheraghian, Rostami, Afrand, 2020; Youssif, Saleh, 2024).

More recently, Nano-EOR has incorporated multiscale concepts and digital tools, increasingly converging with approaches based on digital rock physics, advanced modeling, and artificial intelligence. As shown in Figure 3, this trajectory reflects a transition from strategies centered on isolated properties toward increasingly integrated systems in which recovery efficiency depends on the combined effects of interfacial mechanisms, transport, stability, and multiscale reservoir characterization (Youssif, Saleh, 2024).





Figure 3. Evolution of the physical paradigms of Nano-EOR and dominant research themes in the literature from 2010 to 2026



As illustrated in Figure 3, the evolution of Nano-EOR has been driven by the progressive incorporation of new physical mechanisms. Early studies focused on interfacial engineering, with emphasis on interfacial tension (IFT) reduction, wettability alteration, and disjoining-pressure effects to mitigate capillary trapping of oil (Cheraghian, Hendraningrat, 2016a, 2016b; Sun *et al.*, 2017).

Subsequently, the focus expanded to phenomena associated with nanoparticle transport, mobility, and stability within porous media, demonstrating that Nano-EOR efficiency depends not only on surface properties but also on the ability of nanoparticles to reach regions containing residual oil (Agista, Guo, Yu, 2018; Sun *et al.*, 2020).

Since 2020, hybrid strategies combining nanoparticles with polymers, surfactants, and smart water have gained increasing attention, reflecting a transition toward the simultaneous control of multiple physical mechanisms (Cheraghian, Rostami, Afrand, 2020; Youssif, Saleh, 2024). As shown in Figure 3, the most recent trend involves the integration of wettability, capillarity, transport, mobility, and stability, consolidating Nano-EOR as a multiphysics and multimechanistic approach. Nevertheless, challenges related to aggregation, adsorption,



retention, and scalability continue to constrain field-scale implementation (Sun *et al.*, 2020; Youssif, Saleh, 2024).

Thus, the evolution of Nano-EOR has not occurred through the replacement of individual mechanisms, but rather through the increasing integration of interfacial, transport, and porous-media flow phenomena, mirroring the broader evolution of EOR physics toward increasingly integrated and multiscale approaches (Cheraghian, Hendraningrat, 2016a, 2016b; Agista, Guo, Yu, 2018; Cheraghian, Rostami, Afrand, 2020; Youssif, Saleh, 2024).

9. MICROFLUIDICS

Microfluidics enables direct investigation, at the pore scale, of phenomena that conventional core-flooding experiments can only assess indirectly, including fingering, snap-off, capillary trapping, emulsification, adsorption, pore blocking, and flow diversion (Zhang *et al.*, 2022). Its main contribution lies in linking pore geometry to the capillary and viscous forces governing fluid displacement, thereby enabling the assessment of how properties such as viscosity, interfacial tension, and mobility ratio influence flow patterns (Yang *et al.*, 2021; Jing *et al.*, 2021).

Between 2000 and 2026, microfluidics evolved from a primarily visualization-based tool into a quantitative platform for investigating the physical mechanisms governing EOR. Initially focused on observing displacement and trapping patterns, it was subsequently applied to the investigation of IFT, wettability, capillarity, and mobility, becoming an established tool for analyzing chemical EOR systems and phenomena such as fingering, snap-off, emulsification, and pore blocking (Yang *et al.*, 2021; Jing *et al.*, 2021; Zhang *et al.*, 2022). The current trend is toward integration with micro-CT, core-scale experiments, and numerical simulation, thereby linking pore-scale observations to the macroscopic behavior of reservoirs.





10. DIGITAL ROCK PHYSICS (DRP) AND MICRO-CT

Digital rock physics (DRP) and X-ray microcomputed tomography (micro-CT) enable the three-dimensional structure of rocks to be converted into quantitative models for investigating permeability, capillary pressure, connectivity, saturation, and multiphase displacement. By linking pore geometry to fluid flow, these techniques enable direct analysis of capillary, viscous, and pressure forces, while tracking fluid distributions and the mechanisms governing oil mobilization and trapping (Mehmani, Kelly, Torres-Verdín, 2020).

Recent advances in DRP have been characterized by the integration of micro-CT, 3D reconstruction, numerical simulation, and upscaling, thereby enhancing its predictive capability. More recently, machine-learning methods have been incorporated to assist image segmentation and processing, although they also introduce additional sources of uncertainty. Despite these advances, the primary challenge remains achieving an appropriate balance among spatial resolution, representativeness of the analyzed volume (representative elementary volume, REV), computational cost, and physical fidelity.

DRP and micro-CT have therefore become an important bridge between rock structure, flow mechanisms, and EOR performance, enabling the integration of different observational and modeling scales. However, reliable predictions depend not only on image quality but also on the entire workflow encompassing data acquisition, segmentation, reconstruction, modeling, and upscaling (Mehmani, Kelly, Torres-Verdín, 2020).

11. PHYSICS-INFORMED MACHINE LEARNING, PINNs, AND NEURAL OPERATORS

The integration of machine learning and physics represents one of the most recent stages in the evolution of digital EOR. Physics-informed neural networks (PINNs) incorporate governing equations, boundary conditions, and experimental data into the training process, enabling the network to seek solutions that remain consistent with the underlying physical





laws. A general formulation representing the loss function used to train a PINN is given by Equation 1:

$$\zeta = \lambda_d \zeta_{data} + \lambda_p \zeta_{physics} + \lambda_b \zeta_{boundary}$$

It combines three components:

- ζ_{data} : measures the agreement between the network predictions and experimental or field data;
- $\zeta_{physics}$: measures the extent to which the predicted solution satisfies the governing physical equations, such as mass conservation, pressure, saturation, and transport equations;
- $\zeta_{boundary}$: assesses whether the solution satisfies the boundary and initial conditions of the system;
- $\lambda_d, \lambda_p, \lambda_b$: are weighting coefficients that control the relative contribution of each component.

PINNs (physics-informed neural networks) represent an important advancement in EOR modeling by integrating experimental data with governing physical equations, thereby reducing dependence on large datasets while ensuring that constraints such as mass conservation, boundary conditions, and transport processes are incorporated during training (Almajid, Abu-Al-Saud, 2022; Ihunde, Olorode, 2022). However, their reliability depends on an appropriate balance among data, physical formulation, and boundary conditions, since mathematically consistent solutions may not necessarily provide an adequate representation of reservoir behavior.

Recent developments have sought to explicitly incorporate the spatial structure of porous media into artificial intelligence models. PINNs have been applied to heterogeneous and fractured porous media (Yan *et al.*, 2024), while Physics-Informed Graph Neural Networks (PIGNNs) have been introduced to account for the spatial connectivity governing fluid flow (Chen *et al.*, 2025). In parallel, models for heterogeneous two-phase flow (Lin *et*





al., 2025) and neural operators, such as Fourier neural operators, have expanded the ability to represent complete physical fields and accelerate upscaling procedures.

Overall, the evolution of AI in EOR is moving toward hybrid and multiscale models, in which computational learning and physical laws operate synergistically, enabling a more physically consistent representation of the relationships among pore structure, transport, mobility, and oil recovery (Almajid, Abu-Al-Saud, 2022; Yan *et al.*, 2024; Chen *et al.*, 2025; Lin *et al.*, 2025).

12. POST-2026 FUTURE PERSPECTIVES: MULTISCALE PHYSICS AND INTELLIGENT EOR

The next generation of EOR is expected to evolve from the isolated application of individual technologies toward the integration of physical mechanisms, monitoring systems, and multiscale modeling. Strategies involving *smart water*, nanomaterials, CO₂ foam, sensors, *digital rock physics*, micro-CT, and *physics-informed machine learning* (PIML) may be combined to simultaneously control capillarity, wettability, interfacial tension, mobility, transport, and reservoir heterogeneity.

Within this context, the concept of *closed-loop EOR* is particularly relevant. In such systems, sensors and monitoring technologies continuously provide data, physical and computational models assimilate this information, and algorithms dynamically adjust injection conditions. Physics therefore extends beyond the interpretation of underlying phenomena to become an integral component of decision-making and operational optimization.

Another fundamental perspective is the development of models capable of explicitly representing uncertainty. Rather than providing only point predictions of recovery, probabilistic and physics-informed models may estimate uncertainty intervals associated with properties such as permeability, saturation, mobility, and sweep efficiency. This capability is





particularly important in heterogeneous reservoirs, where relatively small uncertainties in pore structure can produce substantial differences in flow behavior.

The post-2026 research agenda therefore points toward increasingly adaptive, multiscale, and physics-guided EOR, in which experimentation, sensing, simulation, artificial intelligence, and digital rock characterization operate within an integrated framework. The objective shifts from simply increasing recovery to controlling, in real time and with explicit uncertainty quantification, the physical mechanisms that determine where, when, and how much oil can be mobilized.

Fundamentally, the consolidation of this new era of intelligent and multiscale EOR extends its technical role beyond reservoir engineering, establishing a strategic connection with the United Nations (UN) Sustainable Development Goals (SDGs) in the context of the global energy transition:

SDG 12 – Responsible Consumption and Production: The application of advanced EOR to mature reservoirs prioritizes resource efficiency and the revitalization of existing assets. By increasing the recovery factor of fields that have already been drilled and equipped with production infrastructure, the pressure to develop new exploration frontiers in socio-environmentally sensitive areas may be reduced. In addition, the development of smart water formulations and biodegradable environmentally friendly surfactants can reduce the chemical footprint and generation of hazardous industrial waste associated with field operations.

SDG 9 – Industry, Innovation and Infrastructure: The convergence of Digital Rock Physics (DRP), microfluidics, high-resolution tomography, and physics-informed artificial intelligence (PIML and PINNs) represents an important pathway toward the digitalization and modernization of energy-industry infrastructure. This digital transformation strengthens analytical and technological capabilities while promoting innovative, efficient, and scientifically grounded industrial processes.

SDG 13 – Climate Action: The integration of CO₂-EOR and CO₂-foam technologies with the broader Carbon Capture, Utilization and Storage (CCUS) framework provides opportunities to couple oil recovery with geological CO₂ storage. In these processes, CO₂





captured from industrial sources can be injected into reservoirs to mobilize residual oil, while a fraction of the injected CO₂ may remain stored in the subsurface through structural, residual/capillary, dissolution, and, over longer timescales, mineral trapping mechanisms.

SDG 7 – Affordable and Clean Energy: During the transition toward renewable energy systems, continued hydrocarbon demand increases the importance of improving the efficiency and reducing the environmental intensity of remaining fossil-fuel production. Adaptive, closed-loop EOR can contribute to optimizing injection and production strategies, potentially reducing the energy intensity per barrel of oil produced while supporting energy security and supply stability during the transition.

SDG 6 – Clean Water and Sanitation: The transition from conventional water injection toward Smart Water and Low-Salinity Waterflooding strategies may improve water management in field operations by reducing freshwater requirements and encouraging the treatment and reuse of produced and formation waters.

13. CONCLUSIONS

The critical analysis of the literature published between 2000 and 2026 demonstrates that the evolution of EOR has fundamentally involved a shift from approaches based on optimizing isolated properties toward an integrated and multiscale understanding of recovery mechanisms. Mobility, capillarity, wettability, interfacial tension, miscibility, rheology, and transport are increasingly understood as strongly coupled phenomena whose relative contributions depend on the specific characteristics of the rock–fluid system and operating conditions. More than the emergence of new technologies, this period has been characterized by a deeper understanding of the physical principles governing fluid displacement in porous media and residual oil recovery.

Within this framework, technologies such as smart water, polymers, surfactants, CO₂, foams, and nanoparticles should not be evaluated solely on the basis of recovery gains observed under controlled conditions, but also according to their ability to preserve their





mechanisms of action during transport through porous media and during scale-up from the pore to the core and reservoir scales. The incorporation of microfluidics, micro-CT, and digital rock physics has substantially enhanced the ability to observe, quantify, and validate these mechanisms, while physics-informed artificial intelligence methods provide new opportunities for prediction, optimization, and integration of multiscale data.

The main frontier of contemporary EOR therefore lies not in the development of a universal method, but in the integrated engineering of physical recovery mechanisms, combining experimentation, modeling, digital characterization, and computational intelligence according to the specific characteristics of each reservoir. Future advances will depend on the ability to establish quantitative and physically consistent links between microscopic phenomena and macroscopic performance while incorporating heterogeneity, uncertainty, and multiple spatial scales into decision-making.

Physics thus emerges as the central element driving the evolution of EOR, serving not only as an interpretative framework but also as the foundation connecting experimental observations, porous-medium properties, transport mechanisms, computational models, and artificial intelligence algorithms. This transition underpins the concept of Multiscale Intelligent EOR, in which the objective is not merely to increase oil recovery, but to understand, represent, and control the physical phenomena that determine when, where, and how much oil can be effectively mobilized and produced, while aligning scientific and technical rigor with global commitments to innovation, energy efficiency, sustainable resource use, and climate-change mitigation embodied in the UN 2030 Agenda for Sustainable Development.

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Recebido em: 21/09/2026

Aprovado em: 02/10/2026

Publicado em: 14/10/2026

