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REVIEW ARTICLE: APPLICATION OF GRAPHENE OXIDE NANOMATERIALS FOR ENHANCED OIL RECOVERY AND CRUDE OIL TREATMENT

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ABSTRACT

This paper presents a critical and comprehensive review of advanced approaches to enhanced oil recovery (EOR) and crude oil treatment through the use of chemical reagents and engineered fluid systems. Particular attention is given to the emerging role of graphene oxide (GO) nanomaterials in improving the efficiency of displacement processes under challenging reservoir conditions. The study systematically analyzes the fundamental mechanisms governing oil recovery, including interfacial phenomena, wettability alteration, and mobility control. Unlike conventional descriptions, this review distinguishes between true interfacial tension (IFT) reduction and particle-induced interfacial stabilization, highlighting the specific role of GO in forming Pickering-type emulsions and modifying interfacial rheology. The behavior of GO-based nanofluids is critically evaluated with respect to salinity, temperature, and rock–fluid interactions. Limitations related to nanoparticle aggregation, adsorption on porous media, and scale-up challenges are explicitly addressed. Quantitative ranges of performance enhancement reported in laboratory studies are discussed alongside their limitations in field applications. The paper introduces a refined conceptual framework for hybrid EOR systems combining surfactants, polymers, and nanomaterials, emphasizing synergistic and antagonistic interactions. Future research directions are proposed, focusing on surface functionalization, transport control, and environmentally responsible design of nanofluids.

1. INTRODUCTION

The progressive depletion of conventional hydrocarbon reserves and the increasing reliance on mature and complex reservoirs necessitate the development of advanced recovery technologies. Primary and secondary recovery methods typically extract only 20–40% of the original oil in place (OOIP), leaving a substantial fraction trapped due to capillary forces, unfavorable mobility ratios, and reservoir heterogeneity [1].

Chemical enhanced oil recovery (EOR) methods—including surfactant flooding, polymer flooding, and alkaline–surfactant–polymer (ASP) systems—have been widely applied to address these limitations. The effectiveness of such systems strongly depends on interfacial activity, adsorption behavior, and micellization processes of surfactants, as demonstrated in previous studies [3],The molecular structure of surfactants, including head-group composition and hydrophobic chain length, plays a critical role in controlling interfacial properties and adsorption efficiency [4] These methods target key physicochemical parameters such as interfacial tension (IFT), wettability, and fluid mobility [2]. However, their effectiveness is often constrained by harsh reservoir conditions, including high salinity, elevated temperatures, and complex mineralogy, which lead to chemical degradation, precipitation, and adsorption losses [5,6].

In recent years, nanotechnology has emerged as a promising approach to overcome these limitations. Among various nanomaterials, graphene oxide (GO) has attracted significant attention due to its high specific surface area, tunable surface chemistry, and amphiphilic character [7,8]. These properties enable GO to interact with both aqueous and hydrocarbon phases, as well as with solid surfaces [9].

However, despite numerous studies reporting improved oil recovery using GO, the underlying mechanisms are often oversimplified or misinterpreted. In particular, the distinction between true IFT reduction and interfacial stabilization by solid particles is frequently overlooked. Moreover, the stability and transport behavior of GO under realistic reservoir conditions remain insufficiently understood [10,11].

This review aims to provide a critical reassessment of the role of graphene oxide in EOR processes, emphasizing mechanistic clarity, experimental limitations, and pathways toward field-scale implementation [12].

2. FUNDAMENTAL MECHANISMS OF CHEMICAL EOR

Oil displacement efficiency in porous media is controlled by the balance between viscous and capillary forces acting within the pore space. This balance determines the ability of the injected fluid to mobilize and displace trapped oil. When capillary forces dominate, a significant portion of oil remains immobilized within pore throats due to interfacial tension and rock–fluid interactions. In contrast, when viscous forces are sufficiently strong, the displacing fluid can overcome capillary trapping and transport oil toward production wells [13].

An increase in oil recovery efficiency therefore requires a shift in this balance. This can be achieved through two fundamentally different approaches. The first involves reducing interfacial tension between oil and water, typically by using surfactants, which weakens capillary forces and facilitates the detachment of oil from rock surfaces. The second approach focuses on increasing the viscosity of the displacing fluid, commonly through polymer addition, which enhances the stability of the displacement front and improves sweep efficiency. These mechanisms act through distinct physical pathways and should not be considered interchangeable [14].

Another key parameter governing displacement efficiency is the mobility ratio between the displacing and displaced fluids. This parameter reflects the relative ease with which each fluid moves through the porous medium. A favorable mobility ratio, in which the injected fluid is less mobile than the oil, promotes a stable displacement front and reduces the occurrence of viscous fingering, thereby improving macroscopic sweep efficiency [15].

Wettability is an additional critical factor influencing oil recovery. It determines the preferential affinity of the rock surface toward either water or oil and directly affects fluid distribution and capillary trapping within the pore network. In many cases, shifting the system toward more water-wet conditions enhances oil recovery by promoting the release and transport of oil from the rock surface. However, the extent and direction of this effect depend strongly on reservoir-specific factors, including mineral composition, crude oil properties, and brine chemistry [16].

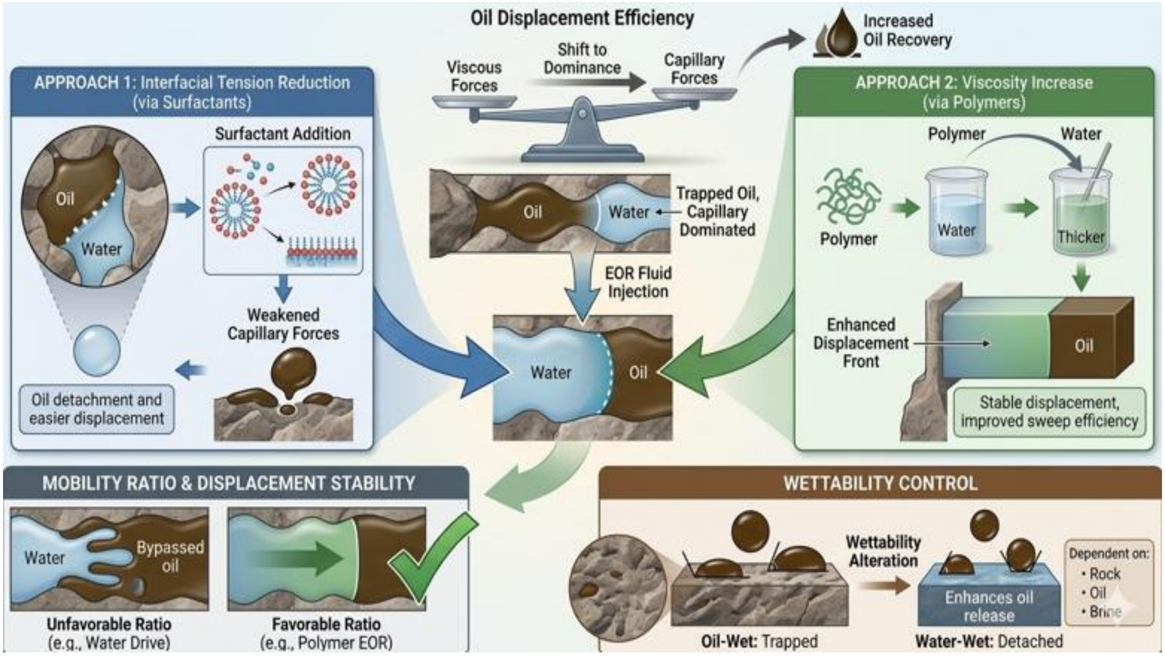

Fig 1. *Fundamental Mechanisms of Chemical EOR*

3. GRAPHENE OXIDE: PROPERTIES AND LIMITATIONS

Graphene oxide consists of single-layer carbon sheets functionalized with oxygen-containing groups such as hydroxyl, epoxy, and carboxyl moieties. These functional groups impart hydrophilicity and enable dispersion in aqueous media, while the graphitic domains retain affinity toward hydrophobic phases. As a result, graphene oxide exhibits amphiphilic behavior, allowing it to interact with oil–water interfaces and participate in multiphase flow processes.

Despite these advantageous properties, several important limitations must be carefully considered when evaluating its applicability in enhanced oil recovery [17].

One of the primary challenges is related to dispersion stability under reservoir conditions. Graphene oxide is prone to aggregation at high ionic strength, particularly in the presence of divalent cations such as calcium and magnesium, which can screen electrostatic repulsion and promote particle clustering. In addition, elevated temperatures may induce partial thermal reduction of graphene oxide, leading to changes in its surface chemistry and a decrease in its hydrophilicity. As a consequence, the stability of graphene oxide dispersions is strongly dependent on parameters such as salinity, pH, and the degree of surface functionalization, and often requires additional stabilization strategies for practical applications [18].

Another critical factor is the interaction of graphene oxide with reservoir rocks. Experimental studies indicate that graphene oxide can exhibit significant adsorption on mineral surfaces, particularly in carbonate formations and clay-rich sandstones. This behavior is driven by a combination of electrostatic interactions and π–π bonding with organic and mineral components. Such adsorption leads to a reduction in the concentration of active nanomaterial in the flowing phase and limits its transport through porous media, thereby decreasing its effectiveness in deeper reservoir regions [19].

In addition to physicochemical limitations, environmental considerations remain an area of uncertainty. The potential toxicity of graphene oxide and its long-term behavior in subsurface environments are not yet fully understood. Questions remain regarding its persistence, possible accumulation, and interactions with ecological systems, which necessitate further investigation before large-scale field deployment can be considered environmentally sustainable [20].

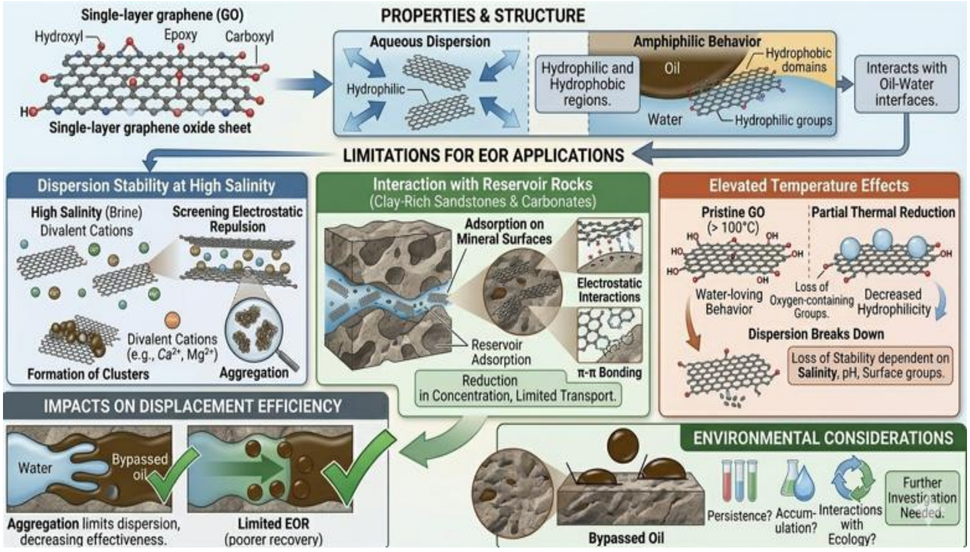

Fig 2. Graphene Oxide: Properties and Limitations

4. MECHANISMS OF GRAPHENE OXIDE IN OIL RECOVERY

4.1 Interfacial Effects

Unlike conventional surfactants, graphene oxide does not inherently act as a strong interfacial tension reducer. Its primary contribution at oil–water interfaces is related to adsorption and the stabilization of dispersed phases. Specifically, graphene oxide sheets can accumulate at fluid interfaces, forming thin, partially rigid layers that act as physical barriers to coalescence. This behavior often leads to the formation of Pickering emulsions, where solid nanoparticles stabilize droplets rather than altering the molecular-level interfacial tension. In addition, the presence of graphene oxide at the interface can modify interfacial rheology, increasing resistance to droplet deformation and breakup [19,20]. Collectively, these effects enhance emulsion stability and can contribute to improved flow diversion within porous media, promoting more uniform displacement of oil.

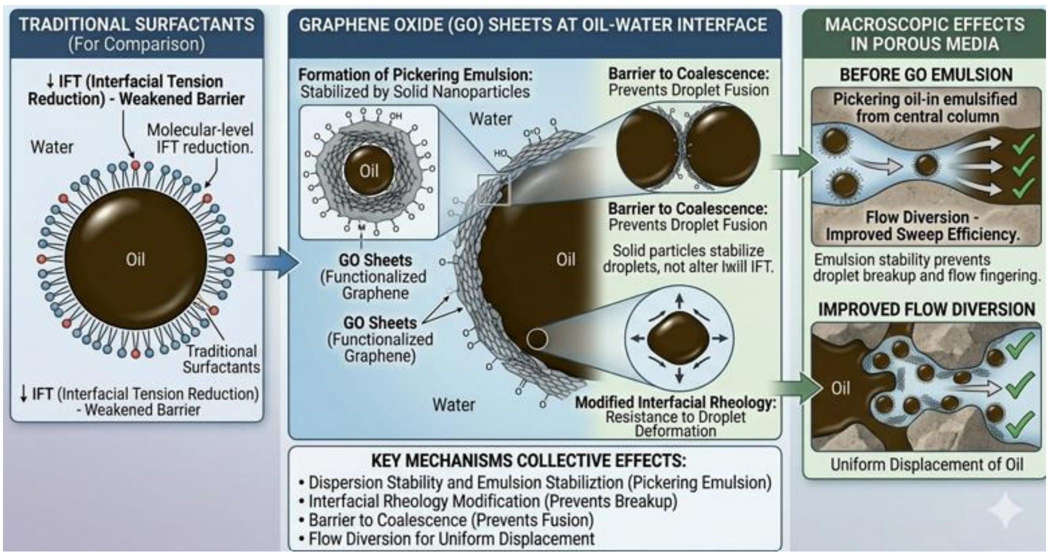

Fig 3. Interfacial Effects

4.2 Wettability Alteration

Graphene oxide has also been reported to influence rock wettability, potentially shifting surfaces toward a more water-wet state by modifying the surface energy of mineral interfaces. However, this effect is highly dependent on reservoir-specific factors, including mineralogy, crude oil composition, and brine chemistry. For example, carbonates and clay-rich formations may interact differently with graphene oxide due to variations in surface charge and organic content. As a result, wettability alteration is not universally observed and should be considered a conditional mechanism that may enhance recovery only under certain reservoir conditions [21,22].

Fig 4. Wettability Alteration

4.3 Flow Modification

Beyond interfacial interactions, graphene oxide particles can influence fluid flow patterns within the reservoir. By selectively accumulating in high-permeability channels, nanoparticles can partially block preferential flow paths, redistributing injected fluids into previously unswept or lower-permeability zones. This mechanism improves macroscopic sweep efficiency, reducing bypassed oil zones. However, such flow modification can also introduce operational challenges, including injectivity reduction or localized formation damage if particle concentration or aggregation is not carefully controlled. Optimizing nanoparticle size, surface functionalization, and injection strategy is therefore critical to harnessing the benefits of graphene oxide while avoiding adverse effects [12,16].

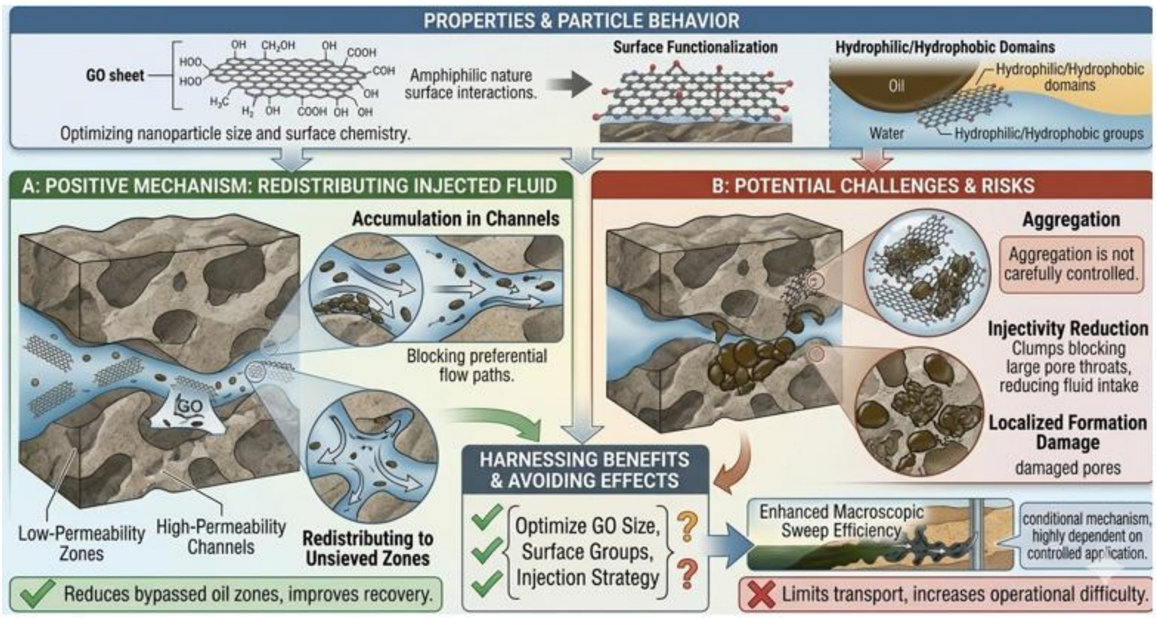

Fig 5. *Flow Modification*

5. HYBRID SYSTEMS INVOLVING GRAPHENE OXIDE

Graphene oxide is frequently integrated with conventional chemical agents, such as polymers and surfactants, to form hybrid systems that leverage complementary mechanisms for enhanced oil recovery. In polymer–graphene oxide formulations, the interaction between graphene oxide sheets and polymer chains can lead to a three-dimensional network structure, which increases solution viscosity and enhances viscoelasticity. This improved rheological behavior can enhance resistance to shear degradation during injection and propagation through porous media [17]. Nevertheless, these systems are sensitive to aggregation phenomena, which can compromise stability, and their effectiveness is strongly dependent on polymer concentration, molecular weight, and the surface chemistry of graphene oxide [18, 19].

Surfactant–graphene oxide combinations exhibit synergistic effects that arise from the complementary roles of each component. While surfactants actively reduce interfacial tension between oil and water, graphene oxide contributes primarily through interfacial adsorption and stabilization, improving the persistence and mechanical integrity of emulsions [20,21]. By combining these mechanisms, hybrid systems can achieve more uniform displacement fronts and potentially mobilize residual oil more effectively than single-component formulations.

Despite promising laboratory results, several performance limitations remain. Core flooding experiments often report incremental oil recovery of up to 20–30% of the residual oil; however, these outcomes are highly system-specific and depend on the particular reservoir analog, fluid properties, and experimental conditions. In practice, field-scale performance is generally lower due to the intrinsic heterogeneity of reservoirs, scale-up challenges, and operational constraints such as injectivity, pressure management, and nanoparticle retention. Consequently, while hybrid graphene oxide systems represent a promising avenue for enhancing recovery efficiency, their translation from laboratory to field requires careful optimization, reservoir-specific design, and rigorous evaluation of economic and operational feasibility [23].

6. TOWARD FIELD IMPLEMENTATION: CHALLENGES AND OPPORTUNITIES

Despite the promising laboratory-scale performance of graphene oxide-based systems, several key barriers hinder their widespread industrial application. One of the primary challenges is related to transport and retention within the reservoir. Graphene oxide is prone to adsorption onto mineral surfaces and can be physically filtered in pore constrictions, which significantly reduces penetration depth and limits the effectiveness of deep reservoir treatments. Ensuring uniform distribution throughout heterogeneous formations remains a major engineering challenge.

Stability control represents another critical limitation. The physicochemical behavior of graphene oxide is highly sensitive to salinity, divalent cations, pH, and temperature. Effective deployment often requires surface functionalization or chemical modification to maintain dispersion stability and compatibility with complex reservoir brines. Without such optimization, aggregation or sedimentation can occur, reducing the activity of the nanofluid and impairing oil recovery efficiency.

Economic viability is an additional concern. The large-scale synthesis and production of graphene oxide with consistent quality and functionalization remain costly, and the predictability of field-scale performance introduces further uncertainty. While laboratory experiments demonstrate significant potential, translating these findings into economically feasible operations requires careful assessment of cost–benefit trade-offs and scalability.

To address these challenges, emerging research directions focus on both fundamental understanding and engineering innovation. Mechanism-based nanofluid design is gaining attention, emphasizing the separation of functional roles, such as interfacial tension reduction versus interface stabilization, to optimize performance. Surface-engineered graphene oxide with controlled charge and hydrophilicity is being explored to improve stability and transport within reservoir formations. The development of smart hybrid systems, including stimuli-responsive nanofluids, offers the potential to dynamically adapt to changing reservoir conditions. Finally, multiscale modeling that links pore-scale physics to field-scale behavior is increasingly recognized as a critical tool for predicting and optimizing the performance of graphene oxide-based enhanced oil recovery strategies.

Collectively, these research avenues not only address current limitations but also define a roadmap for next-generation chemical EOR technologies. By integrating mechanistic understanding, materials engineering, and predictive modeling, future graphene oxide formulations have the potential to overcome existing barriers and enable more efficient, cost-effective, and sustainable hydrocarbon recovery in complex reservoirs.

7. CONCLUSION

Graphene oxide represents a promising but complex additive for enhanced oil recovery. Its primary contribution lies not in conventional surfactant-like behavior, but in interfacial stabilization, wettability modification under specific conditions, and interaction with multiphase flow in porous media.

However, its performance is highly dependent on reservoir conditions, and significant challenges remain regarding stability, adsorption, and scalability. While laboratory studies demonstrate encouraging results, translation to field-scale applications requires further mechanistic understanding and engineering optimization.

Future progress in this field will depend on integrating nanomaterial science with reservoir engineering, supported by quantitative modeling and realistic experimental validation.

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