Review Paper

International Journal of Research and Review
[Indexed, Peer-Reviewed Journal]
Volume 12; Issue: 12; December 2025
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Philosophy Ontology and Epistemology of Enhanced Oil Recovery in the Era of Data - Driven and Sustainable Reservoir Management

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DOI: https://doi.org/10.52403/ijrr.20251274

ABSTRACT

Enhanced oil recovery (EOR) has evolved from a collection of empirical techniques into a multi-scale knowledge system that links molecular design, pore-scale physics, reservoir-scale flow, and global deployment strategies. This article offers a philosophical, ontological, and epistemological reading of contemporary EOR research by integrating earlier reviews with 2020–2025 literature on chemical, thermal, gas-based, and data-driven methods. Ontologically, EOR is understood as an assemblage of entities and processes—polymers, surfactants, biopolymers, nanoparticles, foams, emulsions, supercritical CO_2, steam, catalysts, rock textures, fractures, and digital representations—mapped to their operative scales and mechanisms. Epistemologically, EOR knowledge is produced and validated through corefloods, microfluidics, spectroscopy, numerical simulation, machine-learning workflows, risk-assessment frameworks, and global data syntheses for EOR and CO_2 storage.
Chemical EOR is revisited through high-salinity-resistant polymers, amphiphilic and bio-based polymers, "green" surfactants, emulsions, and polymer–nanoparticle hybrids. Thermal and catalytic methods for heavy oil focus on aquathermolysis, in-situ combustion catalysts, hybrid downhole heaters, and additive-enhanced steam. Gas-based EOR is analyzed in the context of CO_2 mobility control, foam stabilization, smart water, carbonated nanofluids, and integrated value assessment of CCUS. The article concludes with a research agenda for ontology-driven digital twins and epistemically robust decision-making that integrates oil recovery, uncertainty, and decarbonization.

Keywords: Enhanced oil recovery; EOR ontology; EOR epistemology; CO_2 EOR and CCUS; chemical and thermal EOR; data-driven reservoir engineering; sustainable oil recovery

INTRODUCTION

Enhanced oil recovery (EOR) remains central to reconciling energy security with climate and sustainability constraints. Classical taxonomies distinguish chemical, thermal, gas-based and miscible methods, yet contemporary work increasingly blurs these categories through hybrid fluids, catalytic processes, and tight coupling to CO_2 storage, risk management and artificial intelligence. Recent literature illustrates this evolution—from global assessments of CO_2-EOR and self-organizing-map analyses of field performance (Ayumu & Babadagli, 2025; Niedermaier Custodio & Carneiro, 2024) to reviews of oilfield chemicals in the context of net-zero transitions (Bigdeli & Delshad, 2024) and advanced risk-assessment frameworks (Zhang et al., 2025). Building on earlier reviews of chemical and thermal EOR, this article extends the discussion in two ways. First, we introduce an explicit ontology of EOR that catalogues the entities, scales, and interactions underpinning modern methods, from molecular additives and interfacial structures to reservoir architectures and global deployment portfolios. Second, we develop an epistemology of EOR that examines how experimental, numerical, and data-driven evidence is generated, validated and synthesized, and how this shapes decision-making under uncertainty. Using a curated set of 2020–2025 studies across polymers, surfactants, foams, CO_2 mobility control, aquathermolysis, in-situ combustion catalysts, and AI-enabled workflows, we articulate a future vision of EOR as a philosophically grounded, data-centric, and sustainability-aligneddiscipline.

Philosophical and ontological foundations of EOR

Modern EOR research implicitly assumes a rich ontology: a catalogue of "what exists" in the EOR universe and how these entities interact across scales. At the molecular level, recent studies focus on polymers (e.g. HPAM, amphiphilic polymers, polysaccharide derivatives), surfactants (including natural and bio-derived systems), nanoparticles, and organometallic catalysts (Badiri et al., 2022; de Araujo et al., 2024; Tajik et al., 2023). At the mesoscopic level, the relevant entities become micelles, emulsions, foams, viscoelastic gels, and Pickering interfaces (Narukulla & Sharma, 2024; Wang et al., 2021; Alyousef et al., 2021, 2020; Almaskeen et al., 2021). At the pore and core scales, the ontology extends to wettability states, pore-network topologies, and dynamic phase configurations explored through corefloods, spontaneous imbibition and high-pressure visualization (Tripathi et al., 2023; Wang et al., 2020; Burrows et al., 2020). At the reservoir scale, EOR entities include facies, fracture networks, layered heterogeneity and conformance-control volumes, as well as operational variables such as injection strategies and well patterns (Oguntola & Lorentzen, 2022; Fu et al., 2024; Neves-Junior et al., 2023). Finally, at the portfolio and global scales, new ontological categories emerge: "project types", "screening classes", "CO_2-EOR clusters", and "technology archetypes" identified through self-organizing maps, unsupervised clustering and machine-learning workflows (Ayumu & Babadagli, 2025; Niedermaier Custodio & Carneiro, 2024; Motahhari et al., 2021; Purbey et al., 2022; Romel-Antonio et al., 2020). These layers are usually handled implicitly in engineering workflows. Making them explicit provides a scaffold for integrating heterogeneous evidence and for designing ontology-aware digital twins that can reason consistently across experiments, simulations and field data.

LITERATURE REVIEW

Philosophical commitments in contemporary EOR

Philosophically, current EOR practice embodies several key commitments. First, it remains strongly reductionist, assuming that changes in molecular structure or ionic composition can be systematically upscaled to pore-scale displacement and reservoir performance. This is evident in work that tunes polymer architecture and charge density to achieve desired rheology and sweep efficiency in high-salinity formations (Gussenov et al., 2024; de Araujo et al., 2024; Wang et al., 2022) or that optimizes surfactant mixtures and salinity for interfacial tension (IFT) reduction and wettability alteration (Xu et al., 2023; Khan et al., 2021; Kalam et al.,2021).

Second, EOR research is deeply instrumentalist, valuing models and experiments primarily for their predictive and economic utility rather than as literal descriptions of subsurface reality. Ensemble-based optimization and robust value quantification explicitly frame models as decision tools under uncertainty, not as exact replicas of reservoirs (Oguntola & Lorentzen, 2022). Likewise, data-mining and machine-learning studies for EOR screening and appraisal treat large databases as statistical objects to be interrogated for patterns, even when underlying physics is only partially represented (Ayumu & Babadagli, 2025; Motahhari et al., 2021; Purbey et al., 2022).

Third, recent literature embeds sustainability and decarbonization as normative constraints, asserting that "good" EOR is that which increases recovery while reducing greenhouse-gas intensity and enabling CO_2 storage or the use of renewable-derived chemicals (Bigdeli & Delshad, 2024; Lee & Babadagli, 2021; Jiang et al., 2023; Ulfah et al., 2024; Tajik et al., 2023). This philosophical stance reshapes research priorities, privileging low-carbon steam alternatives, bio-based surfactants and CO_2-linked value chains over purely volumetric gains.

MATERIALS & METHODS

Epistemology of EOR: how knowledge is produced and validated

Laboratory studies remain the primary epistemic engine of EOR research. Recent work expands classical corefloods and phase-behavior measurements with designed sequences of static and dynamic tests that couple reactivity, rheology, and flow. High-salinity polymer flooding studies combine rheometry, salinity scans and corefloods to map the parameter space of hydrolyzed polyacrylamide (HPAM) in harsh conditions, revealing trade-offs between injectivity, elasticity and adsorption (Gussenov et al., 2024; Wang et al., 2022; Rodriguez, 2021). Surfactant and natural-surfactant research use IFT measurements, contact angles, and dynamic aging to demonstrate wettability alteration and adsorption mechanisms (Hama et al., 2023; Atta et al., 2021; Kalam et al., 2021; Khan et al., 2021). For CO_2 foams and complex fluids, visualization in unconsolidated media, sand-mobilization tests, and foam stability measurements under varying salinity and pressure provide pore-scale evidence of lamella thinning, grain motion and mobility control (Singh & Sharma, 2023; Alyousef et al., 2020; Alyousef et al., 2021; Almaskeen et al., 2021; Alyousef et al., 2021). Thermal EOR epistemology increasingly relies on chemical and spectroscopic characterization of oil upgrading pathways during aquathermolysis and catalytic steam processes. FTIR and ^{1}H-NMR analyses quantify compositional shifts and functional-group evolution, linking them to viscosity reduction in Colombian heavy oils (León et al., 2024; Núñez-Méndez et al., 2021; Salas-Chia et al., 2025, 2023, 2023; León et al., 2022). These experiments generate mechanistic narratives (e.g., cleavage of resins and asphaltenes, hydrogen donation from solvents or biomass-derived catalysts) that support process design for in-situ upgrading (Pratama & Babadagli, 2022; Tajik et al., 2023; Farhadian et al., 2021).

Numerical simulation, optimization, and uncertainty

Reservoir simulation has long been a cornerstone of EOR epistemology, but recent studies emphasize uncertainty-aware and value-oriented approaches. Numerical work on polymer nanohybrids explores parameter sensitivities in heterogeneous layered reservoirs, highlighting how nanoparticle-polymer synergy influences sweep efficiency and breakthrough profiles under different heterogeneity patterns (Badiri et al., 2022). Robust value quantification of EOR methods uses ensemble-based optimization and risk-weighted objective functions to prioritize projects that remain attractive across geological and economic uncertainties (Oguntola & Lorentzen, 2022). In heavy-oil settings, simulations of hybrid steam, downhole heating and steam-with-additives schemes incorporate chemical reactions, heat transfer and relative permeability changes to reproduce lab and pilot results (Romel-Antonio et al., 2020; Pratama & Babadagli, 2022; Du et al., 2023). Tight-reservoir simulations integrate spontaneous imbibition mechanisms at high pressure and the complex transport of polymer or CO_2-thickened fluids to explain production from ultra-low-permeability rocks (Wang et al., 2020; Fu et al., 2024; Fu et al., 2021). These models are not simply descriptive: they serve as epistemic filters, selecting among competing conceptual models and quantifying which parameter combinations are consistent with observed data. By embedding stochastic representations of geology and operational uncertainty, they shift EOR epistemology from deterministic prediction to probabilistic, decision-focused assessment.

Data mining, machine learning, and global syntheses

The emergence of large EOR databases has enabled a new epistemic style: data-centric synthesis. Field-scale CO_2-EOR and sequestration performance has been assessed using data-mining and machine-learning models that correlate reservoir and operational descriptors with recovery and storage metrics, revealing non-intuitive dependencies and clustering fields into performance archetypes (Ayumu & Babadagli, 2025). Self-organizing maps have been applied to global EOR datasets to identify patterns in technology deployment and to delineate regions where specific methods are under- or over-represented relative to geological potential (Niedermaier Custodio & Carneiro, 2024). More generally, comprehensive reviews of ML-assisted reservoir engineering catalogue supervised and unsupervised algorithms used for property prediction, screening, and optimization (Purbey et al., 2022). Unsupervised workflows integrate Shannon entropy and reference-ideal methods to cluster potential pilot areas and reduce appraisal risk in low-permeability developments (Motahhari et al., 2021). At the field-strategy level, data-driven assessments of EOR options for Brazilian pre-salt reservoirs combine geological characterization, fluid properties, and operational constraints to propose tailored strategies and to highlight knowledge gaps in surfactant and gas-injection design (Neves-Junior et al., 2023). In unconventional resources, literature reviews synthesize evidence on CO_2, natural gas, and water-based injection schemes and their complex interactions with hydraulic fractures and rock fabrics (Burrows et al., 2020; Fu et al., 2021). Collectively, these studies reposition EOR epistemology around pattern recognition and probabilistic inference, complementing physics-based models rather than replacing them.

Risk, value and decision-oriented epistemology

EOR decision-making increasingly rests on formalized notions of risk and value, moving beyond simple incremental-recovery metrics. Zhang et al. (2025) review risk-assessment methods for oil and gas development, including event-tree, Bayesian, fuzzy and ML-based frameworks, and highlight their relevance for EOR projects with complex uncertainties in reservoir response, chemical performance and CO_2 storage integrity. Robust value quantification methods explicitly fold in price volatility, capex/opex uncertainty and policy incentives, aiming to maximize risk-adjusted net present value rather than deterministic profit (Oguntola & Lorentzen, 2022). In CO_2-linked schemes, sorption-based direct air capture coupled with utilization pathways provides a broader system perspective, where EOR is one of several outlets for captured CO_2 (Jiang et al., 2023). Assessments of greenhouse-gas intensity for heavy-oil projects consider life-cycle emissions and the mitigating impact of advanced recovery processes and fuel-switching options (Lee & Babadagli, 2021). This shift toward risk- and value-oriented epistemology suggests that "knowing" in EOR is no longer limited to predicting recovery factors; it also includes understanding how projects perform across economic, environmental and policy scenarios, and how robust they remain in the face of deep uncertainty.

RESULT

Chemical EOR: polymers, surfactants, emulsions and hybrids

Polymer flooding remains a cornerstone of chemical EOR, particularly for medium and heavy oils. Recent work has focused on extending polymer applicability to harsh environments and tight formations. High-salinity and high-temperature conditions challenge classical HPAM formulations due to hydrolysis, precipitation and loss of viscosity; experimental and modelling studies demonstrate that tailored copolymers and salinity-optimized formulations can maintain mobility control while limiting adsorption (Gussenov et al., 2024; Wang et al., 2022; Almaskeen et al., 2021). Polymer nanohybrids, where nanoparticles are physically or chemically associated with polymer chains, offer improved thermal stability, shear resistance and possibly lower adsorption. Numerical investigations in heterogeneous layered reservoirs indicate that nanohybrids can delay water breakthrough and enhance sweep in thief zones, but that benefits depend on nanoparticle concentration and layering contrast (Badiri et al., 2022). Amphiphilic polymers designed to interact favorably with oil–water interfaces have been tested in heavy-oil cores, demonstrating combined viscosity reduction, IFT lowering and wettability alteration (Wang et al., 2022). For tight reservoirs, polymer-assisted and CO_2-thickened injections are being evaluated as alternatives to simple gas flooding. Polymer-viscosity-enhanced $scCO_2$ formulations show improved injectivity and sweep in low-permeability sandstone, with experimental studies quantifying the trade-off between thickener concentration, phase behavior and adsorption (Fu et al., 2024). These developments suggest an ontological expansion of "polymer EOR" from simple viscosity modifiers to multifunctional, stimuli-responsive agents.

Surfactants, natural surfactants and ASP systems

Surfactants remain central to chemical EOR by lowering IFT, altering wettability and stabilizing emulsions or foams. Recent reviews provide comprehensive syntheses of natural surfactants and their application potential, emphasizing saponins, biosurfactants, lignin derivatives, and plant-based systems (Hama et al., 2023; Atta et al., 2021). These reviews highlight advantages such as lower toxicity and biodegradability but also address challenges in large-scale production, stability and cost. Experimental work on sulfosuccinate and extended sulfated surfactants for Malaysian limestone crude demonstrates the importance of salinity, alkali addition, and crude composition on phase behavior and ASP performance (Khan et al., 2021). Other studies investigate surfactant retention mechanisms—electrostatic interaction, hydrophobic adsorption, and mineral dissolution—and review measurement methods ranging from static adsorption tests to dynamic corefloods (Kalam et al., 2021). The development of cationic and mixed surfactant systems further refines control over IFT and wettability. Xu et al. (2023) show that cationic surface-active agents and their mixtures significantly modify water–crude IFT and contact angles, enabling design of formulations tuned to specific rock–fluid systems. In carbonated polymeric nanofluids, surfactants and polymers are combined with dissolved CO_2 to generate complex fluids that mobilize oil via simultaneous IFT reduction, mobility control, and gas exsolution (Chaturvedi & Sharma, 2020; Chaturvedi et al., 2021). These developments enrich the ontology of surfactants from simple IFT-reducing agents to multi-functional components that participate in emulsification, foam stabilization, mineral dissolution, and CO_2 utilization.

Emulsions, foams and complex fluids

Emulsions and foams act as mesoscopic agents that mediate mobility control, sweep improvement and conformance. A recent review of emulsions for EOR summarizes formulations, stability mechanisms and applications in heavy-oil and fractured reservoirs, stressing the role of surfactants, nanoparticles and crude-derived asphaltenes in stabilizing water-in-oil or oil-in-water structures (Narukulla & Sharma, 2024). For heavy oils, Pickering emulsions activated in situ by nanoparticles have been proposed as cost-effective means of generating flowable dispersions and improving mobility (Wang et al., 2021, 2020, 2021). Foam-based EOR has advanced in several directions. Studies on tailored water chemistry demonstrate that specific ion combinations significantly enhance foam stability and mobility control, both in pure foam systems and in foam-gel formulations for conformance control (Alyousef et al., 2020; Alyousef et al., 2021; Almaskeen et al., 2021). Amphoteric foaming agents show promising rheology and adsorption characteristics for CO_2 mobility control under reservoir conditions, bridging chemical EOR and CCUS (Alyousef et al., 2021; Massarweh & Abushaikha, 2022). The behavior of foams in unconsolidated sands introduces additional ontological entities—mobile grains and evolving pore structures. Singh and Sharma (2023) demonstrate that sand mobilization can destabilize or restructure CO_2 foams, altering rheology and transport. These results emphasize that foam stability cannot be understood solely in terms of lamella physics; it must include grain mechanics and geomechanical coupling.

Heavy-oil rheology and compositional change under chemical EOR

Beyond displacement, chemical EOR can transform the oil itself. Studies of heavy-oil rheology under EOR conditions show that chemical and thermal treatments alter asphaltene aggregation, resin content, and colloidal structure, with strong implications for flow behavior and production facilities (Strelets & Ilyin, 2021; Lee & Babadagli, 2021). Catalytic aquathermolysis and steam-with-additives schemes have been extensively investigated in Colombian crudes, using spectroscopy and viscosity measurements to correlate changes in functional groups with mobility improvements (León et al., 2024; Núñez-Méndez et al., 2021; Salas-Chia et al., 2025, 2023, 2023; León et al., 2022; Romel-Antonio et al., 2020). Such work underscores an ontological shift: EOR no longer treats crude oil as a fixed property but as a reactive and engineerable material whose composition and flow behavior can be redesigned in situ.

Table 1. Ontological categories of EOR entities across scales

Domain / scale	Representative entities / processes	Primary roles in EOR	Typical methods / fluids	Key knowledge sources / tools	Ref.
Molecular / chemical	Polymers, surfactants, biopolymers, nanoparticles, catalysts	Viscosity control, IFT reduction, reactivity	Polymer flooding, ASP, nanofluids, catalytic additives	Rheology, IFT, spectroscopy, quantum / MD modelling	Gussenov et al., 2024; de Araujo et al., 2024; Tajik et al., 2023; Hama et al., 2023
Mesoscopic	Emulsions, foams, gels, Pickering interfaces	Mobility and conformance control	Foam EOR, emulsion flooding, foam-gels	Microscopy, sand-pack tests, dynamic foam analysis	Narukulla & Sharma, 2024; Alyousef et al., 2020, 2021; Singh & Sharma, 2023; Wang et al., 2021
Pore / core	Wettability states, pore	Local displacement	Corefloods, imbibition, smart	Core analysis, micro-CT,	Tripathi et al., 2023; Chaturvedi

	networks, capillary structures	efficiency	water, carbonated nanofluids	contact angles	& Sharma, 2020; Wang et al., 2020
Reservoir	Facies, fractures, layered heterogeneity, conformance patterns	Sweep efficiency, breakthrough control	Polymer and surfactant floods, steam and hot water injection	Numerical simulation, history matching	Badiri et al., 2022; Oguntola & Lorentzen, 2022; Neves-Junior et al., 2023; Du et al., 2023
Portfolio / global	Project archetypes, screening classes, CO_2-EOR clusters	Technology selection, policy assessment	Multi-field EOR and CCUS portfolios	Data mining, SOMs, ML screening, techno-economic models	Ayumu & Babadagli, 2025; Niedermaier Custodio & Carneiro, 2024; Purbey et al., 2022; Romel-Antonio et al., 2020

Thermal, catalytic and hybrid methods for heavy oils

Thermal EOR remains indispensable for viscous and extra-heavy oils. A comprehensive evaluation of downhole heating and hybrid cyclic steam methods synthesizes laboratory, pilot and field data, highlighting design parameters such as steam quality, soak time and solvent or chemical additives (Romel-Antonio et al., 2020). Reviews of steam injection mechanics with chemical additives describe how surfactants, nanoparticles and hydrogen-donor agents can enhance heat transfer, reduce interfacial tension and promote in-situ upgrading (Pratama & Babadagli, 2022; Lee & Babadagli, 2021). Aquathermolysis has emerged as a central mechanism for heavy-oil upgrading under steam. Laboratory studies show that reservoir rock mineralogy strongly influences reaction pathways and product distribution, emphasizing the need for rock-specific kinetic models (Salas-Chia et al., 2023). Systematic experiments on operational parameters—temperature, steam quality, catalyst concentration—demonstrate their impact on viscosity reduction and SARA composition of Colombian heavy crudes (Salas-Chia et al., 2023; Núñez-Méndez et al., 2021; León et al., 2024). Catalytic aquathermolysis extends this concept by adding oil-soluble catalysts, often derived from biomass or organometallic precursors. Sunflower-oil-derived high-activity catalysts exemplify a sustainable route to oil-soluble systems that promote cracking and hydrogen transfer during in-situ combustion and steam processes (Tajik et al., 2023; Farhadian et al., 2021). These innovations illustrate a philosophical move toward chemically engineered subsurface reactors rather than passive heating.

Hot-water injection and alternatives to steam

Steam processes are energy-intensive and carbon-intensive; their decarbonization is therefore a key sustainability goal. Hot-water injection with chemical additives has been proposed as a lower-carbon alternative, offering favorable energy balances under certain conditions. Du et al. (2023) present static and dynamic experiments showing that hot water with tailored chemicals can achieve comparable mobilization of heavy crude to steam, depending on rock properties and additive formulation. More broadly, reviews of heavy-oil recovery mechanics with additives highlight strategies such as surfactant-assisted hot water, solvent-co-injection and hybrid electrical heating, aiming to reduce steam-oil ratios and greenhouse-gas intensity (Pratama & Babadagli, 2022; Lee & Babadagli, 2021). These approaches re-cast thermal EOR as a multi-objective optimization problem over recovery, energy use and emissions rather than a singlemetric maximization exercise. Catalytic upgrading and rheological transformation spectroscopic studies of heavy-oil samples subjected to catalytic steam and aquathermolysis treatments reveal deep transformations in oil composition. ^{1}H-NMR and FTIR analyses document decreases in aromatic and resin fractions, changes in heteroatom content, and shifts toward lighter, more paraffinic structures, all of which correlate with viscosity reduction (León et al., 2024; Núñez-Méndez et al., 2021; León et al., 2022; Salas-Chia et al., 2025). Ligand-structure studies of biobased oil-soluble catalysts show that catalytic kinetics and product distribution are highly sensitive to ligand architecture, underlining the importance of rational catalyst design (Farhadian et al., 2021; Tajik et al., 2023). Rheological measurements before and after thermal-chemical treatments indicate transitions from yield-stress fluids to shear-thinning or nearly Newtonian behavior (Strelets & Ilyin, 2021; Lee & Babadagli, 2021). This body of work supports an ontology in which "oil" is no longer a static substance but a tunable material whose properties can be sculpted in situ through carefully designed thermal and catalytic environments.

Table 2. Recent advances in heavy-oil thermal and catalytic EOR

Method / concept	**Key mechanism(s)**	**Reservoir / crude type**	**Main findings**	**Sustainability / decarbonization aspect**	**Ref.**
Hybrid cyclic steam & downhole heating	Convective heating, limited in-situ upgrading	Extra-heavy oils, field-scale	Improved recovery vs. conventional cyclic steam	Potential to reduce steam-oil ratio via hybrid designs	Romel-Antonio et al., 2020
Steam with chemical additives	Aquathermolysis, IFT reduction, wettability change	Heavy oils (lab to pilot)	Additives enhance mobility and reduce SOR	Enables lower steam requirements and tailored chemistry	Pratama & Babadagli, 2022; Lee & Babadagli, 2021
Catalytic aquathermolysis	In-situ catalytic cracking and hydrogen transfer	Colombian heavy crude	Strong viscosity reduction, compositional shifts	Potential to shorten steam exposure and save energy	Núñez-Méndez et al., 2021; León et al., 2024; Salas-Chia et al., 2025
Biobased oil-soluble catalysts	Renewable organometallic catalysts	Heavy oils, in-situ combustion	High catalytic activity with renewable feedstock	Aligns heavy-oil upgrading with biomass valorization	Tajik et al., 2023; Farhadian et al., 2021
Hot-water injection with chemicals	Reduced-temperature thermal EOR	Heavy oils (lab)	Comparable mobilization to steam in some cases	Lower energy use and potential CO_2 intensity reduction	Du et al., 2023

Gas-based and CO_2-linked EOR in a CCUS framework

CO_2 EOR sits at the intersection of hydrocarbon recovery and carbon management. Classical miscible and immiscible schemes aim to swell oil, reduce viscosity and alter phase behavior; contemporary work focuses on mobility control and storage integrity. Reviews of CO_2 mobility control summarize thickening strategies (polymers, surfactants, nanoparticles), foam-based mobility control, and chemical additives that modify relative permeability (Massarweh & Abushaikha, 2022). Polymeric CO_2 thickeners are an active research area. Fu et al. (2024) demonstrate that acetate-type polymers dissolved in $scCO_2$ increase viscosity and improve sweep in tight sandstone, but that performance is sensitive to polymer molecular weight and concentration. Amphoteric foaming agents designed for CO_2 EOR show favorable rheology and low adsorption, enabling stable foams under high salinity and temperature (Alyousef et al., 2021). Evaluations of foam-gels in challenging carbonates indicate that combining polymer gels and foams can significantly improve conformance (Almaskeen et al., 2021). Smart-water formulations that promote CO_2 dissolution and wettability alteration in heterogeneous sandstone further broaden the toolbox, integrating ionic-composition design with gas utilization (Chaturvedi & Sharma, 2022). Carbonated polymeric nanofluids represent another hybrid concept, co-injecting nanofluids and dissolved CO_2 to exploit concurrent mechanisms (Chaturvedi & Sharma, 2020; Chaturvedi et al., 2021).

Data-driven CO_2-EOR and global deployment patterns

Field-scale data-mining approaches have been used to correlate geological and operational characteristics with CO_2-EOR performance metrics and storage efficiency. Ayumu and Babadagli (2025) apply supervised and unsupervised algorithms to global field datasets, identifying key predictors of incremental recovery and CO_2 retention, and clustering fields into performance classes. New screening models incorporate parameter interdependencies, improving on classical single-parameter charts by capturing complex correlations among pressure, miscibility conditions, heterogeneity and operational history (Rosiani et al., 2022). At the global scale, self-organizing maps applied to EOR data reveal clusters of under-utilized opportunities and highlight mismatches between technology deployment and geological suitability across regions (Niedermaier Custodio & Carneiro, 2024). Complementary literature reviews synthesize evidence on CO_2, natural gas and water-based fluids in unconventional reservoirs, providing a broad map of processes and knowledge gaps (Burrows et al., 2020; Fu et al., 2021). These studies transform CO_2-EOR into a data-mapped landscape where ontological categories such as “project type” and “field class” are learned empirically rather than prescribed a priori.

CO_2 EOR, CCUS and low-carbon value chains

The integration of CO_2 EOR with carbon capture, utilization and storage (CCUS) requires system-level perspectives. Sorption-based direct air capture coupled with utilization pathways—of which EOR is one example—illustrates how capture technologies, utilization options, and storage capacities interact in techno-economic and environmental assessments (Jiang et al., 2023). Reviews of oilfield chemicals in the context of net-zero transitions argue that chemical EOR must be evaluated alongside other subsurface uses of CO_2 and hydrogen, including storage, geothermal and underground hydrogen storage (Bigdeli & Delshad, 2024). Heavy-oil recovery techniques are increasingly assessed for greenhouse-gas intensity, with new-generation methods (e.g. solvent-assisted, hybrid thermal-chemical) positioned as pathways to reduce emissions while maintaining production (Lee & Babadagli, 2021). These perspectives emphasize a philosophy of integration, where EOR is not an isolated process but part of broader low-carbon value chains.

Table 3. Gas-based and CO_2-linked EOR: epistemic and design highlights

Focus area	Main mechanism / concept	Epistemic contribution	Design implications	Ref.
CO_2 mobility control review	Thickeners, foams, surfactants, nanoparticles	Synthesizes mechanisms and experimental trends	Guides selection of mobility-control strategies	Massarweh & Abushaikha, 2022
Polymeric CO_2	$scCO_2$ viscosity	Lab evidence for	Enables combined	Fu et al., 2024

thickeners	enhancement	tight-reservoir application	EOR and storage in tight rocks	
Amphoteric foaming agents / foam-gels	CO_2 foam stability and conformance	Quantifies rheology, adsorption, stability	Supports design for harsh carbonate reservoirs	Alyousef et al., 2021; Almaskeen et al., 2021
Data-mining of CO_2-EOR fields	Global performance archetypes	Identifies key predictors and field clusters	Informs screening and benchmarking of new projects	Ayumu & Babadagli, 2025; Rosiani et al., 2022
SOM-based global EOR mapping	Unsupervised pattern discovery	Reveals under-utilized opportunities	Guides regional technology targeting	Niedermaier Custodio & Carneiro, 2024
CO_2 / gas EOR in unconventionals	Multiple injection fluids	Consolidates evidence across plays	Highlights uncertainties and research gaps	Burrows et al., 2020; Fu et al., 2021

Sustainability, circularity and bio-based EOR

Bio-based materials are gaining prominence as EOR agents, motivated by environmental performance and circular-economy considerations. Literature on chitosan—a biopolymer derived from shrimp shells—assesses its rheological properties, salt tolerance and potential as a viscosifier or mobility-control agent in EOR (Ulfah et al., 2024). These studies also exemplify regional perspectives, linking Indonesia's declining oil production with the availability of local biomass resources and waste streams. Natural surfactant reviews emphasize plant- and microbe-derived systems that offer lower toxicity and higher biodegradability than conventional petrochemical surfactants (Hama et al., 2023; Atta et al., 2021). However, they raise epistemic questions about scaling laboratory observations to field conditions, given the variability of natural feedstocks and the complexity of subsurface environments. Biobased catalysts derived from edible oils (e.g. sunflower oil) further extend the bio-economy into thermal EOR, demonstrating that renewable feedstocks can underpin highly active oil-soluble catalysts for in-situ combustion and aquathermolysis (Tajik et al., 2023). Together, these developments re-orient EOR ontology toward renewable-derived agents and foreground the need for life-cycle and sustainability assessments integrated into EOR design.

Environmental interactions and material integrity

Sustainability in EOR also depends on understanding interactions among injected fluids, reservoir rocks and wellbore materials. Studies of mineralization on low-carbon steel in synthetic hydraulic fracture fluids evaluate how brine composition, dissolved gases and flow conditions affect corrosion and scale formation (Mackey et al., 2021). Such work informs the design of completion fluids and CO_2-bearing injections where long-term material integrity is critical. In carbonate and sandstone systems, wettability alteration via smart water, surfactants and natural surfactants must be evaluated for potential negative impacts such as excessive mineral dissolution or fines migration (Tripathi et al., 2023; Hama et al., 2023; Kalam et al., 2021). Reviews of surfactant retention mechanisms highlight how mineralogy, salinity and temperature control losses and thus influence both economic and environmental performance (Kalam et al., 2021). These studies embody a systems epistemology in which EOR is viewed as a coupled chemical–geomechanical–materials problem, with environmental performance emerging from interactions across these domains.

Regional and project-level syntheses

Regional reviews of chemical EOR projects provide a bridge between lab-scale innovation and field deployment. Rodriguez (2021) summarizes chemical EOR in

Venezuela across light to extra-heavy oils, documenting project histories, fluid systems, and performance, and thereby offering an empirical basis for future designs. Similarly, assessments of EOR strategies for Brazilian pre-salt reservoirs integrate local geology, fluid properties and infrastructure constraints to propose tailored combinations of chemical and gas-based methods (Neves-Junior et al., 2023). Reviews of EOR in unconventional reservoirs and of ML-assisted reservoir engineering expand this regional perspective by mapping where particular technologies and workflows have been tested and with what outcomes (Burrows et al., 2020; Purbey et al., 2022; Fu et al., 2021). Such syntheses are essential for constructing an ontology of "what works where and why" and for preventing redundant or poorly informed field trials.

Table 4. Data-driven, AI and risk-oriented frameworks in EOR

Framework type	Primary tool / method	EOR application	Epistemic role	Ref.
ML-assisted reservoir engineering	Supervised and unsupervised ML, data mining	Property prediction, screening, optimization	Organizes large datasets, reveals hidden patterns	Purbey et al., 2022
Unsupervised pilot-area selection	Clustering with Shannon entropy and reference-ideal metrics	Pilot appraisal in low-permeability fields	Reduces appraisal risk, identifies representative areas	Motahhari et al., 2021
Data-mining of CO_2-EOR fields	Regression, clustering, feature importance	CO_2-EOR and storage performance analysis	Quantifies controls on recovery and storage	Ayumu & Babadagli, 2025
SOM-based global EOR mapping	Self-organizing maps	Global EOR technology patterns	Discovers regional clusters and gaps	Niedermaier Custodio & Carneiro, 2024
Robust value quantification	Ensemble-based optimization, risk metrics	Economic evaluation of EOR options	Embeds uncertainty into value assessment	Oguntola & Lorentzen, 2022
Risk-assessment synthesis	Event-tree, Bayesian, fuzzy, ML methods	Oil and gas project risk, including EOR	Structures decision-relevant risk knowledge	Zhang et al., 2025

DISCUSSION

Cross-cutting knowledge systems and future epistemologies

Recent work explicitly frames oilfield chemicals within the broader transition to sustainable energy systems and net-zero emissions, highlighting the convergence of chemical design and AI (Bigdeli & Delshad, 2024). This includes using data-driven models to predict chemical performance, optimize formulations and identify promising combinations for specific reservoirs. ML-assisted design could accelerate discovery of robust surfactant blends, polymer architectures and catalytic systems, especially when coupled with high-throughput experimentation and multi-objective optimization. However, this convergence raises epistemological questions: How should models trained on limited experimental datasets be validated for field conditions? How can extrapolation beyond observed chemistries be controlled? Addressing these questions requires systematic benchmarking, open datasets, and the integration of domain knowledge into AI models.

Ontology-aware digital twins and knowledge graphs

Given the multi-scale ontology of EOR, digital twins that integrate experiments, simulations, field data and economic models need explicit representation of entities (fluids, rocks, wells, projects) and relations (interactions, transformations, causal links).

Knowledge graphs and ontology-based data models can encode this structure, enabling reasoning across scales and facilitating automated consistency checks, data discovery and model coupling.

The recent proliferation of global EOR databases, ML screenings and risk frameworks (Ayumu & Babadagli, 2025; Niedermaier Custodio & Carneiro, 2024; Purbey et al., 2022; Zhang et al., 2025; Oguntola & Lorentzen, 2022) provides raw material for such digital twins but also exposes heterogeneity in data standards and metadata. A future EOR epistemology will likely hinge on community-accepted ontologies that make datasets interoperable and machine-actionable.

Epistemic uncertainty, reproducibility and field learning

Finally, EOR knowledge must confront deep uncertainties, particularly in the translation from laboratory to field. Reviews of surfactant retention, natural surfactants and CO_2 mobility control consistently highlight discrepancies between lab measurements and field outcomes due to scale, heterogeneity and operational complexity (Kalam et al., 2021; Atta et al., 2021; Massarweh & Abushaikha, 2022; Hama et al., 2023). The reproducibility of experimental results across laboratories and the transparency of modelling workflows are key concerns. Field-learning frameworks that systematically capture outcomes of pilots and full-field implementations—successful and unsuccessful—are essential for refining ontologies and priors used in data-driven models. Regional reviews and project databases (Rodriguez, 2021; Neves-Junior et al., 2023; Burrows et al., 2020) are early steps in this direction, but more structured, open repositories are needed.

CONCLUSION

This review has articulated a philosophy, ontology and epistemology of modern EOR grounded in recent (2020–2025) literature on chemical, thermal, gas-based and data-driven methods. We showed that contemporary EOR implicitly operates with a rich ontology spanning molecules, mesoscopic structures, pores, reservoirs and global portfolios; that its epistemology increasingly combines experiments, simulations, and data-centric inference; and that its philosophy is evolving toward sustainability and risk-aware decision-making.

Chemical EOR is broadening from classical polymer and surfactant flooding to multifunctional polymers, nanohybrids, natural surfactants, emulsions and foams capable of mobility control, wettability alteration and in-situ upgrading. Thermal and catalytic methods for heavy oils are transitioning from brute-force steam to chemically engineered subsurface reactors, while gas-based and CO_2-linked methods are increasingly integrated into CCUS value chains. Bio-based materials, regional syntheses and AI-enabled workflows further expand the space of possibilities.

Looking ahead, high-impact research should prioritize: (i) ontology-aware digital twins and knowledge graphs for EOR and CCUS; (ii) multi-objective optimization that couples recovery, cost, emissions and risk; (iii) scalable, reproducible experimental and modelling protocols; and (iv) open, standardized datasets that enable robust machine-learning models and fair benchmarking of technologies. By making its philosophical, ontological and epistemological foundations explicit, EOR can better navigate the intertwined challenges of energy security, economic viability and climate responsibility.

Conclude your research paper here.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

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How to cite this article: Romi Djafar, Hasim, Mahludin Baruadi, Weny J.A Musa. Philosophy ontology and epistemology of enhanced oil recovery in the era of data - driven and sustainable reservoir management. *International Journal of Research and Review*. 2025; 12(12): 718-733. DOI: *10.52403/ijrr.20251274*

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