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Effect of Biosurfactants on Enhanced Oil Recovery: A Systematic Review

Heydi Solórzano-Medranda[1], Joselyne Solórzano[2,3*], Paúl Carrión-Mero[1,2,3]

[1] Facultad de Ciencias de la Ingeniería, Universidad Estatal Península de Santa Elena, 240350 Santa Elena, Ecuador
[2] Centro de Investigación y Proyectos Aplicados a las Ciencias de la Tierra, Escuela Superior Politécnica del Litoral, Campus Gustavo Galindo, 090902 Guayaquil, Ecuador
[3] Facultad de Ingeniería en Ciencias de la Tierra, Escuela Superior Politécnica del Litoral, Campus Gustavo Galindo, 090902 Guayaquil, Ecuador

[*] Correspondence: Joselyne Solórzano (josbasol@espol.edu.ec)

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Abstract: Oil is one of the primary sources of energy worldwide; however, its production brings environmental challenges associated with the use of conventional extraction methods. Biosurfactants have emerged as a sustainable alternative for improving efficiency in Enhanced Oil Recovery (EOR). The objective of this research is to analyze the role of biosurfactants in EOR through a bibliometric analysis and a systematic review, identifying trends, key microorganisms, and their impact on recovery efficiency. The research methodology consisted of three phases: (i) selection of data for analysis, (ii) application of scientific metrics, and (iii) systematic review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, focusing on contributions from the last six years. The bibliometric analysis compiled data from 1988 to 2025, with 745 academic publications indexed in the Scopus and WoS databases from 48 countries, with the main contributions coming from China, India, and Iran, attributing their dominance to state investments in research and development for energy and biotechnology innovation. The systematic review found that the most studied biosurfactants are from *Pseudomonas* and *Bacillus*, with rhamnolipids and surfactins being the most prevalent. They act through multiple mechanisms and show potential in applications involving in situ and ex situ production, with additional oil recovery rates exceeding 10% in laboratory studies.

Keywords: Bibliometrics; Biosurfactants; Biotechnology; Enhanced recovery; Petroleum

1 Introduction

The oil and gas industry plays a significant role globally in the evolution of society [1]. The accelerated growth of the world's population is causing an increase in energy requirements, prompting researchers to study methods for optimizing the efficiency of hydrocarbon supply [2]. Energy requirements are expected to continue rising [3, 4], and by 2040, oil and gas will continue to account for 50% of the global energy mix, reflecting their determining factor for global access to energy [5].

Oil extraction can be classified into three stages, according to its development process: primary recovery, secondary recovery, and tertiary or EOR [6]. Several EOR methods have been studied to increase reservoir recovery, most of which can be classified as thermal, chemical, gas injection (miscible or immiscible) [6, 7], and Microbial Enhanced Oil Recovery (MEOR) [8]. Thermal methods inject steam, hot water, or combustible gases to increase the temperature of the crude oil and facilitate the displacement of hydrocarbons [9]. Chemical methods, on the other hand, use solvents, surfactants, or gases to mobilize the oil by reducing the interfacial tension (IFT) between water and oil [10]. These methods present significant challenges, such as high energy consumption, emission of pollutants into the environment, and excessive heat generation, among others [11, 12]. To address these challenges, the oil industry and researchers must explore innovative methods with sustainable routes that ensure a stable energy supply. MEOR processes involve the use of native or exogenous microorganisms to promote microbial development in the reservoir [13] and induce the in situ or ex situ generation of microbial metabolites such as biosurfactants, biopolymers, solvents, biogenic acids, biogases, and biomass, capable of increasing the swept volume and improving oil displacement efficiency, consolidating MEOR as a promising technique in oil recovery [14, 15].

In the oil industry, biosurfactants have gained increasing interest due to their ability to reduce surface and interfacial tension [16]. Furthermore, they are stable across a wide range of pH, temperature, and salinity levels [17], making them suitable for application in EOR. Some research has shown that the critical micelle concentration (CMC) of biosurfactants is significantly lower than that of chemical surfactants, which means that much smaller doses of biosurfactants can be used to achieve the same effect [18]. Biosurfactants are also capable of altering the wettability of rock [19].

In recent decades, various studies have explored aspects related to MEOR, including the taxonomic characterization of microorganisms, the influence of environmental factors on their metabolic activity, the production of metabolites, and their potential to improve oil mobilization and optimize the efficiency of EOR processes [20–22]. However, these studies have significant limitations and gaps. First, there is little scientific literature reporting field tests to validate the injection of biosurfactants into reservoirs, which makes it impossible to evaluate their actual performance under operating conditions [22]. Furthermore, there is little scattered information available on essential aspects for large-scale implementation, such as production and implementation costs, technical feasibility compared to conventional synthetic surfactants, and a comprehensive assessment of their environmental impacts. Before undertaking field tests, it is essential to have a detailed understanding of the factors that determine their effectiveness, including the stability of biosurfactants under extreme conditions of pressure, temperature, and salinity, as well as their behavior with different types of rocks and crude oils.

A systematic review supplemented by a bibliometric analysis on the use of biosurfactants in oil recovery can serve as a complementary analysis to synthesize existing information and guide this field of research, strengthening the link between scientific research and field application, detect emerging technologies, and highlight the sustainability of biosurfactants as a biotechnological alternative capable of reducing the environmental impact of EOR processes without compromising their efficiency. This study poses the following research questions: What are the research trends surrounding the use of biosurfactants for EOR processes? Which microorganisms and types of biosurfactants have been most studied in this area? What impact have biosurfactants had on improving oil recovery processes? This research seeks to analyze the application of biosurfactants in EOR based on publications indexed in Scopus and WoS, using bibliometric analysis, together with a systematic review applying the PRISMA guidelines for classifying trends, key microorganisms, and their impact on enhanced hydrocarbon recovery efficiency. In general terms, bibliometric analysis shows the integration of disciplines such as nanotechnology, genetic engineering, and machine learning to optimize the production and application of biosurfactants in EOR. China, India, and Iran lead research in this field, which has shown sustained growth in the number of publications over the last decade. For their part, recent research included in the systematic review focuses not only on identifying effective microorganisms and compounds but also on developing combined strategies that improve the performance of recovery processes, demonstrating the potential of this technology as a sustainable alternative in the energy sector.

This research paper is structured into the following sections: (i) introduction to the topic of study, (ii) literature review, (iii) materials and methods used for the search, selection, and analysis of the studies included in the review, (iv) main results and findings organized into figures and tables, (v) discussion of the most relevant trends and findings, and (vi) conclusions.

2 Literature Review

In recent years, interest in biosurfactants has increased significantly due to their biodegradability, low toxicity, and ability to operate in extreme conditions, characteristics that make them sustainable alternatives for EOR processes [23]. Biosurfactants are amphiphilic surfactant compounds produced mainly by microorganisms, although they can also be of plant or animal origin [24]. Their molecular structure, with affinity for both aqueous and oily media, allows them to reduce surface and interfacial tension. Depending on their charge, they are classified as anionic, cationic, nonionic, or zwitterionic [25]. They can also be classified as glycolipids, lipopeptides, phospholipids, fatty acids, polymeric surfactants, and particulate surfactants [26].

In the context of EOR, glycolipids and lipopeptides have great industrial and commercial potential, which is why they have been the subject of numerous studies [14]. Current research on biosurfactants for EOR focuses mainly on evaluating their performance based on the producing microorganism, the type of compound generated, and the application conditions. The mechanisms of action that enable crude oil recovery are also evaluated, including the reduction of the interfacial tension between oil and water, the emulsification of crude oil, and the alteration of rock wettability [14].

A representative example is the work of Biktasheva et al. [27], who used *Pseudomonas putida* to produce a mixture of mono- and di-ramnolipid biosurfactants, evaluating their effectiveness in recovering heavy crude oil from the Romashkino field in Russia. In their experiments, the biosurfactant increased oil recovery by up to 22%

in core flooding tests and by up to 48% in packed sand columns. The authors attribute this effectiveness to the biosurfactant's ability to alter the IFT significantly. The lower recovery recorded in the cores highlights the effects of the heterogeneity of the natural environment. However, the results demonstrate the good performance of ramnolipids in different environments, highlighting their potential to improve the mobility of heavy crude oil.

Complementarily, Câmara et al. [28] evaluated a rhamnolipid produced by *Pseudomonas aeruginosa* isolated from soil contaminated with crude oil. The compound showed a high capacity to reduce surface tension and emulsify oil, confirming its viability for EOR applications. In recovery tests, the biosurfactant successfully recovered an additional 11,91% of oil. Furthermore, it was found to remain functional even after two months of production, indicating that its biodegradability does not limit its performance. These findings highlight the stability and functional persistence of ramnolipid even after prolonged periods following application, underscoring its potential as an effective and reliable biosurfactant for improving recovery.

For their part, Park et al. [29] demonstrated that the production of surfactin by *Bacillus subtilis* is an effective mechanism for MEOR under adverse reservoir conditions. The study showed that this lipopeptide acted efficiently in high-pressure, high-salinity environments and a temperature range of 35-45°C, both aerobic and anaerobic, modifying the wettability of the rock and reducing interfacial tension in complex systems, thus confirming the viability of *Bacillus subtilis* as a MEOR enhancer under conditions representative of a real reservoir.

Finally, the study by El-Sheshtawy et al. [30] compared the EOR efficacy of a lipopeptide biosurfactant from *Bacillus licheniformis* with that of a sophorolipid biosurfactant from *Candida albicans*. Although both biosurfactants reduced surface tension and demonstrated emulsifying capacity, their performance in packed sand column tests was markedly different. The bacterial lipopeptide achieved an additional recovery of 16,6%, significantly higher than that achieved with yeast soforolipid (8,6%), indicating a clear superiority of the bacterial biosurfactant for EOR applications. These results clearly demonstrate that the microbial source has a significant impact on the efficiency of the biosurfactant, underscoring the importance of selecting suitable producer strains.

3 Material and Methods

To address the issue comprehensively, this research combines two approaches: Bibliometric analysis and systematic review [31]. A systematic review allows for the establishment of a well-founded state of the art, contributing to the development of research by identifying new and valuable trends [32]. On the other hand, bibliometric analysis is a widely used and comprehensive procedure for identifying and examining large amounts of data linked to citations, authors, keywords, journals, countries, institutions, among others [33], allowing this data to be represented through graphs, clusters, and networks that could be used to obtain a general overview of scientific production in specific areas of study [34]. The methodology adopted in this study is described in Figure 1 and comprises three phases: (i) selection of data for analysis; (ii) application of scientific metrics; (iii) systematic review using PRISMA guidelines focused on contributions from the last six years.

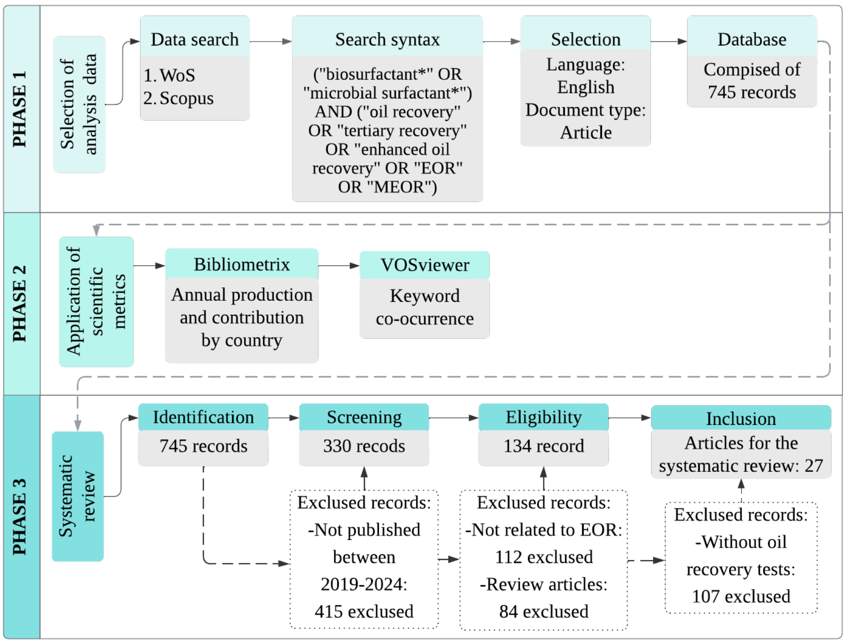

Figure 1. Methodology diagram for bibliometric analysis and systematic review

3.1 Stage 1: Selection of Analysis Data

This article used Web of Science (WoS) and Scopus due to their wide coverage of peer-reviewed publications in the field of science and technology [35, 36]. Boolean operators (AND and OR) were used, and the search syntax was: ("biosurfactant*" OR "microbial surfactant*") AND ("oil recovery" OR "tertiary recovery" OR "enhanced oil recovery" OR 'EOR' OR "MEOR") in titles, abstracts, and keywords.

The search in WoS yielded 858 publications, which were filtered using the platform's tools by document type (article) and language (English), resulting in 701 records. Scopus initially yielded 933 publications; after applying the filters available in the Scopus interface by document type and language, 566 records were selected. A total of 1,267 publications were selected from both databases and exported in BibTeX format. The records were processed in two complementary stages. First, the data obtained from WoS and Scopus were integrated using RStudio (version 2025.05.1-513), which allowed the information to be unified and duplicates to be eliminated, resulting in 811 unique records. Subsequently, bibliographic validation was conducted in Microsoft Excel, where records with incomplete information (author, title, year of publication, or DOI) were removed, resulting in 745 valid records for the subsequent stages of bibliometric analysis and systematic review [37].

3.2 Stage 2: Application of Scientific Metrics

Bibliometrix 4.0 (R package, run in RStudio) was used for the analysis of the intellectual structure, including annual publication output, distribution, and scientific contribution by country [38]. VOSviewer (v.1.6.20) was also used to examine the most common keywords, see how they are linked to each other, and group them into clusters according to their relationship [39, 40].

3.3 Stage 3: Systematic Review using PRISMA Focused on Contributions from the Last Six Years

The systematic review followed the PRISMA guidelines, which consist of four stages [41]. In the first stage, called identification, the 745 valid records resulting from the data selection stage were used. In the second screening stage, the 745 records available in Microsoft Excel were filtered by year of publication, retaining only articles from the last six years to capture the current state of knowledge, the latest advances, and trends in the field of research. The six-year interval (2019-2024) was defined based on the trend observed in the bibliometric analysis (Figure 2), which shows the period of highest recent production. Including earlier years would have incorporated studies with outdated approaches. This stage reduced the number of results to 330 documents. In the third stage of eligibility, the titles and abstracts of the 330 documents were reviewed, and review articles and studies not related to EOR were excluded to ensure thematic relevance, leaving 134 papers for the final phase. In the final stage, called inclusion, the full text was read, articles evaluating the efficiency of oil recovery through experimental tests were included, and articles with tests under conditions representative of a reservoir environment were prioritized. Ultimately, 27 documents were selected to form the basis of the systematic review.

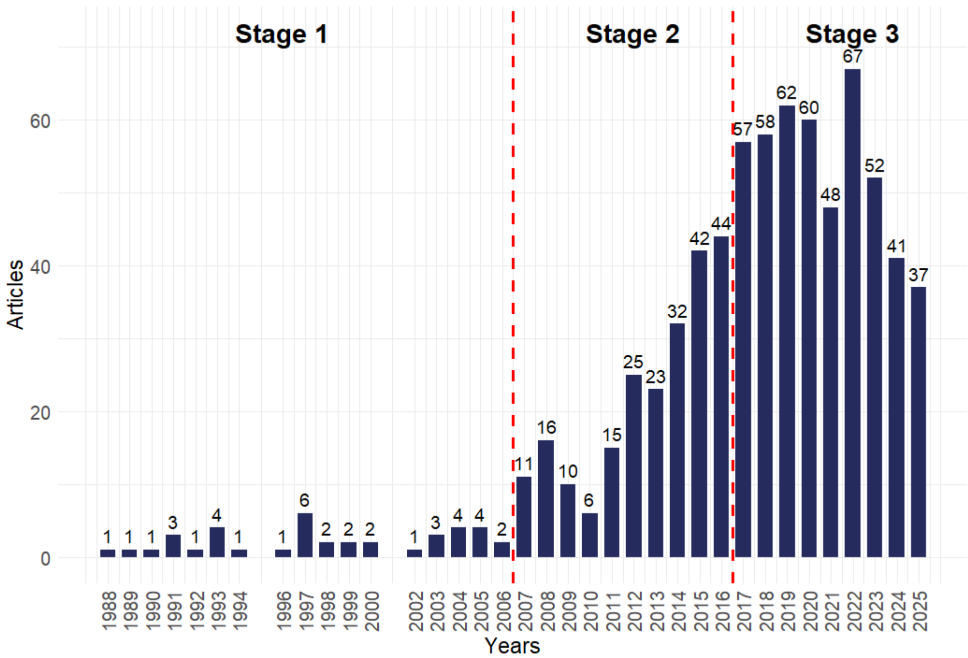

Figure 2. Evolution of publications over time, divided into three stages

4 Results

4.1 Bibliometric Analysis

4.1.1 Analysis of the annual evolution of scientific publications

Scientific output was analyzed from 1988 to 2025, covering a total of 745 articles. Figure 2 illustrates the annual rate of scientific production, divided into three stages, which consider changes in the number of publications, reaching a participation of 2745 authors. In the first stage from 1988 to 2006, there was no significant growth in the number of scientific publications, with a total of 39 publications, reflecting exploratory research focused on the production of biosurfactants by different bacterial strains [42], the characterization of biosurfactants [43], and the evaluation of the physicochemical properties of biosurfactants [44]. In the second stage, 224 articles were published, representing an increase of 574% compared to the 39 articles published in the previous 19 years. In this second stage, significant advances were made in research on biosurfactants for EOR, for example, studies reported the combination of biosurfactants and nanoparticles [45], the use of micromodels and pore-scale imaging techniques to visualize crude oil mobilization mechanisms [20], the implementation of genetic engineering to optimize biosurfactant synthesis [46], and the application of advanced statistical and mathematical techniques, such as Response Surface Methodology (RSM), Plackett-Burman designs [47], and the Taguchi method [48], to optimize biosurfactant production. The third stage was characterized by a rapid and sustained increase in scientific production, which indicates growing interest in ecological, sustainable, and efficient alternatives for enhanced oil recovery in recent years [49]. In the last nine years, the most significant number of publications was recorded, with 568, representing 76% of all publications. At this stage, Physics-Informed Machine Learning (PIML) was reported to optimize the selection of microorganisms and nutrients and predict oil recovery from limited experimental data [50].

4.1.2 Scientific contribution by country

Research on biosurfactants in enhanced oil recovery involves 48 countries worldwide, according to the results of the bibliographic coupling. Among them, China, India, and Iran stand out as leaders in scientific output, with 206, 131, and 80 publications, respectively, representing approximately 57% in total production (Figure 3). China, with 28,18% of total publications, leads both in research and implementation of MEOR, as it has been a leader in the successful implementation of this method in recent decades [26]. India and Iran rank second and third with 17,92% and 10,94% of publications, respectively.

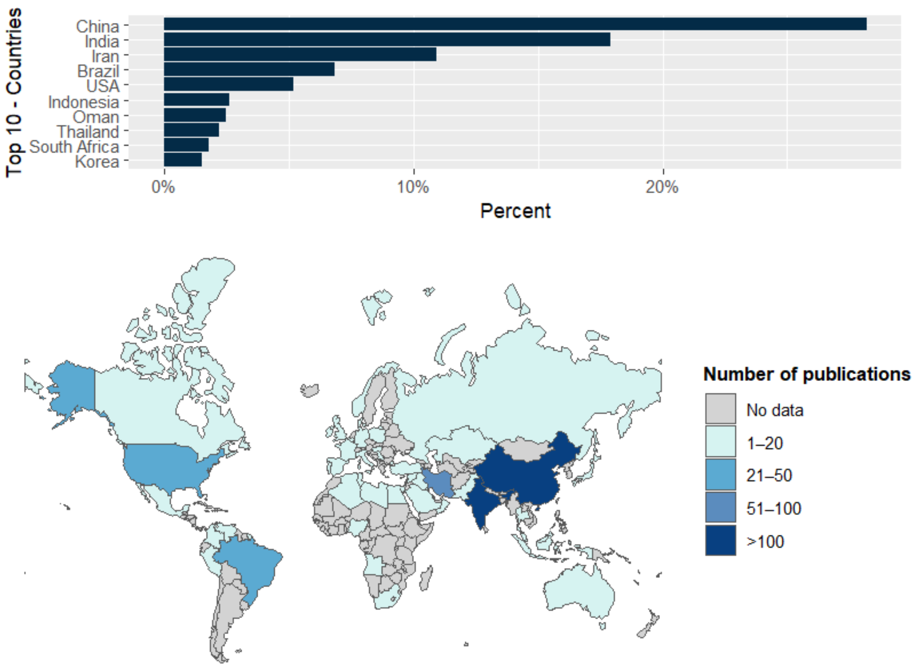

Figure 3. Distribution of the number of scientific publications by country on research into biosurfactants in EOR (1988-2025)

4.1.3 Keyword co-occurrence analysis

In the co-occurrence analysis of keywords in VOSviewer, a minimum occurrence threshold of six terms was established, and four distinct color clusters were identified in the co-occurrence map shown in Figure 4.

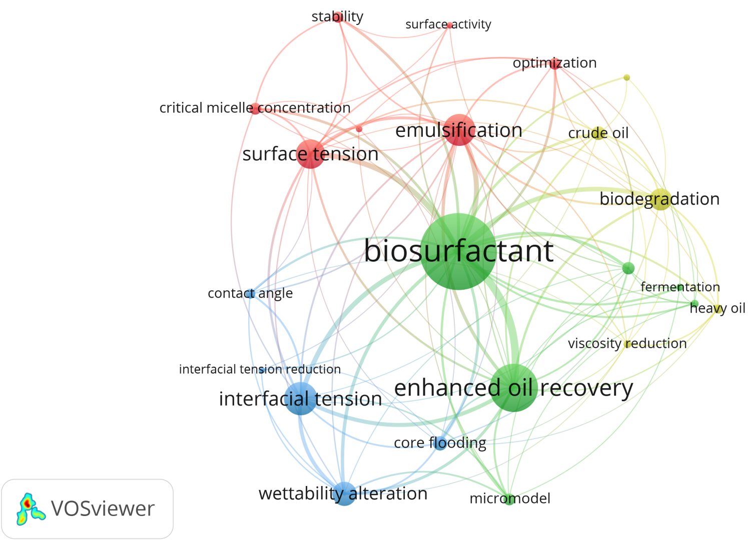

Figure 4. Bibliometric map of keyword co-occurrence for the author, with four clusters

Cluster 1. Properties of biosurfactants (red): This cluster groups together seven terms, with "emulsification" being the most frequent, appearing 54 times. This cluster is linked to research on the stability of biosurfactants [17], surface activity [51], and critical micelle concentration [52], key parameters that determine the efficiency of biosurfactants.

Cluster 2. Production and application of biosurfactants (green): This cluster groups together six terms and presents topics related to fermentation processes [53] for the production of biosurfactants, as well as studies that use response surface methodologies [54] to optimize production and reduce costs. This cluster includes research that uses micromodels [55] as representative systems of porous media.

Cluster 3. Physicochemical mechanisms (blue): This cluster groups together five terms and relates to research on the mechanisms of action of biosurfactants. The reduction of interfacial tension, with 61 occurrences, is the central theme [56], accompanied by studies on the alteration of rock wettability [57] and core flooding experiments to evaluate the performance of biosurfactants in oil recovery [27].

Cluster 4. Biodegradation of heavy crude oil (yellow): This cluster groups together five terms, with "biodegradation" being the most frequent, occurring 40 times. The yellow cluster reveals that biodegradation is directly associated with viscosity reduction in heavy crude oils, where microorganisms degrade hydrocarbons to produce biosurfactants [58, 59].

4.2 Systematic Review

Table 1. Biosurfactants applied in enhanced oil recovery

Microorganism / Biosurfactant	Type of Test	Experimental Conditions	EOR (%)	EOR Mechanisms	Reference
Bacillus licheniformis / Surfactin	Core flooding	T = 80°C; P = 20 MPa	19.58	Reduction of interfacial tension; Alteration of wettability	[60]
Pseudomonas aeruginosa / Ramolipid	Sand-packed column	T = 80°C	15.47	Reduction of interfacial tension	[61]
Bacillus subtilis / Surfactin	Core flooding	T = 55°C	5.66	Surface tension reduction	[51]
Bacillus subtilis / Surfactin	Core flooding	T = 55°C	18.7	Reduction of surface tension; Reduction of interfacial tension; Alteration of wettability	[57]
Pseudomonas aeruginosa / Ramolipid	Core flooding	T = 55°C	15.45	Surface tension reduction; Emulsification; Alteration of wettability	[62]
Brevibacillus borstelensis / Fengicin	Core flooding	T = 30°C	11.8	Reduction of interfacial tension; Emulsification	[63]
Bacillus licheniformis / Lipopeptide	Core flooding	T = 50°C	5.4	Reduction of interfacial tension	[17]

Twenty-seven articles published between 2019 and 2024 were selected, developed in laboratory settings, with core flooding tests being the most frequent (19 studies), followed by experiments in packed sand columns (5 studies), and injection tests in micro-models (3 studies). In addition, field tests were reported. The results of all articles included in this review were compiled and are detailed in Table S1. As a representative subset, Table 1 summarizes the reported microorganisms, biosurfactants, experimental conditions, mechanisms of action, and recovery efficiencies. Overall, the data show that the effectiveness of the process depends critically on the type of biosurfactant, the mechanisms involved, and the specific operating conditions.

Among the microorganisms used for biosurfactant production, the genera *Pseudomonas* and *Bacillus* stand out due to their higher frequency in the reviewed studies (Table S1). Consequently, the predominant biosurfactants in the studies were rhamnolipids (37% of studies) and surfactins (26% of studies), reflecting their importance as key compounds in MEOR processes. Various factors influence the production efficiency of these compounds, including the type of microorganism used and the composition of the culture medium. Twenty studies reported the production of biosurfactants, highlighting the use of glucose [64–66], sucrose [51, 60], and yeast extract [17, 67] as the most used substrates in culture media. The use of inexpensive substrates such as vegetable oils [54, 68] and organic waste [69] has also been reported.

The results summarized in Table 1 show the relationship between the reported EOR mechanisms and oil recovery efficiency. Biosurfactants that act simultaneously on multiple mechanisms (interfacial tension reduction + wettability alteration) [57, 60] achieve efficiencies of 18,7% and 19,58%, generally outperforming those that only reduce surface or interfacial tension in isolation [17, 51, 61], suggesting that synergy between mechanisms is an essential factor in maximizing recovery.

Delving deeper into their interfacial behavior, various studies have evaluated the ability of biosurfactants to reduce the IFT between water and oil. Sakthipriya et al. [61] documented a CMC of 30 mg/L, with which the water-oil IFT was reduced from its initial value of 29 mN/m to 21,7 mN/m. Other studies have reported that the efficiency of biosurfactants can be improved by combining them with chemical surfactants [70], silica nanoparticles [71], biopolymers [69], or green surfactants [72]. In the latter case, the combination with lecithin allowed ultra-low IFT values 0,0189 mN/m to be achieved, which was reflected in good performance in oil recovery.

The influence of biosurfactants on wettability was evaluated by measuring the contact angle. The results of six studies showed a consistent reduction in the contact angle, with final values between 42° and 24°, indicating an effective change in the wettability of the rock. For example, in the study by Feng et al. [62], it was observed that the contact angle decreased from 105,23° to 24,99° after the application of a rhamnolipid fermentation broth. This reduction of approximately 76% reflects a clear transition from a rock initially wet with oil to one with a marked preference for water. Furthermore, this study highlights the application of genetic engineering to improve the yield of rhamnolipid production.

The stability of biosurfactants is another key factor for their application in EOR. Various studies have demonstrated their tolerance to high temperatures and salt concentrations of up to 10% (w/v) NaCl [51, 54, 57, 67], as well as pH ranges from 4 to 10 [60].

To evaluate the relative efficiency of biosurfactants, several studies compared them with synthetic surfactants under the same experimental conditions. Paul et al. [73] reported a 44,3% oil recovery with crude biosurfactant, comparable to the 49,85% obtained with Tween 80. Sakthipriya et al. [61] evaluated surfactin and rhamnolipid against sodium dodecyl sulfate (SDS) and cetyltrimethylammonium bromide (CTAB). The results showed that biosurfactants increased oil recovery by 15,43% and 15,47%, respectively, while SDS and CTAB achieved improvements of 8,82% and 7%.

Studies such as those by Kapse et al. [74], Okoro et al. [75], and Wang et al. [76] conducted core flooding trials using the injection of microorganisms for the in situ production of biosurfactants. On a larger scale, two studies [77, 78], documented field trials involving the injection of water enriched with microbial consortia to promote the in situ production of biosurfactants and other metabolites. The results obtained were satisfactory, although limited by the reduced control over the experimental variables. Kang et al. [78] evaluated the injection of a consortium of *Pseudomonas aeruginosa* and *Bacillus subtilis* into a low-permeability reservoir, resulting in a cumulative increase of 3,250 tons over 10 months. This increase in recovery was attributed not only to the mechanisms of action of the biosurfactants produced but also to the ability of the microbial communities in the reservoir to degrade hydrocarbons and metabolize methane, thus contributing to recovery. They also reported that production returned to its previous levels six months after the injection was suspended, indicating a temporary effect.

5 Discussion

Research into biosurfactants in EOR dates back more than three decades to 1988, with the first documented record in Scopus. Scientific output in this field has increased significantly since 2015, accounting for 76% of total publications. This increase can be attributed both to advances in biotechnological techniques that have made it possible to optimize the sustainable production of biosurfactants at a lower cost through the use of inexpensive substrates [79], and to the global adoption of the 2030 Agenda for Sustainable Development Goals (SDGs) [80, 81], which has encouraged the oil industry to seek alternatives in line with the aforementioned goals. The participation of 2745 authors from 48 countries suggests strong international collaboration, highlighting the participation of China, India, and Iran as the countries with the highest number of publications. In the case of China, this prominence is backed by state investment in research and development (R&D) in both energy innovation in oil and gas [82] and biotechnology [83]. India in its effort to strengthen its energy security and reduce its dependence on crude oil imports, is promoting research and application of EOR techniques in mature fields [84, 85]. Co-occurrence analysis reveals a thematic structure representing the main lines of research on biosurfactants in EOR. Although the clusters have been divided into specific groups for general analysis, they are not studied in isolation, as the properties (cluster 1) and mechanisms (cluster 3) presented are interdependent and act synergistically in real oil recovery applications. Overall, the 27 studies included in the systematic review indicate a preference for the use of *Pseudomonas* and *Bacillus* in biosurfactant production, which aligns with previous reviews that highlight rhamnolipids and surfactins as the most extensively studied biosurfactants with the most significant potential in MEOR processes [86]. However, the intense concentration of studies in these genera suggests the need to explore other microbial sources with biotechnological potential that have yet to be fully evaluated. The effectiveness of biosurfactants in EOR is based on their ability to: (i) reduce the interfacial tension between water and oil, promoting the mobilization of trapped crude oil; (ii) modify the wettability of the rock to conditions more favorable for production; (iii) form stable emulsions that improve hydrocarbon transport; and (iv) maintain their stability in the face of variations in temperature, salinity, and pH typical of oil reservoirs. In addition, emerging strategies such as the use of genetic engineering to optimize biosurfactant production and the combination with biopolymers, nanoparticles, or green surfactants reinforce these effects, pointing toward hybrid solutions with greater efficiency and sustainability.

On the other hand, comparative studies with synthetic surfactants indicate that biosurfactants can be competitive or superior in terms of recovery. This evidence is relevant when considering that, in addition to their effectiveness, biosurfactants offer additional advantages in terms of biodegradability and lower toxicity [87]. Although biosurfactants offer environmental and functional advantages over synthetic surfactants, their large-scale production faces challenges related to the use of suitable substrates, optimization of the fermentation process, recovery, separation, and purification, which can account for between 60% and 70% of the total cost [73, 88]. In addition, comparative life cycle assessments (LCA) indicate that the production of biosurfactants has a lower environmental impact than that associated with synthetic surfactants [89]. However, it has also been shown that, within their own production process, the main contributors to this impact are mainly associated with raw material inputs and the energy required in fermentation processes [90].

Finally, in terms of their production and application in EOR, biosurfactants can be produced either in situ or ex situ, which differ in terms of efficiency and cost. In terms of efficiency, Shabani et al. [91] report that the yield of biosurfactants produced in situ is limited because they do not reach the required critical micelle concentrations. This can be attributed both to microbial competition with the native microbial community at the site and to environmental factors such as salinity, temperature, and pH. In contrast, biosurfactants produced ex situ can be injected with the optimal CMC to achieve maximum reduction in IFT. Although most studies included in the systematic review report promising additional recovery efficiencies following the injection of biosurfactants, a gap remains between the results obtained in the laboratory and their application at the field scale. This limitation is associated not only with the processes of production, purification, transport, and injection, which increase the costs and complexity of operational logistics [92], but also with the heterogeneity of the reservoirs, which affects the distribution and mobility of biosurfactants as they move through the porous medium [93]. Consequently, implementations reported at the field level or in pilot tests have primarily focused on in situ approaches rather than the direct injection of biosurfactants produced ex situ [14].

6 Conclusions

Research on biosurfactants in enhanced oil recovery has experienced sustained growth for more than three decades. This growth reflects a transition from exploratory approaches to multidisciplinary research that integrates advances in nanotechnology, genetic engineering, and machine learning to optimize the production and application of biosurfactants in EOR. This demonstrates the consolidation of the field and growing collaboration among numerous authors globally.

The results show that China, India, and Iran lead scientific production in this field, accounting for approximately 57% of global publications. This dominance can be explained by substantial state investment in research and development, aimed at both energy innovation in oil and gas and biotechnological advances that encourage the exploration of sustainable methods. In relation to the most studied microorganisms and biosurfactants, it was identified that the genera *Pseudomonas* and *Bacillus* are the most widely used, with the production and use of rhamnolipids and surfactins as predominant compounds standing out. It was also determined that combining biosurfactants with chemical surfactants, nanoparticles, and biopolymers significantly improves recovery efficiency.

Much of the existing literature has focused on experimental studies or reviews with specific scopes, which limited a comprehensive view of the field. The combination of bibliometric analysis with a systematic review made it possible to consolidate this information by managing all the knowledge generated in this field and highlighting the state of technological maturity and its applications in EOR. This work contributes to scientific progress in the field by deepening our understanding of the behavior of biosurfactants in EOR processes, their mechanisms of action, stability, and synergies with other recovery agents to improve their performance. This research highlights the growing preference for ex situ MEOR approaches and their efficiency in the laboratory, facilitating the translation of scientific advances into field applications.

Looking ahead, it is essential to continue promoting rigorous collaborative research that consolidates the advances made and explores new multidisciplinary collaborations and EOR process optimization techniques to accelerate the transition toward cleaner, more sustainable energy technologies. It is recommended that research on biosurfactants in EOR include standardized testing protocols to facilitate comparison of results between studies, pilot studies to evaluate their scalability and efficiency under controlled conditions that simulate the reservoir, and finally, long-term field studies to validate the performance and stability of biosurfactants under actual operating conditions. It is recommended that research on biosurfactants in EOR include standardized testing protocols to facilitate comparison of results between studies. In addition, long-term field studies should be conducted to validate the performance and stability of biosurfactants under actual reservoir conditions. Furthermore, the integration of digital technologies such as artificial intelligence, machine learning, and digital twins can optimize experimental design, predict the behavior of biosurfactants, and improve the planning of injection strategies.

Limitations of this study include the specific use of the Scopus and WoS databases, which may have excluded relevant publications indexed in other databases. Furthermore, limiting the analysis to articles in English may have excluded relevant studies published in languages other than English. Another limitation of this study is the restricted availability of information on field tests for biosurfactant injection. Much of this data is found in technical reports from oil companies, regulatory documents, and pilot projects from government agencies, which are not publicly accessible.

Author Contributions

Conceptualization, H.S.-M., J.S. and P.C.-M.; methodology, H.S.-M., J.S. and P.C.-M.; software, H.S-M.; validation, H.S.-M., J.S. and P.C.-M.; formal analysis, H.S.-M., J.S. and P.C.-M.; investigation, H.S.-M.; resources, H.S.-M., J.S. and P.C.-M.; data curation, H.S.-M.; writing-original draft preparation, H.S.-M., J.S. and P.C.-M.; writing-review and editing, H.S.-M., J.S. and P.C.-M.; visualization, H.S.-M. and J.S.; supervision, P.C.-M.; project administration, H.S.-M., J.S. and P.C.-M.; funding acquisition, J.S. and P.C.-M. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Appendix

Table S1. Biosurfactants, producing microorganisms, test conditions, and their respective recovery mechanisms [86]

Microorganism / Biosurfactant	Type of Test	Experimental Conditions	EOR (%)	EOR Mechanisms	Reference
Bacillus licheniformis / Surfactin	Core flooding	T = 80 °C; P = 20 MPa	19,58	Reduction of interfacial tension; Alteration of wettability	[60]
Pseudomonas aeruginosa / Ramolinid	Sand-packed column	T = 80°C	15,47	Reduction of interfacial tension	[61]
Bacillus subtilis / Surfactin	Core flooding	T = 55°C	5,66	Surface tension reduction	[51]
Bacillus subtilis / Surfactin	Core flooding	T = 55°C	18,7	Reduction of surface tension; Reduction of interfacial tension; Alteration of wettability	[57]
Pseudomonas aeruginosa / Ramolipid	Core flooding	T = 55°C	15,45	Surface tension reduction; Emulsification; Alteration of wettability	[62]
Brevibacillus borstelensis / Fengicin	Core flooding	T = 30°C	11,8	Reduction of interfacial tension; Emulsification	[63]
Bacillus licheniformis / Lipopeptide	Core flooding	T = 50°C	5,4	Reduction of interfacial tension	[17]
Pseudomonas mendocina / Glyscolinids and linopentides	Sand-packed column		44,3	Emulsification; surface tension reduction	[73]
Bacillus safensis / Pumilacidina	Core flooding		12,7	Reduction of interfacial tension	[52]
Pseudomonas aeruginosa / Ramolinid + Chitosan	Sand-packed column		34,28		[69]
Pseudoxanthomonos sp. / Silvcolinids	Sand-packed colunn		20	Interfacial tension reduction; high emulsifying activity	[67]
Thermococcus petroberoxtus sp. nox	Core flooding	T = 96°C; P = 900 psi	29,5		[74]
Pseudomonas qerpojuasg and Bacilluc subtilis	micromodel flooding		94,48	Interfacial tension reduction	[78]
Gondonia quicalis and Rhodosescuse enathronolis,	Core flooding	T = 24°C; P = 8 MPa	53		[77]
Pseudomonas sp. / Ramolipid	Core flooding	T = 27°C	28,7	Interfacial tension reduction	[68]
Bacillus licheniformis / Surfactin complex	Core flooding	T = 55°C; P = 350 psi	59,21	Reduction of interfacial tension; Alteration of wettability	[66]
Pseudomonas sz / Ramolipid	Core flooding	T = 70°C	16,7	Reduction of interfacial tension; Alteration of wettability	[65]
Pseudomonas geruginosa / Ramnolinids + silica nanopanticles	Core flooding		26,1	Reduction of interfacial tension; Alteration of wettability	[71]
Bacillus subtilis / Surfactin + schizophyllan	Core flooding	T = 50°C	32	Interfacial tension reduction	[64]
- / ramnolinids + lecithin	Core flooding	T = 52°C; P = 1050 psi	24	Interfacial tension reduction	[72]
Bacillus subtilis/alkaline-polymer	Core flooding		13,31	Interfacial tension reduction	[76]
Bacillus amelolious facisens	Core flooding	T = 27°C; P = 3 MPa	46,4		[75]
Bacillus subtilis	micromodel flooding		19,4		[55]
Pseudomonas aeruginosa/ramnolipid + toctulphenoxymolvethoxyethanol	Core flooding	T = 60°C	66,07	Reduction of interfacial tension; Alteration of wettability	[70]
Pseudomonas aeruginosa / Ramolinid	micromodel flooding		43	Reduction of interfacial tension; Alteration of wettability	[54]
Bacillus subtilis / Surfactin	Sand-packed column	T=39°C	16,7	Interfacial tension reduction	[94]
Pseudomonas / Ramolipid	Core flooding		10,18		[95]