



Polymer flooding for enhanced oil recovery: A review

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Abstract

Polymer flooding is a chemical enhanced oil recovery method that improves waterflood performance by reducing the mobility of the injected aqueous phase and enhancing reservoir sweep. This review comprehensively examines the principles and mechanisms of polymer flooding, the polymer systems used, their interactions with reservoir conditions, and the operational factors that influence performance. It also evaluates laboratory and numerical methods, field applications, economic and environmental considerations, and recent technological advances. The discussion covers conventional synthetic polymers, particularly partially hydrolysed polyacrylamide, as well as biopolymers, associative polymers, thermoviscosifying polymer (TVP) systems, zwitterionic and salt-tolerant polymers, and polymeric nanocomposites. Particular emphasis is placed on adsorption and retention, inaccessible pore volume, mechanical degradation, thermal and chemical stability, injectivity, reservoir heterogeneity, and polymer–rock interactions. Laboratory core-flooding experiments and numerical simulations are examined as key methods for polymer evaluation and field-scale design. Case studies from China, Canada, Oman, and other regions demonstrate that performance is strongly dependent on reservoir-specific conditions. The review also considers economic and environmental factors, including chemical use, water management, produced-water treatment, and the potential sustainability advantages of advanced biopolymer systems. Recent developments in smart polymers, nanocomposites, hybrid injection strategies, and data-driven reservoir optimisation are also assessed. Overall, reliable and economically viable polymer flooding requires an integrated approach that brings together polymer chemistry, reservoir characterisation, laboratory testing, numerical modelling, and field surveillance.

Keywords: Polymer flooding, enhanced oil recovery, HPAM, mobility control, sweep efficiency, polymer-reservoir interaction

Introduction

Enhanced oil recovery methods are used after primary and secondary recovery to mobilise additional hydrocarbons remaining in a reservoir. In conventional waterflooding, the injected water often has substantially greater mobility than the oil it displaces. This unfavourable mobility contrast can cause viscous fingering, premature water breakthrough, channelling through high-permeability layers, and poor areal and vertical sweep. Chemical EOR methods address these challenges by modifying the properties or interfacial behaviour of injected or reservoir fluids. Polymer flooding is among the most established chemical EOR methods because it primarily improves mobility control rather than relying on a substantial reduction in interfacial tension^[1]. During polymer flooding, a water-soluble polymer is mixed with the injection water and injected into the reservoir either as a discrete slug or as a continuous solution. By increasing the aqueous phase's apparent viscosity, the polymer lowers its mobility relative to that of oil. This produces a more favourable mobility ratio, stabilises the displacement front, and enables the injected fluid to sweep reservoir regions that might otherwise remain inadequately contacted^[2]. Polymer solutions may also display shear-thinning and viscoelastic behaviour, which affects their propagation through porous media and their interaction with the pore structure^[3, 4]. Historically, partially hydrolysed polyacrylamide has been the predominant polymer in field-scale applications, owing to its comparatively high viscosity-building efficiency, widespread commercial availability, and established preparation and injection practices^[5]. Nevertheless, HPAM

performance may be compromised by elevated temperatures, high salinity, divalent ions, oxygen exposure, shear, adsorption, and mechanical retention. These constraints are particularly significant in high-temperature, high-salinity reservoirs, where viscosity reduction and polymer degradation can weaken mobility control. In response, research has increasingly focused on biopolymers, associative polymers, sulfonated and zwitterionic polymers, thermoviscosifying polymer systems, and polymer–nanoparticle formulations^[6, 7].

Polymer-flooding performance depends on more than polymer viscosity. It is shaped by the combined effects of reservoir permeability and pore structure, heterogeneity, formation-water composition, temperature, crude-oil viscosity, injection rate, polymer concentration and molecular weight, adsorption, retention, and injectivity. Laboratory rheology and core-flooding tests are essential for screening polymers, while reservoir simulation helps translate experimental findings into field-scale injection strategies^[1]. Field experience has also demonstrated that polymer selection and project design must be adapted to reservoir-specific conditions rather than based on a universal set of operating parameters^[8]. Extensive field deployment of polymer flooding in China, especially in the Daqing oilfield, has demonstrated the effectiveness of polymer-based mobility control and significantly advanced the technology's development^[9]. Studies of heavy-oil and mature reservoirs show that polymer flooding can be tailored to diverse geological and fluid conditions, but injectivity, polymer consumption, and economic viability remain central design considerations^[10, 11].

This review adopts an integrated laboratory-to-field perspective on polymer flooding. It begins by outlining the fundamental principles and mechanisms of mobility control, then examines polymer classes and their interactions with reservoir materials. The influence of polymer concentration, molecular weight, temperature, salinity, permeability, heterogeneity, shear, and oil viscosity is considered. Laboratory evaluation methods and numerical modelling are discussed alongside representative field applications. The review also addresses economic and environmental considerations and recent advances in thermoviscosifying polymers, associative systems, polymeric nanofluids, advanced biopolymers, and data-driven methods. Finally, it identifies key technical challenges and research priorities for improving the predictability and sustainability of polymer flooding.

Fundamentals and Principles of Polymer Flooding

Polymer flooding is fundamentally a mobility-control process. For a phase i flowing through porous media, phase mobility can be expressed as $\lambda_i = k_{ri}/\mu_i$, where k_{ri} is relative permeability and μ_i is phase viscosity. For water and oil, the mobility ratio can be represented as $M = \lambda_w/\lambda_o = k_{rw}/\mu_o(k_{ro}/\mu_w)$. A lower and more favourable mobility ratio reduces the tendency of the injected phase to finger through the oil-bearing formation and improves displacement stability^[12]. When a polymer is added to water, the apparent viscosity of the aqueous phase increases. The magnitude of this increase depends on polymer concentration, molecular weight, degree of hydrolysis, temperature, water chemistry, and shear rate. Polymer solutions are frequently non-Newtonian and may exhibit shear-thinning behaviour, meaning that apparent viscosity decreases as shear rate increases. This behaviour is particularly important near injection wells, where flow velocities and shear rates can be high^[13].

Polymer flooding may also modify the effective mobility of the aqueous phase through polymer adsorption and retention. The resistance factor is an experimental measure defined as the ratio of the pressure drop during polymer flow to that during water flow under comparable conditions. The residual resistance factor, in turn, quantifies the reduction in water permeability after polymer injection followed by waterflooding. Together, these parameters are used to assess polymer transport, permeability alteration, and conformance effects^[14]. Improvements in sweep efficiency can be divided into areal and vertical components. Areal sweep may increase when polymer

reduces preferential flow through high-permeability zones and stabilizes the displacement front. Vertical sweep may also improve as mobility control limits water bypassing lower-permeability layers. These effects are particularly relevant in reservoirs characterized by permeability contrasts, fractures, or high-permeability streaks.^[1]

Polymer flooding does not necessarily depend on maintaining a permanently elevated viscosity in the injected fluid. Rather, polymer concentration and slug size are selected to provide the required degree of mobility control across the target reservoir volume. Polymer-bank design must account for losses associated with adsorption and retention, dilution, inaccessible pore volume, degradation, and mixing with formation water. Collectively, these processes determine the polymer concentration that reaches the intended region of the reservoir^[15]. The central design objective is to provide adequate mobility control while avoiding excessive pressure gradients that could compromise injectivity. Accordingly, polymer-flood design must balance viscosity enhancement with transportability, polymer use, reservoir coverage, and economic considerations. This balance guides laboratory screening and subsequent numerical optimisation. Polymer rheology is also scale-dependent: bulk rheometry characterises fluid response under controlled shear, whereas flow through porous media involves converging and diverging pathways, extensional deformation, adsorption, retention, and inaccessible pore volume. These processes may cause polymer behaviour in situ to differ from its bulk response, underscoring the importance of porous-media experiments during design^[4]. The target viscosity should not be defined simply by the highest value attainable under laboratory conditions. Excessive viscosity may raise injection pressures, impair injectivity, and promote undesirable polymer retention. Polymer-flood design therefore aims to achieve a practical mobility ratio that can be sustained across the reservoir distance of interest. The viscosity required depends on factors including oil viscosity, permeability distribution, interlayer crossflow, well spacing, and the presence of fractures^[2]. Polymer flooding is best understood by distinguishing among phase mobility, displacement stability, and reservoir sweep. Mobility refers to the ease with which a fluid phase flows through the pore network, whereas sweep efficiency describes the extent to which the injected phase contacts the reservoir. By increasing the apparent viscosity of the aqueous phase, polymer injection primarily reduces its mobility and can promote a more stable oil-displacement regime^[2].

Table 1: Fundamental parameters used in polymer flooding.

Parameter	Role	Importance
Mobility	$\lambda = kr/\mu$	Controls phase movement through porous media
Mobility ratio	$M = \lambda_w/\lambda_o$	Indicates displacement stability
Resistance factor (RF)	Pressure-drop ratio during polymer vs water flow	Measures mobility reduction during polymer injection
Residual resistance factor (RRF)	Post-polymer water-mobility reduction	Indicates permeability modification/retention
Sweep efficiency	Fraction of reservoir contacted effectively	Controls macroscopic recovery improvement
Polymer rheology	Viscosity response to concentration and shear	Controls injectivity and propagation

Mechanisms of Polymer Flooding

The principal mechanism of polymer flooding is mobility control. By increasing the viscosity of the injected aqueous phase, polymer reduces its mobility and improves the

mobility ratio between water and oil. A more favourable mobility ratio stabilises the displacement front, delays water breakthrough, and enables a larger proportion of the reservoir to contribute to oil production^[2]. A second

mechanism involves suppressing viscous fingering. In conventional waterflooding, the relatively low-viscosity water preferentially flows through high-permeability pathways, potentially reaching production wells rapidly. Adding polymer increases resistance to aqueous-phase flow and reduces mobility contrasts among flow paths. This effect is especially significant in heterogeneous formations, where permeability variations can promote premature channeling. Polymer viscoelasticity may contribute to displacement mechanisms beyond those attributable to increased viscosity alone. Under extensional or converging flow in porous media, high-molecular-weight polymers can exhibit elastic behaviour. Experimental studies have linked polymer elasticity to changes in residual-oil mobilization; however, the extent and field-scale significance of these effects depend on polymer characteristics, pore structure, flow conditions, and reservoir heterogeneity^[16]. Polymer adsorption and retention can also alter flow distribution. Interactions between polymer molecules and rock surfaces, together with mechanical entrapment in pore throats, may reduce the effective permeability to subsequent water flow. This reduction can divert later-injected water toward previously less-accessible zones, thereby improving conformance. However, these processes may also increase polymer consumption and injection-pressure requirements^[17]. In heterogeneous reservoirs, these mechanisms operate at different scales. At the pore scale, polymer rheology and polymer–rock interactions influence transport and local displacement. At the core scale, mobility reduction and permeability modification affect pressure drop, breakthrough, and oil recovery. At the reservoir scale, the combined effects determine sweep distribution, polymer-bank propagation, water cut, and incremental oil recovery^[15]. Polymer flooding integrates both macroscopic and

microscopic mechanisms to enhance oil recovery. Primarily, it improves macroscopic sweep efficiency by optimizing mobility control and addressing conformance challenges, while viscoelasticity and localized flow phenomena may further facilitate oil mobilization. Determining the relative significance of these mechanisms is critical for the accurate interpretation of laboratory data and its subsequent upscaling to field applications. Specifically, in heterogeneous reservoirs, flow diversion is of paramount importance; polymer solutions tend to gravitate toward high-permeability strata, which exhibit reduced hydraulic resistance. Subsequent polymer retention and the resulting permeability reduction within these high-conductivity channels serve to divert subsequent water injection into under-swept regions. Consequently, quantifying the resistance factor and residual resistance factor is as essential as assessing bulk viscosity for comprehensive process evaluation.^[18] The effect of polymer concentration on recovery illustrates the distinction between viscosity and sweep. Increasing concentration typically increases solution viscosity and reduces water mobility, but the incremental benefit of additional viscosity eventually diminishes. Meanwhile, polymer consumption and pressure requirements continue to increase. Therefore, design must optimise the complete mobility-control profile rather than maximise viscosity^[1]. Polymer-flooding mechanisms can be classified as macroscopic or microscopic. At the macroscopic scale, mobility control generally enhances reservoir sweep. At the microscopic scale, contributions include localized flow effects, viscoelastic behaviour, and the redistribution of injected water associated with polymer retention. These mechanisms act concurrently and may not be readily distinguished through experiments.^[4]

Table 2: Major mechanisms contributing to polymer-flood performance.

Mechanism	Main effect	EOR contribution
Mobility control	Reduces aqueous-phase mobility	Improved displacement stability
Fingering suppression	Delays preferential water movement	Higher areal/vertical sweep
Viscoelastic response	Changes the polymer flow in porous media	Potential additional residual-oil mobilization
Retention/permeability modification	Restricts selected flow paths	Improved conformance and diversion
Heterogeneity control	Redistributes injected water	Greater reservoir contact

Polymers Used in EOR

1. Synthetic polymers

Synthetic polymers are the predominant materials in commercial polymer flooding because their molecular structure, molecular weight, charge density, and degree of hydrolysis can be tailored during production. Partially hydrolysed polyacrylamide is the most widely used polymer, owing to its high molecular weight and ability to generate substantial viscosity at relatively low concentrations^[5]. Its anionic carboxylate groups interact with water chemistry and rock surfaces, making solution properties sensitive to salinity and divalent ions. Acrylamide-based copolymers can be tailored to enhance thermal and chemical stability. Incorporating sulfonated monomers, such as AMPS-type structures, can improve tolerance to high salinity and divalent ions relative to conventional HPAM. These polymers are particularly suited to reservoirs in which conventional HPAM undergoes substantial viscosity loss^[19]. Hydrophobically associating polymers contain hydrophobic moieties that form reversible

intermolecular associations in aqueous solutions. These interactions can enhance viscosity and influence the polymer network’s response to concentration, temperature, salinity, and shear conditions. Their performance depends strongly on molecular architecture and reservoir conditions^[6].

2. Biopolymers

Biopolymers originate from biological or renewable resources and include xanthan gum, scleroglucan, welan gum, guar derivatives, and other polysaccharides. Xanthan is of particular interest because its molecular architecture confers relatively good salinity and temperature tolerance, enabling it to retain useful rheological properties across a range of reservoir conditions^[20]. Although biopolymers may offer benefits in terms of chemical stability and environmental compatibility, their use can be constrained by biodegradation, microbial contamination, high viscosity at low concentrations, and plugging risks. Their performance therefore depends on water quality, storage conditions, filtration, and compatibility with the reservoir^[21].

3. Advanced polymer systems

Thermoviscosifying and thermoassociative polymers are formulated to maintain or increase viscosity as temperature rises, making them promising candidates for high-temperature reservoirs where conventional polymers may experience thermal viscosity loss. Laboratory studies indicate that suitably designed systems can preserve effective mobility-control properties under elevated-temperature and high-salinity conditions [22]. Zwitterionic and salt-responsive polymers are under investigation for applications in high-ionic-strength reservoirs. Their molecular designs aim to mitigate the effects of salts and divalent ions on polymer conformation. Other emerging materials include graft copolymers, associative polymers, and polymeric nanocomposites, which are being developed to enhance thermal stability, rheological performance, or resistance to mechanical degradation [23, 24].

4. Comparison of polymer systems

Biopolymers and modified natural polymers provide an alternative means of enhancing salt tolerance and environmental compatibility. Their practical application, however, requires careful management of biological

stability, solution preparation, filtration, storage, and product consistency. Although advanced synthetic systems allow greater control over molecular architecture, their formulation complexity and cost may constrain adoption at scale. [22]. HPAM remains the most widely used polymer in field applications, owing to its favourable balance of cost, availability, thickening efficiency, and established operational experience. Its limitations arise primarily under high-temperature and high-salinity conditions, in the presence of divalent ions or oxygen, and when subject to mechanical degradation. These constraints have driven the development of sulfonated copolymers, associative polymers, biopolymers, and thermoviscosifying systems [19]. Polymer selection should be guided by reservoir-specific compatibility. A polymer that achieves high viscosity in fresh water may exhibit substantial viscosity loss in formation brine, particularly in the presence of divalent ions. Similarly, although high-molecular-weight polymers can provide effective mobility control, they may be more susceptible to retention and mechanical degradation. Selection should therefore account for viscosity efficiency, chemical stability, injectivity, adsorption, retention, and cost. [4].

Table 3: Comparison of major polymer systems used for EOR

Polymer system	Type	Major advantages	Major limitations	Application	References
PAM/HPAM	Synthetic	Low cost, commercial availability, strong thickening ability, and established field experience	Sensitive to salinity, hardness, temperature, oxidative and mechanical degradation	Conventional polymer flooding	[7]
AMPS-based polymers	Synthetic copolymer	Improved thermal and salt tolerance compared with conventional HPAM	Higher cost and formulation complexity	High-temperature/high-salinity reservoirs	[19]
Xanthan gum	Biopolymer	Good rheology, shear-thinning behavior, relatively good salt tolerance	Biodegradation, plugging/filtration and injectivity concerns	Harsh-condition and environmentally oriented EOR	[25, 26]
Scleroglucan	Biopolymer	Strong thermal and salt stability; good viscosity retention	High cost and poor filterability	High-temperature/high-salinity reservoirs	[27]
Schizophyllan	Biopolymer	High viscosity, good thermal and salt tolerance	Biodegradation and limited large-scale field experience	Advanced biopolymer EOR	[28]
Guar gum / HEC / CMC	Biopolymer/derivative	Renewable origin, good thickening ability and tunable properties	Thermal/biological stability and injectivity limitations depending on polymer	Laboratory and modified-polymer research	[23]
Thermoviscosifying polymers	Advanced	Potential viscosity retention or increase at elevated temperature	Developing technology and limited field validation	High-temperature reservoirs	[29]
Zwitterionic polymers	Advanced	Potential tolerance to high salinity and ionic strength	Higher formulation complexity/cost and limited field-scale evidence	High-salinity reservoirs	[30]
Polymer nanocomposites	Advanced	Potential improvement in thermal stability, rheology and flow control	Dispersion, transport, retention, cost and scale-up uncertainties	Emerging EOR research	

Polymer–Reservoir Interactions

Retention has a dual role. Moderate permeability reduction in highly conductive zones can improve conformance, but excessive retention can cause injectivity impairment and increase chemical consumption. The appropriate level depends on the reservoir architecture and the location of the retained polymer relative to the injection and production

wells [18]. Inaccessible pore volume is important in interpreting core floods. If the polymer does not access the same pore volume as water, the polymer-bank propagation and concentration history differ from simple piston-like displacement. Ignoring IPV can therefore produce errors in estimated adsorption, slug size, and reservoir-scale propagation. [31] Adsorption is affected by mineralogy and

brine composition. Changes in ionic strength can modify electrostatic interactions between polymer molecules and rock surfaces. In sandstone reservoirs, clay minerals and surface charge can be particularly important. Modern studies therefore increasingly treat the polymer–brine–rock system as a coupled chemical system rather than considering polymer

viscosity independently. Polymer–reservoir interactions determine how much injected polymer remains mobile. Adsorption removes polymer from solution at mineral surfaces, while mechanical retention can trap polymer in pore throats or inaccessible regions. These processes alter polymer concentration and permeability as the polymer bank moves through the reservoir^[17].

Table 4: Major polymer–reservoir interactions

Interaction	Primary consequence	Potential EOR effect
Adsorption	Loss of polymer from mobile phase	Higher polymer requirement
Mechanical retention	Permeability reduction	Flow diversion or injectivity impairment
IPV	Delayed/modified polymer propagation	Changes polymer-bank design
Thermal/chemical degradation	Molecular-weight and viscosity loss	Reduced mobility control
Biological degradation	Polymer deterioration	Reduced stability of susceptible biopolymers

Factors Affecting Polymer Flooding Performance

Reservoir heterogeneity can either enhance the benefits of polymer flooding or complicate project implementation. Moderate permeability contrasts may be mitigated through mobility control, whereas severe fractures and thief zones may necessitate selective conformance treatments or modifications to the well pattern. Horizontal wells can improve injectivity and reservoir contact in some cases, although their flow geometry must be incorporated into the design. Water chemistry is also a key determinant of performance. High salinity and hardness can reduce the hydrodynamic size of charged polymers, thereby lowering solution viscosity. Oxygen and other reactive species may accelerate chemical degradation, while elevated temperatures can increase the rate of many degradation reactions. Accordingly, oxygen control, water treatment, and appropriate polymer storage should be incorporated into field design^[32].

Polymer concentration and molecular weight should be optimised in combination. Lower-molecular-weight polymers may improve injectivity and reduce retention but may require higher concentrations. Conversely, higher-molecular-weight polymers may achieve the target viscosity at lower concentrations, although they may be more vulnerable to mechanical degradation and retention. The practical optimum depends on the overall pressure, viscosity, and transport response. The factors that govern polymer-flooding performance are interdependent: temperature affects both polymer viscosity and degradation rate, while salinity influences molecular conformation and the resulting viscosity. Injection rate determines shear exposure, and permeability affects both the pressure gradient and access to pore throats. Accordingly, a realistic screening program should evaluate combinations of reservoir conditions rather than vary a single parameter in isolation^[9].

Table No 5: Major factors affecting polymer-flooding performance.

Factor	Influence on polymer flooding	Design implication
Concentration	Controls solution viscosity and mobility	Optimize viscosity against cost/injectivity
Molecular weight	Controls thickening and retention	Balance viscosity and transport
Temperature	Changes viscosity and degradation	Select thermally stable chemistry
Salinity/divalent ions	Can reduce chain expansion and viscosity	Control water chemistry and polymer type
Permeability	Controls injectivity and retention	Match polymer size to pore structure
Heterogeneity	Controls sweep and channelling	Use mobility control/conformance design
Shear	May degrade polymer molecules	Evaluate near-wellbore and surface shear
Oil viscosity	Determines required mobility control	Adjust polymer rheology and slug design

Economic and Environmental Aspects

Environmental assessment should extend beyond biodegradability to encompass the full life cycle, including raw-material sourcing, manufacturing energy, transportation, chemical use, injection-water treatment, produced-water management, and end-of-life disposal. Although biopolymers may offer benefits in some environmental categories, their biological stability and production requirements also require assessment. Produced-water treatment is a key consideration because residual polymer can affect viscosity, separation behaviour, filtration requirements,

and reinjection performance. Treatment systems should therefore be incorporated into project design, given the interdependence of chemical performance and surface-facility operations. The economic viability of polymer flooding depends on the incremental oil recovered relative to the costs of polymer manufacture, transportation, preparation, injection, water treatment, produced-water handling, and surface facilities. Consequently, the concentration that maximizes laboratory recovery may not maximize project economics. Economic optimization should link polymer consumption to reservoir-scale recovery forecasts^[32].

Table No 6: Economic Potential in Polymer Flooding

Aspect	Potential concern	Evaluation focus
Polymer consumption	High chemical expenditure	Cost per incremental barrel and slug optimisation
Injection facilities	Mixing, filtration and pumping requirements	Capital and operating cost
Produced water	Polymer affects treatment behaviour	Separation, filtration and reinjection
Environmental footprint	Chemical persistence and waste	Lifecycle assessment
Biopolymers	Potential sustainability benefit but biological sensitivity	Stability and end-of-life behavior

Recent Advances

Nowadays, the Data-driven approaches offer a complementary means of optimising chemical formulations and reservoir operations. Machine-learning models can reveal relationships among polymer properties, reservoir characteristics, injection parameters, and recovery outcomes. Their predictive value, however, depends on the representativeness of the training data; mechanistic simulation remains essential for extrapolating beyond the conditions covered by those data. Nanocomposite systems combine polymer-based mobility control with nanoparticle functions. Depending on their formulation, nanoparticles may influence polymer conformation, thermal stability, adsorption, and interfacial properties. Key challenges include maintaining dispersion stability, ensuring transport over long distances, limiting retention in the formation, achieving compatibility with brines, and scaling up

economically [33]. Thermoviscosifying polymers are promising because they can exhibit a more favourable viscosity response as temperature rises, potentially mitigating a key limitation of conventional polymer flooding, where aqueous viscosity and polymer performance often decline at elevated temperatures. However, their thermally responsive behaviour must remain compatible with transport through porous media and acceptable injection pressures [24].

Recent advances focus on making polymer flooding more robust rather than simply increasing viscosity. The main objective is to maintain mobility control under high temperature, high salinity, hardness, and high shear. This has led to polymers with sulfonated groups, associative structures, temperature-responsive behaviour, and nanoparticle reinforcement [19].

Table no. 7: Emerging technologies in polymer flooding

Advanced system	Main development	Potential advantage	Current limitation
Thermoviscosifying polymers	Temperature-responsive association	Improved viscosity at elevated temperature	Limited field validation
Thermoassociating polymers	Stimuli-responsive intermolecular networks	Improved rheology under harsh conditions	Molecular-design complexity
Zwitterionic polymers	Charge-balanced polymer architecture	Potential high-salinity tolerance	Limited field-scale evidence
Polymeric nanofluids	Polymer–nanoparticle combinations	Improved rheology/stability and possible interfacial effects	Dispersion, cost and transport
Modified biopolymers	Functionalized natural polymers	Renewable backbone with enhanced functionality	Scale-up and reproducibility
Smart polymer systems	Response to temperature/salinity	Reservoir-specific mobility control	Long-term stability
Data-assisted optimization	Simulation + experimental/data methods	Improved formulation and injection design	Data quality and model uncertainty

Challenges and Future Perspectives

A key future priority is to develop adaptive polymer-flooding workflows that integrate laboratory measurements, reservoir simulation, and field data. Such workflows could support adjustments to polymer concentration, injection rate, slug size, and water-treatment conditions as understanding of reservoir behaviour evolves. Scaling laboratory findings to field conditions remains challenging because core-flood experiments cannot reproduce all reservoir features. Core length, permeability distribution, fractures, well spacing, pressure history, and crossflow can differ substantially between laboratory and field settings. Accordingly, numerical models should be calibrated against realistic transport parameters and field surveillance data, rather than against bulk viscosity alone. A central difficulty is that the polymer encounters changing conditions as it moves through the formation: temperature, salinity, shear, pressure, adsorption, and pore geometry vary along the flow path. Degradation can alter molecular weight and charge density, thereby affecting adsorption, retention, injectivity, and subsequent degradation. These interacting effects are particularly important in high-salinity, high-temperature reservoirs [34, 35].

Conclusions

Polymer flooding is a widely used chemical enhanced oil recovery method for improving reservoir sweep and increasing recovery in mature fields. This review examined its underlying principles and mechanisms, including mobility control, suppression of viscous fingering, flow

diversion, and enhanced areal and vertical sweep. It also evaluated synthetic polymers, biopolymers, associative polymers, and emerging modified systems in terms of their properties and applications. Key factors considered included polymer-reservoir interactions, adsorption, retention, inaccessible pore volume, degradation, salinity, temperature, permeability, heterogeneity, and injection conditions. Laboratory studies, numerical modelling methods, and selected field applications illustrated the progression from experimental assessment to field implementation. The review further considered economic and environmental factors, as well as recent developments in thermoviscosifying polymers, nanocomposites, advanced biopolymers, and data-driven methods. Overall, effective polymer flooding depends on integrating polymer design with reservoir properties, laboratory evaluation, numerical modelling, field conditions, and operational planning.

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