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ENHANCED OIL RECOVERY METHODS USING BIODEGRADABLE MATERIALS IN DIFFERENT RESERVOIRS.

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Keywords

Biopolymers, Chemical Enhanced Oil Recovery (EOR), Mobility Ratio, Polyacrylamide (PAM), Polymer Flooding, Surfactant-Polymer Flooding, Viscoelasticity.

Abstract

This review examines the use of biodegradable materials in Enhanced Oil Recovery (EOR) techniques, highlighting their environmental benefits compared to traditional methods. It explores the effectiveness of biosurfactants, biopolymers, and microbial formulations in different reservoir types. Biosurfactants, derived from microorganisms and plants, reduce interfacial tension and enhance oil recovery in sandstone and carbonate reservoirs. Biopolymers like guar gum and xanthan gum improve fluid stability and sweep efficiency in heavy oil and unconventional reservoirs. Microbial Enhanced Oil Recovery (MEOR) leverages bacteria to maximize oil displacement. The review discusses both the advantages and limitations of biodegradable materials, including technical challenges and industry adoption. It concludes with recommendations for advancing biodegradable technologies and research, emphasizing the importance of integrating these materials into EOR practices for improved sustainability and reduced environmental impact.

1. Introduction

Enhanced Oil Recovery (EOR) techniques are essential for maximizing the extraction of crude oil from reservoirs that have been partially depleted by primary and secondary recovery methods.[1, 2, 3] Traditional EOR methods, including thermal recovery, chemical flooding, and miscible gas injection, have significantly contributed to increasing oil recovery. Thermal recovery, such as steam injection, reduces the viscosity of heavy oil, making it easier to extract. Chemical flooding involves injectingsubstances like polymers, surfactants, or alkaline agents to improve oil mobility and increase recovery rates [4]. Miscible gas injection, including CO2 and methane, helps in reducing the oil's viscosity and enhancing displacement efficiency [6]. Despite their effectiveness, traditional EOR methods face challenges related to environmental impact and economic feasibility [7]. The use of chemicals in EOR can lead to environmental pollution and sustainability concerns due to the persistence of these substances in the environment [8]. Furthermore, the high costs associated with some EOR techniques can limit their widespread application, particularly in economically sensitive areas [9]. Biodegradable materials have emerged as a promising alternative to conventional EOR techniques. These materials, including biodegradable polymers, surfactants, and microbial formulations, offer several advantages over traditional methods. They are designed to break down into non-toxic byproducts, thus reducing environmental impact and aligning with global sustainability goals [10,11]. For instance, biodegradable polymers like xanthan gum and guar gum have been shown to enhance oil recovery while decomposing into harmless substances [12, 13]. Similarly, biosurfactants, produced by microorganisms, can effectively reduce interfacial tension between oil and water while being biodegradable[14, 15, 16]. The objective of this review is to provide a comprehensive overview of recent advancements in EOR methods utilizing biodegradable materials. This includes an examination of the mechanisms of these materials, their applications in various reservoir types, and future trends in this field. The review aims to summarize current EOR methods using biodegradable materials, evaluate their effectiveness across different reservoirs, and identify research gaps [17].

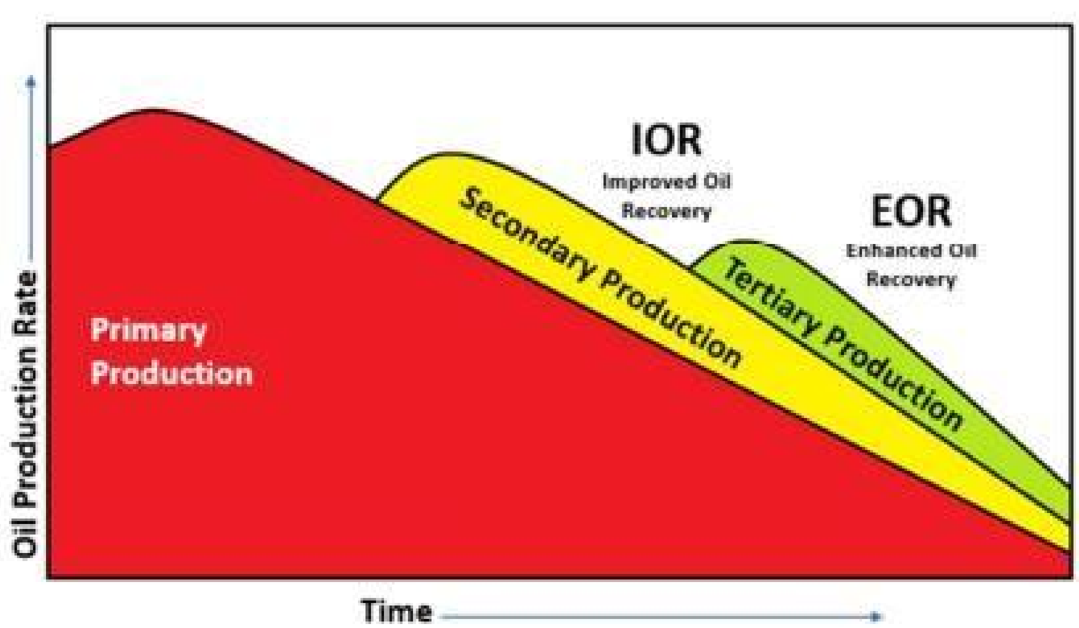

Figure 1 : Graphical Representation of the effect of EOR on production rate versus time [18].

2. Enhanced Oil Recovery (EOR) Methods

Enhanced Oil Recovery (EOR) involves various techniques aimed at extracting more crude oil from reservoirs after the completion of primary and secondary recovery processes. This section outlines the traditional EOR methods and introduces the role of biodegradable materials in enhancing these processes.

2.1 Traditional EOR Methods

Thermal recovery methods are designed to reduce the viscosity of heavy oil, which can be particularly thick and difficult to extract. One of the most widely used techniques in this category is steam injection. This involves injecting steam into the reservoir to heat the oil, thereby reducing its viscosity and improving its flowability [17, 19, 20]. Steam injection can significantly increase oil production, but it is also energy-intensive and may lead to increased greenhouse gas emissions [21, 22, 23]. The efficiency of thermal recovery methods depends on factors such as reservoir temperature, pressure, and oil characteristics [24, 25]. Chemical flooding involves injecting various chemicals into the reservoir to improve oil recovery. Polymers are used to increase the viscosity of the injected water, which helps to improve the sweep efficiency of the water drive [26, 27]. Polymers like xanthan gum and polyacrylamide are commonly used in this approach [28, 29]. Surfactants which reduce the interfacial tension between oil and water, making it easier for the oil to be displaced [30, 31]. Surfactants can enhance oil mobilization and increase recovery rates significantly [32, 33]. Alkaline chemicals react with the crude oil to form in-situ surfactants that further reduce interfacial tension [34, 35]. Although chemical flooding can be highly effective, it involves the use of synthetic chemicals, which may pose environmental risks and increase operational costs [36, 37]. Gas injection methods involve introducing gases like CO2, methane, or nitrogen into the reservoir to improve oil recovery. These gases help to lower the viscosity of the oil and increase reservoir pressure, which facilitates the displacement of oil [38, 39]. CO2 injection, in particular, is used for its ability to dissolve in oil and reduce its viscosity [40]. Gas injection methods can also provide a means of sequestering CO2, mitigating greenhouse gas emissions [41, 43]. However, the effectiveness of gas injection depends on factors such as gas injectivity, reservoir pressure, and gas-oil ratio [44].

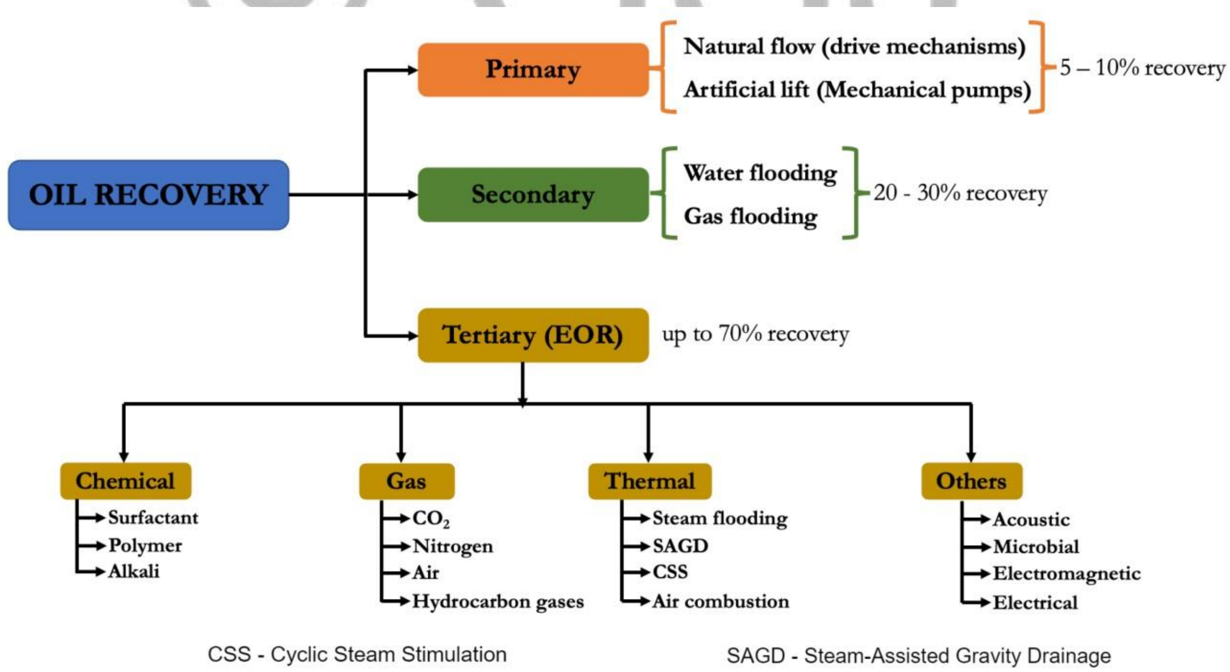

Figure 2 : Stages of Traditional EOR methods [46].

2.2 Biodegradable Materials in EOR

Biodegradable materials are substances that decompose into non-toxic byproducts through the action of microorganisms. These materials offer a sustainable alternative to conventional EOR chemicals by minimizing environmental impact and reducing the accumulation of harmful substances in the reservoir [47]. The use of biodegradable materials aligns with global sustainability goals and offers several advantages, including reduced ecological footprint and enhanced safety [48]. Biosurfactants which are produced by microorganisms, biosurfactants are naturally occurring compounds that can reduce surface and interfacial tension, enhancing oil recovery [49, 50]. They are inherently biodegradable and break down into harmless byproducts, making them an environmentally friendly choice [51, 52]. Biosurfactants such as rhamnolipids and sophorolipids have been shown to improve oil recovery in various reservoir conditions [53, 54]. Biopolymers such as Polysaccharides like xanthan gum and guar gum are commonly used in EOR for their viscosity-modifying properties. These biopolymers enhance the stability of injected fluids and improve their performance in reservoirs [55]. For example, xanthan gum can thicken water, enhancing sweep efficiency and minimizing water channeling [57]. Guar gum is recognized for its capacity to improve oil recovery by modifying viscosity and controlling mobility [58]. Biosurfactants are surface-active substances generated by microorganisms such as bacteria and yeasts, or obtained from plants. They play a crucial role in Enhanced Oil Recovery (EOR) because of their capacity to lower surface and interfacial tension, thereby improving oil mobilization. Key types of biosurfactants include: Rhamnolipid produced by Pseudomonas aeruginosa, rhamnolipids are glycolipid biosurfactants that lower interfacial tension between oil and water. They are effective in mobilizing heavy oils and have been utilized in various EOR applications due to their high efficacy and biodegradability [59]. Sophorolipids which are synthesized by yeasts such as Candida bombicola, sophorolipids are lipopeptides with strong surfactant properties. They are particularly useful in improving oil recovery by altering the wettability of the reservoir rock and stabilizing emulsions [60, 61]. Lipopeptides are produced by bacteria like Bacillus subtilis and exhibit excellent surface activity. Lipopeptides are effective in reducing interfacial tension and have been employed in field trials to enhance oil displacement [61, 62]. Biosurfactants are characterized by their low toxicity, high biodegradability, and environmental compatibility. They are effective at reducing the surface and interfacial tension, which enhances oil recovery by improving the mobilization and displacement of oil from reservoirs [63, 64]. Rhamnolipids in Sandstone Reservoirs: Rhamnolipids greatly enhanced oil recovery in sandstone reservoirs. Studies demonstrated that the decrease in interfacial tension resulted in improved oil displacement and higher recovery rates [67, 68]. In Carbonate Reservoirs, sophorolipids enhanced oil recovery by altering the wettability of the rock surface and boosting the effectiveness of water flooding [69, 70]. Bio-polymers: Xanthan gum is a polysaccharide produced by Xanthomonas campestris. It is used in EOR to increase the viscosity of water, which enhances the stability of injected fluids and improves the sweep efficiency. By increasing the viscosity, xanthan gum helps to reduce water channeling and improves oil displacement [69, 70]. Guar Gum derived from the seeds is another polysaccharide used in EOR. It acts similarly to xanthan gum by modifying the viscosity of injected fluids. Guar gum helps in controlling the mobility ratio between oil and water, which improves the efficiency of water flooding and enhances oil recovery [71, 72]. Xanthan Gum in Sandstone Reservoirs: Xanthan gum-based fluids increased oil recovery in sandstone reservoirs by enhancing the waterflood efficiency and reducing oil bypassing [73, 74]. Guar Gum in Carbonate Reservoirs: Guar gum improved oil recovery in carbonate reservoirs by modifying fluid viscosity and enhancing mobility control [75, 76]. Microbial Enhanced Oil Recovery (MEOR) uses microorganisms to improve oil recovery by altering reservoir conditions or producing compounds that enhance oil mobilization. They utilizing bacteria that generate biosurfactants, biopolymers, or other metabolites to aid in oil displacement [79, 80]. Various microorganisms are employed in MEOR, including bacteria such as Bacillus, Clostridium, and Pseudomonas. These microbes are selected based on their ability to survive and function under specific reservoir conditions, producing beneficial substances that aid in oil recovery [79, 80]. The effectiveness of MEOR depends on the ability of microorganisms to thrive in the harsh conditions of oil reservoirs. Conditions such as temperature, salinity, and pressure play a crucial role in microbial activity and, consequently, the success of MEOR [81, 82]. Successful MEOR Application in Carbonate Reservoirs: A combination of Bacillus and Clostridium species improved oil recovery in carbonate reservoirs by producing biosurfactants that enhanced oil displacement [83, 84]. Field Trial in Heavy Oil Reservoirs showed that microbes produced biopolymers that reduced oil viscosity and improved oil recovery [85].

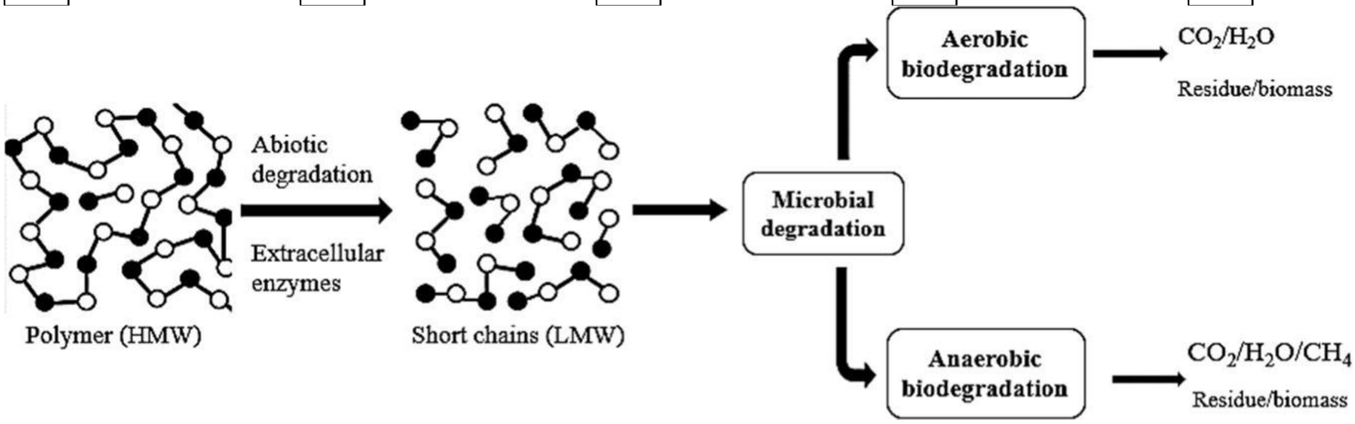

Figure 3: Biodegradation steps of polymers [88].

3. Application of Biodegradable Materials in Different Reservoir Types

3.1 Carbonate Reservoirs

Carbonate reservoirs, composed mainly of limestone and dolomite, are characterized by their complex pore structures and high variability in permeability. The application of biodegradable materials such as biosurfactants and biopolymers in these reservoirs aims to improve oil recovery by altering reservoir conditions and enhancing fluid displacement. Biosurfactants have shown promising results in carbonate reservoirs due to their ability to reduce interfacial tension and alter rock wettability. For instance, rhamnolipids have been effective in increasing oil recovery by enhancing oil displacement in carbonate formations [87, 88]. Biopolymers like xanthan gum and guar gum are used to modify the viscosity of the injected fluids. This adjustment aids in regulating water mobility and enhances sweep efficiency in carbonate reservoirs. Microbial EOR techniques in carbonate reservoirs involve using microbes that produce biosurfactants or biopolymers to improve oil recovery. Guar Gum Applications: the application of guar gum in carbonate reservoirs, finding that it improved oil recovery by modifying fluid viscosity and enhancing water flood efficiency [89, 90].

3.2 Sandstone Reservoirs

Sandstone reservoirs are predominantly composed of sand grains cemented together, creating a porous medium with relatively high permeability. The application of biodegradable materials in these reservoirs focuses on enhancing oil recovery by improving fluid flow and displacement. In sandstone reservoirs, biosurfactants like rhamnolipids and sophorolipids are used to lower interfacial tension and improve oil displacement [91]. Biopolymers such as xanthan gum and guar gum are applied to modify fluid viscosity and improve sweep efficiency. Xanthan gum was particularly effective in reducing water channeling and enhancing oil recovery in sandstone reservoirs [92]. MEOR techniques in sandstone reservoirs involve the use of specific microbes that produce biosurfactants or biopolymers to enhance oil recovery. Microbial applications improved oil recovery by altering the reservoir's fluid properties [93]. Xanthan Gum in Sandstone Reservoirs increased oil recovery by improving the viscosity of injected fluids and enhancing sweep efficiency [94]. Sophorolipids in Sandstone Reservoirs enhanced oil recovery by modifying rock wettability and stabilizing emulsions in sandstone reservoirs [95].

3.3 Heavy Oil Reservoirs

Heavy oil reservoirs are distinguished by their elevated viscosity and density. The application of biodegradable materials aims to reduce the viscosity of the oil and improve its flowability, enhancing oil recovery. In heavy oil reservoirs, biosurfactants like rhamnolipids are used to reduce oil viscosity and improve flowability. Biosurfactants effectively increased oil recovery by lowering the viscosity of heavy oil [96]. Biopolymers such as xanthan gum and guar gum are used to modify the viscosity of injected fluids and enhance oil recovery. Biopolymers improved oil recovery in heavy oil reservoirs by reducing oil viscosity and enhancing fluid displacement [97].MEOR techniques in heavy oil reservoirs involve using microbes to produce biopolymers or biosurfactants that reduce oil viscosity and improve recovery. It’s applications in heavy oil reservoirs led to increased oil recovery by effectively reducing oil viscosity [98]. Rhamnolipids in Heavy Oil Reservoirs decreased the viscosity of heavy oil, resulting in enhanced oil recovery [101]. Guar Gum Applications: Guar gum enhanced oil recovery in heavy oil reservoirs by improving fluid flow and reducing oil viscosity [100].

3.4 Unconventional Reservoirs

Unconventional reservoirs, such as shale and tight reservoirs, present unique challenges due to their low permeability and complex rock properties. The use of biodegradable materials in these reservoirs aims to enhance oil recovery by improving fluid mobility and reducing formation damage. Biosurfactants like rhamnolipids and sophorolipids can improve oil recovery in unconventional reservoirs by reducing interfacial tension and altering rock wettability. Biopolymers such as xanthan gum and guar gum are applied to improve fluid flow and reduce formation damage. These biopolymers enhanced oil recovery in unconventional reservoirs by modifying fluid properties and improving sweep efficiency [101]. MEOR techniques in unconventional reservoirs involve using microbes to produce biopolymers or biosurfactants that improve oil recovery. Microbial applications in unconventional reservoirs led to increased oil recovery by improving fluid flow and reducing formation damage [102]. Sophorolipids in Unconventional Reservoirs improved oil recovery in unconventional reservoirs by enhancing oil displacement and reducing formation damage [103].

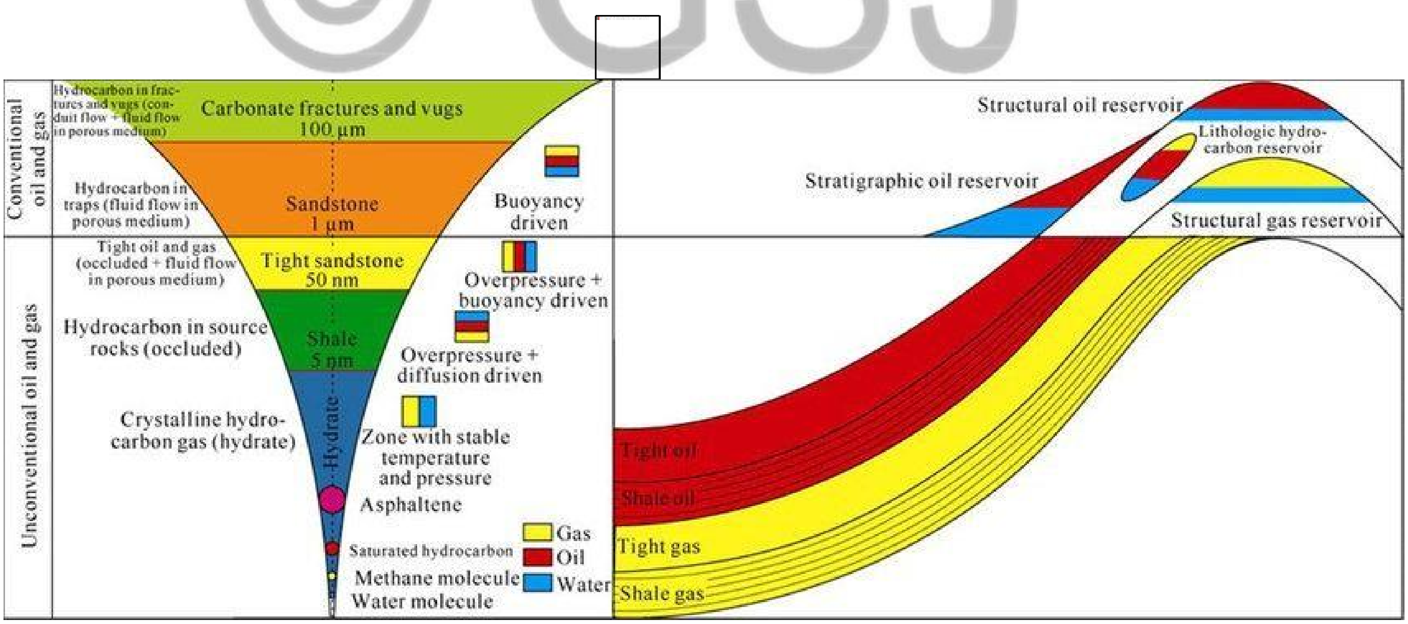

Figure 4 : Conventional and unconventional pore throat structures and accumulations [106].

4. Comparative Analysis of EOR Methods Using Biodegradable Materials

4.1 Effectiveness and Efficiency

Biosurfactants, including rhamnolipids and sophorolipids, have demonstrated significant effectiveness in enhancing oil recovery. They reduce interfacial tension between oil and water, which improves oil mobilization and displacement. Studies have shown that biosurfactants can enhance recovery rates by altering rock wettability and increasing the volume of oil that can be displaced [105]. Biopolymers like xanthan gum and guar gum are essential for enhancing oil recovery by altering the viscosity of fluids. This modification helps in controlling the mobility of the displacing fluid and enhances sweep efficiency. Research has shown that biopolymers can effectively improve the efficiency of water flooding operations by reducing water channeling and improving the distribution of injected fluids [106]. MEOR involves using microorganisms to produce biosurfactants or biopolymers that enhance oil recovery. The success of Microbial Enhanced Oil Recovery (MEOR) relies on the type of microorganisms employed, their metabolic byproducts, and the conditions within the reservoir. Studies indicate that MEOR can significantly increase oil recovery by producing compounds that lower oil viscosity and improve fluid displacement [107].

4.2 Comparative Analysis

When comparing the effectiveness of these methods, biosurfactants are generally superior in reducing interfacial tension and enhancing oil displacement. Biopolymers excel in viscosity modification and mobility control, making them highly effective in improving sweep efficiency. MEOR offers a combination of both effects, as microbes can produce multiple enhancing agents simultaneously. However, the efficiency of MEOR can be influenced by the microbial growth conditions and the reservoir environment. Biosurfactants: Studies demonstrated that rhamnolipids significantly improved oil recovery in carbonate and sandstone reservoirs by reducing interfacial tension and altering rock wettability [108]. Biopolymers: Research found that xanthan gum and guar gum effectively improved oil recovery in various reservoir types by modifying fluid viscosity and reducing water channeling [109]. MeOR: Studies reported that microbial formulations enhanced oil recovery in heavy oil reservoirs by producing surfactants and polymers that reduced oil viscosity and improved fluid flow [110].

4.3 Economic Considerations

The cost of biodegradable materials varies significantly depending on their type and source. Biosurfactants are generally more expensive to produce compared to biopolymers, due to the complexity of microbial fermentation processes and the need for specific growth conditions [111]. Biopolymers, such as xanthan gum and guar gum, are relatively more affordable and have established production processes that make them cost-effective for large-scale applications [112]. The implementation of EOR techniques involving biodegradable materials often requires additional infrastructure and operational adjustments. For instance, the injection of biosurfactants or biopolymers may require modifications to injection equipment and monitoring systems [113]. MEOR, while potentially cost-effective due to its dual benefits of reducing viscosity and producing surfactants, involves the cost of microbial cultivation and maintenance [114]. The return on investment (ROI) for EOR methods using biodegradable materials depends on the increased oil recovery achieved relative to the costs involved. Biosurfactants can offer high returns in terms of enhanced recovery rates but come with higher initial costs [115]. Biopolymers provide a balanced cost-to-benefit ratio with their effectiveness in improving oil recovery while being more cost-effective [116]. MEOR presents a promising ROI by potentially reducing both oil viscosity and formation damage, but its success can be highly variable depending on microbial performance and reservoir conditions [117]. While biosurfactants are more costly, their application in enhanced oil recovery can lead to significant increases in oil recovery rates, justifying their use in certain high-value applications [118]. Studies highlighted the cost-effectiveness of biopolymers like guar gum and xanthan gum in improving oil recovery, with lower production costs and successful application in various reservoir types [119]. Field trials demonstrated that MEOR, despite its initial costs, offers a good return on investment due to its ability to simultaneously reduce viscosity and enhance oil recovery [120].

4.4 Environmental Impact

Biosurfactants are generally considered environmentally friendly due to their natural origin and biodegradability. Their use in EOR can lead to reduced environmental impact compared to synthetic surfactants. However, the production process for some biosurfactants can still have environmental implications [121]. Biopolymers such as xanthan gum and guar gum are derived from natural sources and are biodegradable, which minimizes their environmental impact. Their application in EOR helps to reduce the use of synthetic polymers and lowers the overall environmental footprint of oil recovery operations [122]. MEOR has a relatively low environmental impact, especially when using indigenous or naturally occurring microbes. The production of microbial products is often less resource-intensive compared to synthetic chemical methods. However, the introduction of non-native microbial species into reservoirs can pose ecological risks if not properly managed [123]. Reviews emphasized the environmental benefits of using rhamnolipids in EOR, as they are biodegradable and derived from natural sources [124]. Research noted that biopolymers like xanthan gum and guar gum contribute to reducing the environmental impact of EOR by replacing synthetic polymers [125]. MEOR, particularly with native microbial strains, can be an environmentally sustainable option for enhancing oil recovery, with minimal negative impact on reservoir ecosystems [126].

5. Emerging Trends

5.1 Advanced Biosurfactants

Research Focus: Explore the development of novel biosurfactants with improved performance and cost-effectiveness. This includes engineering microbes to produce more efficient surfactants or discovering new microbial strains that naturally produce high-performing biosurfactants [127] .Potential Applications: Enhanced oil recovery in challenging reservoirs, such as those with high salinity or temperature, where conventional biosurfactants may be less effective [128].

5.2 Innovative Biopolymer Formulations

Research Focus: Investigate new biopolymer blends or composites that enhance the properties of individual biopolymers. For example, combining xanthan gum with other biopolymers to achieve better viscosity control and stability in various reservoir conditions [129]. Potential Application involves tailoring biopolymer formulations for specific reservoir types to improve sweep efficiency and reduce operational costs [130].

5.3 Integration of Microbial Technologies

Research Focus: Develop and optimize microbial enhanced oil recovery (MEOR) techniques that leverage genetic engineering or synthetic biology to create microbes with enhanced oil recovery capabilities. This includes optimizing microbial growth conditions and improving the efficiency of microbial production processes [131]. Potential Applications: Large-scale application in diverse reservoir environments, including deep and unconventional reservoirs where traditional methods may be less effective [132].

6. Technological Developments

6.1 Improved Production Methods

Focus: Enhance the scalability and cost-effectiveness of producing biodegradable materials for EOR. This includes developing more efficient fermentation processes for biosurfactants and biopolymers or exploring alternative production methods such as using waste materials [133]. Outcomes: Reduced production costs and increased availability of biodegradable materials for EOR applications [134].

6.2 Enhanced Monitoring and Control Technologies

Focus: Develop advanced monitoring and control technologies to better manage the injection and behavior of biodegradable materials in reservoirs. This includes real-time tracking of material performance and reservoir conditions using advanced sensors and data analytics [135].

Outcomes: Improved accuracy in the application of EOR techniques, leading to better recovery rates and reduced operational risks [136].

6.3 Environmental Impact Assessment Tools

Focus: Create more sophisticated tools and models for assessing the environmental impact of biodegradable materials in EOR. This includes life cycle assessments and real-time monitoring of environmental parameters [137]. Outcomes: Better understanding of the ecological impact and sustainability of EOR techniques using biodegradable materials [138].

7. Collaborative Research and Industry Partnerships

7.1 Academic and Industry Collaboration

Focus: Foster collaboration between academic researchers and industry practitioners to accelerate the development and deployment of biodegradable materials in EOR. This includes joint research projects, pilot studies, and technology transfer initiatives [139]. Outcomes: Faster innovation and practical implementation of new EOR technologies [140].

7.2 Public and Private Sector Involvement

Focus: Engage with both public and private sectors to secure funding and support for research and development in biodegradable materials for EOR. This includes seeking grants, investment, and public-private partnerships [141]. Outcomes: Increased resources for research and development, leading to the advancement of EOR technologies [142].

7.3 Future Perspectives and Research Directions

7.3.1 Advanced Biopolymer Formulations

Development: New biopolymer formulations are being developed to enhance their stability, efficiency, and compatibility with diverse reservoir conditions. Innovations include genetically engineered microorganisms that produce more robust and tailored biopolymers. These advanced formulations aim to address the challenges of degradation and stability under extreme reservoir conditions. Potential: These emerging biopolymers are expected to perform better in high-temperature, high-salinity reservoirs, expanding the applicability of biodegradable materials in EOR. Continued research and development in this area could lead to significant improvements in oil recovery rates while maintaining environmental sustainability .

7.3.2 Nanotechnology Integration

Development: The integration of nanotechnology with biodegradable materials in EOR is an emerging area of interest. Nanoparticles can be combined with biopolymers or biosurfactants to improve their performance, such as enhancing oil displacement efficiency, controlling fluid flow, and providing better reservoir sweep. Potential: Nanotechnology can help overcome some of the limitations of conventional EOR methods by providing more precise control over material behavior within the reservoir. This approach holds promise for enhancing the efficiency of biodegradable materials in various reservoir types .

7.3.4 Microbial Consortia

Development: Research is advancing in the use of microbial consortia—combinations of different microbial species that work synergistically to enhance oil recovery. These consortia can be engineered to produce a mix of biosurfactants, biopolymers, and gases that improve oil mobilization and recovery. Potential: The use of microbial consortia represents a significant leap forward in MEOR, offering the potential for more effective and sustainable oil recovery. This approach can be customized for specific reservoir conditions, making it a versatile option for the industry .

7.4 Knowledge Gap and Recommendations for Future Research

7.4.1 Enhanced Stability of Biodegradable Materials

Recommendation: Future research should focus on improving the thermal, chemical, and mechanical stability of biodegradable materials under extreme reservoir conditions. This includes exploring new formulations, cross-linking techniques, and protective coatings that can prolong the effective lifespan of these materials in the reservoir .

7.4.2 Understanding Reservoir Interactions

Recommendation: There is a need for more in-depth studies on the interactions between biodegradable materials and different reservoir types. This includes understanding how factors like pH, salinity, and mineralogy affect the performance of these materials. Such studies will help in optimizing material selection and application strategies .

7.4.3 Scaling Up Production and Application

Recommendation: Research should also address the challenges of scaling up the production of biodegradable materials for commercial use. This includes optimizing production processes, reducing costs, and ensuring consistency in material quality during large-scale field applications. Pilot projects in diverse reservoirs could provide valuable insights into the practical challenges of using these materials on a larger scale.

7.4.4 Environmental Impact Assessments

Recommendation: Comprehensive environmental impact assessments (EIAs) are necessary to evaluate the long-term ecological effects of biodegradable materials in EOR. Future research should include the development of standardized methodologies for assessing the biodegradability and environmental safety of these materials under various reservoir conditions .

7.5 Potential for Industry Adoption

7.5.1 Integration into Existing EOR Strategies

Recommendation: The oil and gas industry should consider integrating biodegradable materials into their existing EOR strategies. This can be achieved by conducting pilot tests in different reservoir environments to evaluate the effectiveness of these materials and developing best practices for their application. Industry collaborations with academic and research institutions could accelerate the adoption of these technologies .

7.5.2 Training and Capacity Building

Recommendation: Training programs and workshops should be established to inform industry professionals about the advantages and uses of biodegradable materials in Enhanced Oil Recovery (EOR). Enhancing industry knowledge and capability to understand and apply these technologies is essential for their broad adoption. This may include collaborations with educational institutions and the creation of specialized curricula focused on sustainable EOR practices.

7.5.3 Incentives for Sustainable Practices

Recommendation: Governments and regulatory bodies should consider providing incentives for the adoption of biodegradable materials in EOR. This could include tax benefits, grants, or subsidies for companies that invest in sustainable technologies. Such incentives would encourage the industry to prioritize environmentally friendly practices and accelerate the transition towards more sustainable oil recovery methods .

8. Conclusion

The review highlights the significant potential of biodegradable materials, such as biosurfactants, biopolymers, and microbial enhanced oil recovery (MEOR) techniques, in enhancing oil recovery (EOR) across various reservoir types. These materials improve oil mobilization, increase sweep efficiency, and minimize environmental impact by breaking down into non-toxic byproducts, outperforming traditional synthetic chemicals in many cases. Their application in heavy oil, carbonate, and unconventional reservoirs demonstrates their broad effectiveness. For the oil and gas industry, transitioning to biodegradable materials in EOR aligns with global sustainability goals, reduces environmental contamination, and offers long-term economic advantages by lowering remediation costs. The industry's shift toward these eco-friendly technologies is not only a regulatory necessity but also a strategic move to balance energy production with environmental responsibility.

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