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Review

Nanotechnology Impact on Chemical-Enhanced Oil Recovery: A Review and Bibliometric Analysis of Recent Developments

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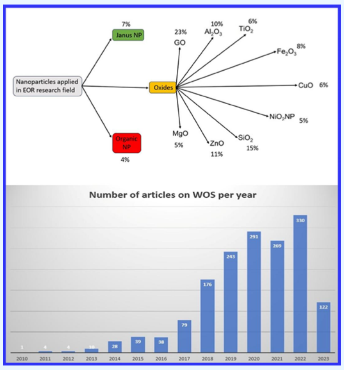

ABSTRACT: Oil and gas are only two industries that could change because of nanotechnology, a rapidly growing field. The chemical-enhanced oil recovery (CEOR) method uses chemicals to accelerate oil flow from reservoirs. New and enhanced CEOR compounds that are more efficient and eco-friendly can be created using nanotechnology. One of the main research areas is creating novel nanomaterials that can transfer EOR chemicals to the reservoir more effectively. It was creating nanoparticles that can be used to change the viscosity and surface tension of reservoir fluids and constructing nanoparticles that can be utilized to improve the efficiency of the EOR compounds that are already in use. The assessment also identifies some difficulties that must be overcome before nanotechnology-based EOR can become widely used in industry. These difficulties include the requirement for creating mass-producible, cost-effective nanomaterials. There is a need to create strategies for supplying nanomaterials to the reservoir without endangering the formation of the reservoir. The requirement is to evaluate the environmental effects of CEOR compounds based on nanotechnology. The advantages of nanotechnology-based EOR are substantial despite the difficulties. Nanotechnology could make oil production more effective, profitable, and less environmentally harmful. An extensive overview of the most current advancements in nanotechnology-based EOR is provided in this paper. It is a useful resource for researchers and business people interested in this area. This review's analysis of current advancements in nanotechnology-based EOR shows that this area is attracting more and more attention. There have been a lot more publications on this subject in recent years, and a lot of research is being done on many facets of nanotechnology-based EOR. The scientometric investigation discovered serious inadequacies in earlier studies on adopting EOR and its potential benefits for a sustainable future. Research partnerships, joint ventures, and cutting-edge technology that consider assessing current changes and advances in oil output can all benefit from the results of our scientometric analysis.

1. INTRODUCTION

Primary, secondary, and tertiary oil recovery stages are distinct.[1] Natural displacement energy in reservoirs, such as solution-gas drive, gas-cap drive, natural water drive, and so on, results in primary production.[2] Water flooding and gas injection are secondary recovery procedures. Tertiary oil recovery, often known as enhanced oil recovery (EOR), is a chemical injection method. It can extract 30 to 60% or more of a reservoir's oil, compared to the 20 to 40% achieved by employing primary and secondary recovery.[3]

In the first stage, producing hydrocarbons by natural energy is the primary recovery mechanism. Only a reservoir with internal energy allows the oil to flow toward production wells. This natural energy includes the following drives: 1, gas-cap drive; 2, solution-gas drives; 3, water drive; and 4, rock expansion and gravity drainage, which push the oil upward. This phase also comprises an artificial lift process using the gas lift that enhances oil rising from the wellbore to the surface. The recovery factor of this stage is still low, so oil production improvement through the other methods (secondary and tertiary) is still required. Primary recovery only recovers about ten percent of the oil in place.

Secondary recovery is a technique that yields oil from a reservoir through natural flow and artificial lift operations. The secondary recovery stage is conducted if the reservoir does not have enough energy to maintain production and needs additional energy. The external energy from the surface can be an injection of gas or water, which sustains the pressure of the reservoir and pushes oil in the direction of producer wells. Water is highly available and inexpensive, so water injection is generally the more applicable technique in the secondary stage. The recovery increase can extend from thirty-five percent to 50 percent of the oil in place (OOIP). However, considerable

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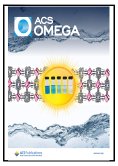

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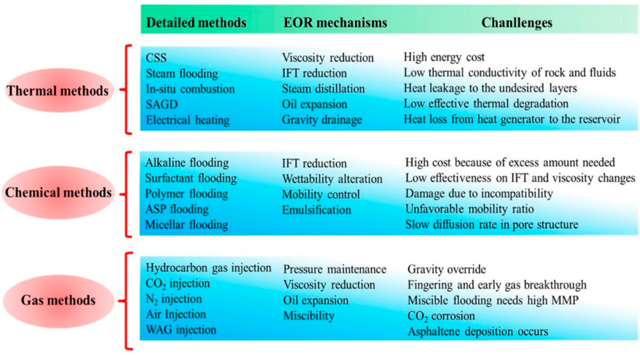
amounts of oil are trapped in the reservoir due to high capillary forces even after a long-term water flooding operation.[4]

After primary and secondary recovery, tertiary recovery (or enhanced oil recovery) reduces residual oil saturation, as shown in Figure 1. Approximately 60−70% of the oil in place cannot be produced by conventional methods.[5] EOR methods are gaining importance, particularly considering the limited worldwide crude oil resources. EOR procedures can involve chemical and gas floods, steam, combustion, electric heating, etc. Gas floods, which can include immiscible and miscible processes, are often described by the fluids injected into the reservoir (carbon dioxide, flue gas, nitrogen, or hydrocarbon). "Huff and puff" refers to the cyclic steam used in steam projects.[6]



	Detailed methods	EOR mechanisms	Chanllenges
Thermal methods	CSS Steam flooding In-situ combustion SAGD Electrical heating	Viscosity reduction IFT reduction Steam distillation Oil expansion Gravity drainage	High energy cost Low thermal conductivity of rock and fluids Heat leakage to the undesired layers Low effective thermal degradation Heat loss from heat generator to the reservoir
Chemical methods	Alkaline flooding Surfactant flooding Polymer flooding ASP flooding Micellar flooding	IFT reduction Wettability alteration Mobility control Emulsification	High cost because of excess amount needed Low effectiveness on IFT and viscosity changes Damage due to incompatibility Unfavorable mobility ratio Slow diffusion rate in pore structure
Gas methods	Hydrocarbon gas injection CO_2 injection N_2 injection Air Injection WAG injection	Pressure maintenance Viscosity reduction Oil expansion Miscibility	Gravity override Fingering and early gas breakthrough Miscible flooding needs high MMP CO_2 corrosion Asphaltene deposition occurs

Figure 1. EOR technologies.[10]

New technologies use different materials and processes during tertiary oil recovery, including the following four types: carbon dioxide injection, natural gas miscible injection, surfactant injection, and steam recovery.[7,8]

The injection of miscible gas can enhance oil production by recovering reservoir pressure, decreasing the interfacial tension between the displacing gas and oil, and increasing the displacement and microscopic efficiency.[9]

Commonly, thermal methods use a variety of ways to heat heavy oil reservoirs, such as cyclic steam stimulation (CSS), steam flooding, and steam-assisted gravity drainage (SAGD). Viscosity and density can be changed by improving the reservoirs' heavy oil or bitumen flow. Gases can be the hydrocarbon gases (CH_4, C_3H_8, or natural gas) or non-hydrocarbon gases (N_2 or CO_2) found in the oil. By making the oil less viscous and increasing the volume of the oil, the injected gas can help to extract more oil. These methods mostly use polymers, long-chained molecules that can help improve water flood, or detergent-like surfactants that help lower IFT,[10] often stopping oil droplets from moving through a reservoir.[7]

In the past, three different EOR techniques (thermal, gas injection, and chemical injection) were used and proven to improve hydrocarbon recovery significantly. New technologies include microbial and low-salinity flooding. Since nanoparticles can enter the pore throat and alter the reservoir's characteristics to promote oil recovery, they have been proposed as a promising EOR technique in recent years.[10] In accordance with the latest technology, nanomaterial-enhanced oil recovery can be thermal or chemical.[11] Future investigation is required to ascertain how temperature and pressure affect the functionality of these nanoparticles.

This review intends to incorporate an evaluation of recent changes and improvements for enhancing oil output, particularly chemical flooding. Nanomaterials are classified into several types based on whether natural or synthetic, with an explanation of the mechanism of action of these materials during the process of EOR in addition to clarification regarding their future use and the challenges they face.

The review also collects, synthesizes, and analyzes available research on enhanced oil recovery (EOR), which is critical to enhancing oil production, conducts a scientometric review of the bibliometric data, and highlights the evolution, present trends, patterns, and future lines. All types of nanomaterial used in improving oil production are listed in detail. Scientometric evaluation provides objective criteria for evaluating the work done by researchers and the macroscopic view of a large amount of research documents. By incorporating a deep understanding of these contributions and offering a critical perspective, this tool resolves the challenges of manual review studies to gather relevant and objective information for future research. As a result, this study significantly contributes to the body of information already in existence by highlighting the research field's trends and patterns, delineating its research themes, outlining researcher networks, and suggesting areas for further investigation.

This review article deals with modern modifications and additions for improving oil production, especially chemical flooding. Nanomaterials fall into various categories depending on their natural or synthetic sources. All types of nanomaterial used in improving oil production are listed, with an explanation of the mechanism of action of these materials during the process of EOR, in addition to clarification regarding their future use and the challenges they face. Existing EOR methods have several limitations, including the following. (i) Inefficiency: Many EOR methods are inefficient, leaving significant oil in the reservoir. For example, thermal EOR methods, such as steam flooding, can only recover about 5−10% of the remaining oil. (ii) High cost: EOR methods can be expensive, especially compared to conventional oil production methods. For example, chemical EOR methods can cost upward of $100 per barrel of oil. (iii) Environmental impact: Some EOR methods can have a negative impact on the environment. For example, thermal EOR methods can produce greenhouse gases, and chemical EOR methods can pollute groundwater.

1.1. How Nanotechnology Aims to Address These Limitations.

Nanotechnology has the potential to address many of the limitations of existing EOR methods. For example, nanoparticles can be used to (i) Improve the efficiency of EOR methods: Nanoparticles can be used to create more effective surfactants, which can help to mobilize trapped oil. Nanoparticles can also create more stable emulsions, which can help transport oil through the reservoir. (ii) Reduce the cost of EOR methods: Nanoparticles can be used to develop more efficient EOR processes, reducing the overall cost of oil production. (iii) Minimize the environmental impact of EOR methods: Nanoparticles can be used to develop more environmentally friendly EOR methods. For example, nanoparticles can be used to create biodegradable surfactants and to encapsulate harmful chemicals.[12,13]

2. NANOTECHNOLOGY AND ENHANCED OIL RECOVERY

Nanotechnology is the science of materials arranged in very close to molecular dimensions (1−100 nm). Many scientific aspects have changed our perspective and have shown new paths for old problems that remained unsolved through previous technologies.[14−16] Because of their small size, nanoparticles (NPs) have new chemical and novel properties compared to their bulk counterparts. These properties include (a) higher sorption capacity; (b) optical properties [transparency (e.g., copper) and color change (e.g., gold)]; (c) greater chemical reactivity (catalysis), e.g., platinum; (d) electrical/electronic properties (conductivity), e.g., silicone; (e) thermal properties [faster cooling, enhanced thermal properties (heat transfer, insulation)]; and (f) mechanical properties (ultrahigh strength).[17] Electronics, cosmetics, medicinal and pharmaceutical sciences, energy technology, catalytic and material applications, and environmental remediation benefit from their particular features.[18−20] However, the following distinctive nanoscale features may be relevant in production engineering:[21] A higher surface-to-volume ratio means more activity and contact. Electron or positive charge confinement changes elements of the material structure: the dielectric constant, conductivity, optical characteristics, chemical, electronic, etc.

Surfaces treated chemically experience wettability alteration at the nanoscale. Reservoir engineering received the greatest attention for nanotechnology applications because nanotechnology provides a means to enhance the rheological properties of liquids at ambient and elevated temperatures despite the adverse effects identified in certain concentrations of nanoparticles.[22,23] Figure 2 shows the considerable number of scientific articles published in this sector, even during the petroleum industry's downturn.[24−30]

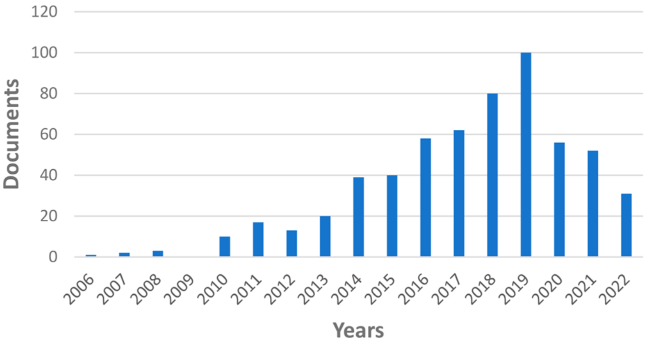


Figure 2. Nanotechnology application research in the petroleum industry.[31,32]

Nanotechnology has the potential to play a significant role in enhanced oil recovery. However, there are still a number of challenges that need to be addressed before nanotechnology can be widely deployed in the field. One of the biggest challenges is developing scalable and economical nanoparticle production methods. Another challenge understands the interactions between nanoparticles and reservoir rocks and fluids.

Despite these challenges, nanotechnology is a promising technology for enhanced oil recovery. With continued research and development, nanotechnology has the potential to help us produce more oil from existing reservoirs and extend. A number of standards are required to characterize nanoparticles for EOR applications. These standards include the following. (i) Size distribution: The size distribution of nanoparticles is important to ensure they can be effectively transported through the reservoir and interact with the rock and oil. The size distribution of nanoparticles can be measured using various techniques, such as dynamic light scattering and laser diffraction. (ii) Surface chemistry: The surface chemistry of nanoparticles can affect their interaction with the rock and oil. The surface chemistry of nanoparticles can be characterized using various techniques, such as X-ray photoelectron and Fourier transform infrared spectroscopy. (iii) Stability: Nanoparticles need to be stable in the reservoir environment to be effective. The stability of nanoparticles can be characterized using various techniques, such as zeta potential and turbidity measurements.[33,34]

2.1. Reversible Nanofluid-Rock Interactions. Nanofluid-rock interactions can be reversible, meaning the nanoparticles can be attached to and detached from the rock surface. The reversibility of nanofluid-rock interactions can impact injectivity on cycling, as nanoparticles attached to the rock surface can reduce the permeability of the reservoir. The reversibility of nanofluid-rock interactions depends on a number of factors, including the size and surface chemistry of the nanoparticles, the composition of the reservoir rock, and the reservoir fluids.[35]

2.2. Scalable and Economic Nanoparticle Production Methods. Scalable and economical nanoparticle production methods need to be developed for field use. Several nanoparticle production methods are currently being used in the laboratory, but these methods are not yet scalable to field applications. One promising approach to scalable and economic nanoparticle production is flow synthesis methods. Flow synthesis methods allow for continuously producing nanoparticles with high precision and control.[36,37]

2.3. Comparative Advantages/Disadvantages of Different Nanoparticle Types. Different nanoparticle types have different advantages and disadvantages for EOR applications. The most common nanoparticle types used for EOR are metal oxides, silica, and polymers. Metal oxides, such as iron oxide and aluminum oxide, are effective at mobilizing trapped oil and reducing interfacial tension. However, metal oxides can be expensive and interact with the reservoir rock, reducing injectivity. Silica nanoparticles are also effective at mobilizing trapped oil and reducing interfacial tension. Silica nanoparticles are relatively inexpensive and less likely to interact with the reservoir rock than metal oxides. However, silica nanoparticles can be less stable than metal oxides in the reservoir environment. Polymer nanoparticles can be used to improve the stability of emulsions and to reduce the viscosity of oil. However, polymer nanoparticles can be expensive and interact with the reservoir rock, reducing injectivity.[38,39]

2.3.1. Iron Oxide Nanoparticles (Fe_2O_3/Fe_3O_4NPs). Iron oxide's magnetic and electrical qualities make it helpful in magnetic and electrical fields such as data storage, sensors, and imaging.[40] It was found that iron oxide NPs could only achieve 57% ultimate recovery, whereas other NPs could achieve 85%.[41] Others demonstrated that dispersed iron oxide NPs in water could enhance recovery by up to 24% (additional).[42] They can raise the displacing fluid's viscosity, increasing sweep efficiency, but ethanol has little effect. However, the chosen dispersal agent was spontaneous imbibition in sandstone rocks. Iron oxide nanoparticles work mostly by lowering the viscosity. They can be a good choice for EOR because they have been used in cases where the total amount of oil was recovered 82.5% of the time, which is a good percentage.[43]

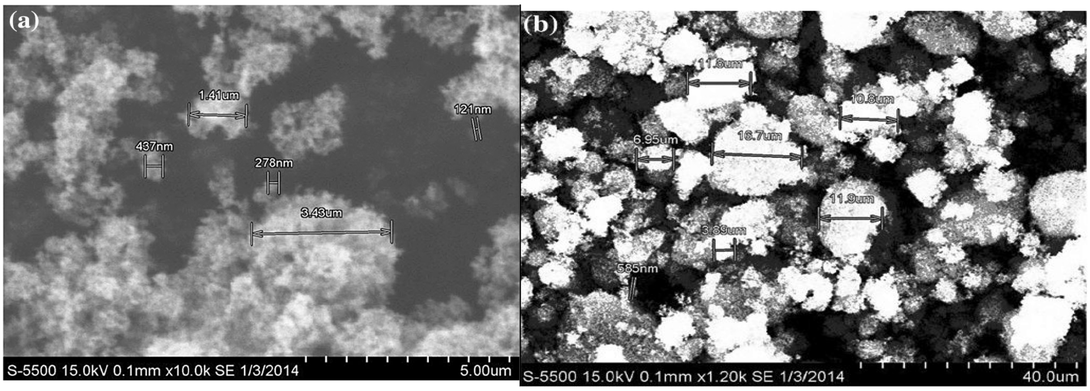


Figure 3. (a) TiO_2 and (b) SiO_2 NPs according to SEM analysis.[47]

2.3.2. Nickel Oxide Nanoparticles (Ni_2O_3 NPs). Hydrophilic nickel oxide (Ni_2O_3), like Al_2O_3, can be an effective EOR agent for heavy oil recovery.[44] When nickel oxide nanoparticles (NPs) are introduced into sandstone cores following water flooding, they boost oil recovery.[45] Using Ni_2O_3 NPs in core flooding can increase the displacing fluid's viscosity while decreasing the displaced oil's viscosity.

2.3.3. Titanium Dioxide Nanoparticles (TiO_2 NPs). Of the oil in oil-wet sandstone, 80% could be recovered by an EOR process using water flooding tests with TiO_2 nanoparticles.[46] This percentage was only 49% in the absence of these nanoparticles. Measurements of the contact angle showed that TiO_2 NPs can change the wettability of the sandstone cores from oil-wet to water-wet. Figure 3 shows the morphology of TiO_2 NPs according to SEM analysis. A nonstable emulsion was formed by dispersing TiO_2 nanoparticles in a saline solution of 3% by weight of sodium chloride, and they started to precipitate in the first hour. Therefore, adding a stabilizer was necessary. Povidone (polyvinylpyrrolidone), as a stabilizer agent with 1 wt % concentration, successfully stabilized the emulsion.[23] Core floods conducted on different wettability sandstones at room temperature showed that more oil could be recovered than SiO_2 in wet medium oil and less Al_2O_3 in oil-wet formations. TiO_2 nanoparticles minimize oil−brine IFT when utilized as a recovery agent. The main mechanism is wettability change.

2.3.4. Magnesium Oxide Nanoparticles (MgO NPs). Core flood tests in sandstone rocks found that when magnesium oxide and zinc oxide are dispersed in brine or ethanol, MgO NPs cause impairment in permeability.[48] On the positive side, soaking the rock samples in a nanoparticle solution of ethanol and magnesium oxide can significantly reduce the oil's viscosity.[49] MgO NPs are generally weak oil recovery agents. However, their effects on EOR require greater investigation.

2.3.5. Tin Oxide Nanoparticles (SnO_2 NPs). Scientists have shown much interest in tin oxide nanoparticles in recent years due to their unique properties. Among the many ways for them to be put to use are "n-type semiconductors, a transparent conductive electrode for solar cells, gas sensing material for gas sensing devices, transparent conducting electrodes, photochemical and photoconductive devices in liquid crystal displays, gas discharge displays, and lithium-ion batteries," etc. Most importantly, SnO_2 has not been extensively utilized in EOR procedures. SnO_2 is similar to zirconium oxide, enhancing oil extraction in the sandstone core while dispersing it in distilled water. However, the recovery factor fell when ethanol or brine was utilized as a dispersion agent.[45]

2.3.6. Zinc Oxide Nanoparticles (ZnONPs). Applications of ZnO in EOR processes have been very limited, but ZnONPs can be used as stabilizers for ointments, semiconductors, food, ceramics, rubber material, and photocatalysis.[50] In EOR processes, ZnO nanoparticles were found to have very limited applications. ZnO had a detrimental effect on the permeability of samples, like magnesium oxide, when used as an EOR agent in sandstones.[49] The oil extraction factor decreases because zinc oxide nanoparticles agglomerate at the injection point, causing clogged pores.

2.3.7. Zirconium Oxide Nanoparticles (ZrO_2 NPs). Zirconia nanopowders are widely used in industry as ceramics, a thermal barrier coating, for catalysis, etc.[51] Prepared ZrO_2 NPs dispersed in nonionic surfactant can be applied to EOR.[52] It was found through the adsorption of NPs onto a carbonate surface that ZrO_2 NPs could change the wettability of the carbonate core from strongly oil-wet to strongly water-wet, but this (adsorption and growth) was a slow process that took about 2 days. However, when ZrO_2 NPs and cationic surfactants are combined, better results in changing the wettability of carbonate rocks can be achieved.[53] Comparatively, cationic surfactants can form ion pairs with a cation head and acidic oil component, whereas NPs create a continuous, wedge-shaped structure around the liquid−solid surface. Additionally, ZrO_2 can significantly reduce the interfacial tension between two liquids.[54] Air and water interfaces require less absorption energy than oil and water interfaces.

2.3.7.1. Silica-Based Nanoparticles. In oil recovery, silica nanoparticles are the most widely used (SiNPs). Compared to other nanomaterials, silica nanoparticles are more environmentally friendly. The surface modification of silica nanoparticles can also control their chemical properties. Silicon dioxide's primary sandstone component accounts for 99.8% of silica nanoparticles. Silica nanoparticles may enhance oil production through displacement mechanisms, which are widely accepted. In the first instance, there is a mechanism called disjoining pressure. Because silica nanoparticles are present in the dispersing medium, a wedge-shaped film forms when the particles contact the discontinuous oil phase.[55] Oil is separated from the rock by the wedge film, shown in Figure 4, to increase the amount of oil recovered. That which separates a liquid's wedge film from its surrounding bulk is known as its disjoining pressure.[56] The Brownian motion and the electrostatic repulsion of molecules cause this pressure to exist.

Another mechanism is called log jamming. As the pore throat is smaller and the differential pressure in the pore is

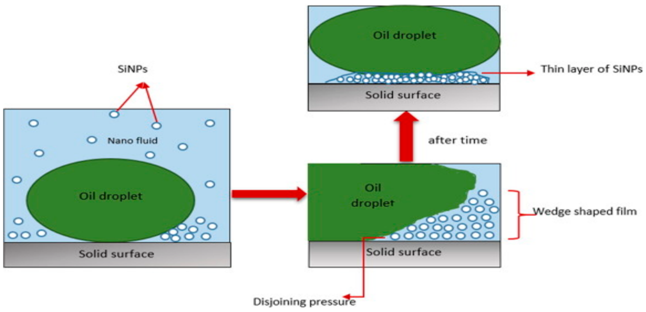


Figure 4. A schematic and structurally distinct pressure gradient mechanism among solid, oil, and nanofluids as the aqueous phase.[57]

constant, the velocity of the silica nanofluid is higher than in the pore body. Silica nanoparticles may accumulate and eventually block the pore entrance if water molecules move faster than the nanoparticles. This may be due to this phenomenon. More oil may be recovered if the water flow is forced to change and pass through other, uninvaded pores. The wettability alteration mechanism is the third mechanism. Silica nanoparticles can improve the compatibility of two immiscible fluids by altering their wettability, interfacial tension, and contact angle.[1,9,10,58]

Nanofluid concentration, particle size, injection rate, and slug size are some variables affecting oil recovery by nanofluid flooding. One of the key factors for improving oil recovery is nanofluid concentration. This work examines silica nanofluid's effectiveness as an agent for increased oil recovery in sandstone rocks.

2.3.8. Silicon Dioxide Nanoparticles (SiO_2 NPs). Sand and sandstone are mostly made of silicon dioxide (silica), one of the most prevalent substances on earth. Wet-water sandstone's enhanced oil recovery agent has proven to benefit from using SiO_2 in these reservoirs.[59] In the presence of ethanol as a dispersant, it changed the wettability to intermediately wet and reduced IFT. Since they scarcely change even when heated to temperatures as high as 650 °C, SiO_2 particles offer good thermal stability. They also do not require a stabilizer since they have been shown to create a more stable emulsion in 3% weight NaCl brine than metal oxide.[23] Core floods with SiO_2 NPs at room temperature reduced recovery. Despite this, they are nevertheless frequently recognized as successful EOR agents under various wettability conditions, including water-, intermediate-, and oil-wet conditions. So, with high salinity and high temperatures, the stability of this nanofluid is always a worry when it is utilized as an EOR agent (Figure 5).

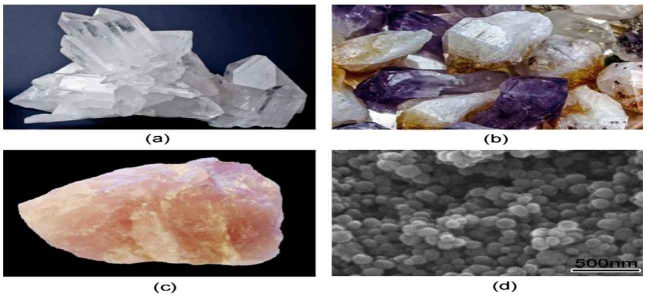

(a) (b) (c) (d)

Figure 5. (a) Quartz, (b) amethyst, (c) rose quartz, and (d) mesoporous silica NPs.[60]

2.3.9. Alumina-Coated Silica NPs. The alumina coating on SiO_2 nanoparticles generates a positive charge on its surface, thus completely changing its properties.[61] When compared to naked SiO_2 nanoparticles, their surface area is significantly greater. Consequently, they show lower toxicity if released into the environment than SiO_2 nanoparticles (bare) at concentrations of 46 mg/L, except at pH 6.0.

Adding propyl gallate (PG) to alumina-coated silica nanoparticles can modify their surface area by up to 20 nm and convert them to be partially hydrophobic. It was discovered that the silica-coated nanoparticles with alumina on a modified surface are more stable when foaming and can recover more oil from the sandstone core than surfactants or nanoparticles alone, as shown in Figure 6.

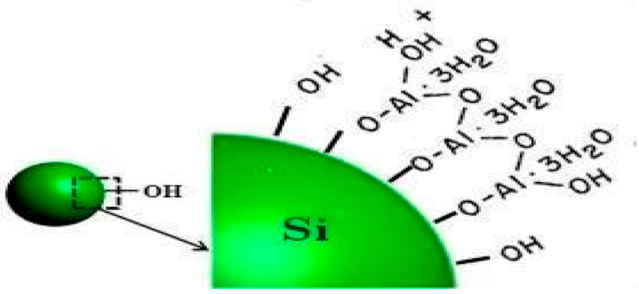


Figure 6. Sketch of the silica-coated nanoparticles with alumina on a modified surface.[62]

In most cases, silanol groups in the alumina-coated silica NPs, which initially form hydrophilic particles, can be combined with hydrocarbon groups to make hydrophobic silica particles. These hydrocarbon groups include alkyl or dimethyldichlorosilane and hexamethyldisilazane chains.

When ethanol is utilized as a dispersant, hydrophobic silica nanoparticles, which can be characterized as fumed silica, precipitated silica, or aerosol-assisted self-assembly, are an effective enhanced oil recovery agent for sandstone reservoirs.[59] Aluminum oxide, magnesium oxide, iron oxide, nickel oxide, zinc oxide, zirconium oxide, and tin oxide all had lower recovery factors than they did.

2.3.10. Spherical, Fumed Silica Nanoparticles. Spherical, fumed silica nanoparticles are the most frequently used for stabilizing oil/water emulsions.[63] The more silanol groups on the surface of the particles, the more likely they will be wet. The high level of coating (more than 90%) helps to form a hydrophilic surface around the particles needed to make stable oil-in-water emulsions that can be kept in place. The hydrophobic characteristics of the surface are unaffected by a silanol coating that is applied to only 10% of the surface. People who make water-in-oil emulsions can now use these particles. These nanoparticles have been used only as stabilizing agents in EOR so far.

2.3.10.1. Core–Shell-Based Nanoparticles. Core–shell-based nanoparticles, such as inorganic silica/polymer nanocomposites, consist of SiO_2 nanoparticles in the core coated with a shell of a synthetic polyacrylamide polymer. In the presence of the solid ions often present in offshore reservoirs, these composite nanoparticles are appropriate for high-salinity and high-temperature applications. These particles increase viscosity, reduce IFT at critical concentrations, and have salt tolerance and high thermal stability. Injecting 200 ppm core–shell nanoparticle mixtures and 800 ppm blends of two surfactants (anionic and nonionic) in a fractured granite sample at 92 °C and 3.44 wt % salinity could increase oil recovery by 6.2%.[64]

2.3.10.2. Silicon Oxide Treated with Silane NPs. Different types of silane functional groups can be found on the market. Amino propyl triethoxysilane, 3-glycidoxy propyl-trimethoxysilane, and 3-ethacryloxypropyltrimethoxysilane are used for SiO_2 particle modification. This leads to "increasing the final monomer conversion, decreasing the particle size, and narrowing the particle size distribution of the poly(methyl methacrylate) (MMA)—hydroxyethyl methacrylate (HEMA)/SiO_2 composite emulsion". Other silanes can be used as coupling agents to treat activated nanosilica surfaces, such as glycidyloxy propyl trimethoxysilane (GPTMS) and aminopropyl triethoxysilane (APTES), trimethoxy silyl propyl methacrylate (TMPM), and dichloro dimethyl silane (DCMS).[65] When mixed with ethanol, this nanoparticle is an excellent EOR agent for sandstone reservoirs.[49] Experimental results demonstrated that a few of these nanoparticles are great EOR operators, and ethanol can improve the performance of some of these nanoparticles. Moreover, these nano-operators' mechanisms have been investigated via which oil is improved. These include alteration of rock wettability, interfacial tension reduction, viscosity reduction, reduction of mobility proportion, and permeability changes. The test results indicated that a few nanoparticles applied in EOR could maximize recovery and boost hydrocarbon generation. Experimental effects predicted that a few nanoparticles' utilized in EOR would maximize recovery and boost hydrocarbon production. Consequently, this nanoparticle results in the highest recovery rate compared to other nanoparticles such as aluminum oxide, nickel oxide, iron oxide, magnesium oxide, zirconium oxide, zinc oxide, tin oxide, and hydrophobic silicon oxide (Figure 7).

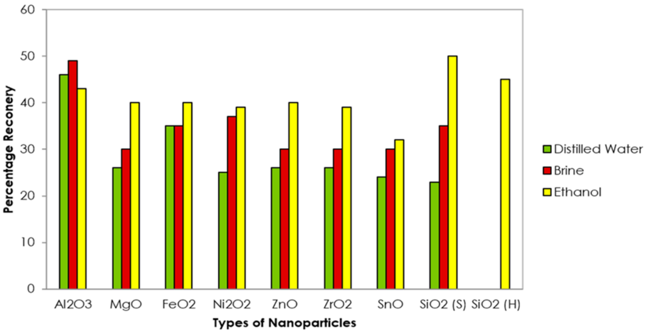


Figure 7. Results of various nanofluids used for EOR experiments from sandstone.

2.3.10.3. Non-Silica Nanoparticles. Nanostructured Zeolite. There are two types of zeolite: one that is natural and one that is synthesized. In most cases, they serve as adsorbents and catalysts. Refineries and petrochemical facilities are used in the cracking process.[66] Up to 40% more gasoline can be obtained from nanostructured zeolite than from the other catalysts they replaced.[67] A highly selective nanocomposite membrane made of nanocrystal-derived hierarchical porous zeolite 4A membrane was designed.[68] The membrane worked well in segregating O_2/N_2 molecules. There are no studies on zeolites in EOR; however, zeolite's porous structure may allow it to act as an ion exchanger. Zeolite can absorb cations such as Na^+, K^+, Ca^{2+}, and Mg^{2+} from water formation, particularly in high-salinity situations. High cation concentrations are always a problem in EOR.

2.3.10.4. Organic Nanoparticles. Organic refers to all carbon-containing compounds.

Carbon Nanoparticles. Hydrothermal synthesis produces a black powder of spherical nanoparticles with specific characteristics. Organic compounds or polymers chemically bonded to the particles' surfaces can be desirable surface modifications. Carbon nanoparticles are just one type of carbon-based nanomaterial and include fullerene C60 (Buckeyballs), fullerene C70, diamond nanoparticles, fullerene C84, fullerene C76, fullerene C78, graphite nanopowder, and graphene. Carbon nanotubes are the second family member, and their usage in carbonate samples increased the oil recovery factor to more than 96%.[69]

Carbon Nanotubes (CNT NPs). Single- or multiwalled carbon nanotubes are made of graphene. The wall's carbon atoms establish three sp^2-hybridized bonds, allowing electrons to travel between them. This family includes carbon nanotubes, which scientists recently realized could be used for EOR MWNT fluid in high-temperature and high-pressure reservoirs. Two different core-flooding tests were performed, first in the absence and then in the presence of electromagnetic waves. Injection of MWNT nanofluid produced 36% oil recovery without electromagnetic waves.[70] In the second test, electromagnetic fields helped almost double the recovery rate. The increased oil recovery directly reduced the oil viscosity associated with the electromagnetic field.[71] Additionally, these nanotubes increased the efficiency of drilling fluids (Figure 8).

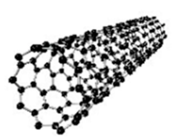
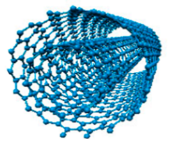
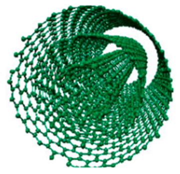
Single-walled Carbon nanotube (SWCNT	Double-walled Carbon nanotube (SWCNT	Triple-walled Carbon nanotube (SWCNT
		

Figure 8. Carbon nanotubes ball-and-stick illustrations of single- (left), double- (center), and triple-walled.[72]

Polysilicon Nanoparticles (PSNPs). Nanoparticles of SiO_2 make up the bulk of polysilicon.[56] Lipophobic and hydrophilic polysilicon nanoparticles (LHPN) and hydrophobic and neutrally wet polysilicon nanoparticles (NWPN) are the three types of polysilicon nanoparticles that may be distinguished.[73] HLPN and NWPN nanofluids improve oil recovery through the key processes of interfacial tension decrease and wettability, which achieve a less water-wet state from a strongly water-wet condition. NWP nanoparticles have a greater impact on rock wettability, while HLP nanoparticles primarily reduce oil—water IFT. Three distinct PSNPs were tested for their capacity to alter rock wettability in diverse ways for EOR applications. (a) Hydrophobic and lipophilic polysilicon (HLPN) NPs: For poor-permeability formations, this nanoparticle is recommended.[56] The decreased absolute permeability of water treated with this nanoparticle enhances the effective permeability of water in sandstone cores.[74] A 4g/L amount of HLPN is ideal for EOR reduction of IFT and altered wettability, pore-scale displacement efficiency, and increased oil recovery. HLP nanoparticles have a stronger influence on IFT than the wettability of rock.[74] To improve the wettability of water-wet forms, these nanoparticles should be used. As surfactants, the nanoparticles dispersed in ethanol act as a dispersion agent for this nanoparticle. These nanoparticles can recover up to 80% of the in situ oil at room temperature and pore pressures of 2000 psi. (b) Hydrophilic and lipophobic polysilicon nanoparticles (LHPN): Adding an activated material to the SiO_2 main component produces lipophobic and hydrophilic polysilicon (LHP), a modified, ultrafine powder.[75] During core flood experiments, injection of 2−3% by volume of 10−500 nm LHP nanoparticles into distilled water helped to recover more oil.[75] The adsorption of nanoparticles to the rock sample surfaces led to the hydrophobic pore surfaces being changed to be hydrophilic, decreasing the water phase relative permeability (K_{rw}) and the oil phase relative permeability (K_{ro}). Moreover, nanoparticle detention has the downside of blocking the pore, leading to absolute permeability (K) and reducing the porosity of the porous media.[76] For wet oil deposits, these nanoparticles can be an effective EOR agent. (c) Naturally wet polysilicon nanoparticles (NWPN): Naturally, wet polysilicon (NWP) nanoparticles are comparable to HLPN. The two primary recovery mechanisms, particularly in water-wet formations, are NWP wettability modification to reduce water-wetness and IFT decrease.[74] NWP NPs, however, have a more substantial effect on wettability than HLPN. Because ethanol is a bipolar dispersant, it is suited to this nanoparticle because it can contain hydrophilic and hydrophobic particles. NWP can change a surface's wettability from oil- or water-wet to an intermediate-wet condition. Ethanol is employed as a dispersant, causing the nanoparticles to behave as surfactants, further reducing the IFT.[77] It is possible that these nanoparticles are not suited for reservoirs containing intermediate to heavy oil. The EOR recovery factor from water-wet sandstone core samples using 3% g/L of these nanoparticles dispersed in ethanol ranged from 50% to 70%. However, this experiment did not include diverse temperatures, pressures, salinity, porosity, or viscosity conditions, so we cannot say that this is the most appropriate chemical flooding method for EOR (Table 1).

2.3.10.5. Polymer Nanoparticles (PNP). These nanoparticles are either nanocapsules or nanospheres produced via different methods such as "salting-out, microemulsion, solvent evaporation, mini-emulsion, interfacial polymerization, and supercritical fluid technology, dialysis, and surfactant-free emulsion".[78] Different "particle size distribution, an application area, particle size, etc." were developed using various analysis methods. As far as we know, no research has been performed on using pure nanosized polymers in the EOR process.

Table 1. Different Conditions for HLPN, HLPN, and NWPN Flooding in EOR

	HLPN	LHPN	NWPN
wettability	more hydrophobic		neutral
contact angle	130 to 95.44		135.5 to 81.8
oil recovery (%)	32.2%	15.5	28.57%
treated with	a single layer of the organic chain		silane
IFT	25.6 to 1.75 mN/m		25.06 to 2.55 mN/m
porosity	17%		17%
permeability	186 md		186 md
salinity, ppm	30.000		30.000
API	33.53		33.53

Polymer-Coated NPs. These nanoparticles have a polymer coating on their surface to prevent adsorption and other phenomena, such as electrostatic response, in conjunction with metal oxide's regularly implanted core.[79] Polyethylene glycol is a typical polymer used in reservoirs with extreme conditions such as high salinity and temperature (PEG). It is possible to adapt polymer-coated nanoparticles (PNPs) for specific applications. This distinct property of PNPs has captivated many researchers to date. These particles have also been utilized to reduce IFT, improve mobility control, change surface wettability, increase displacing agent viscosity, and stabilize foam and emulsions.[80]

Polymer-Grafted Nanoparticles (PGNs). The development of PGNs as a surface modification approach was made possible because nanoparticles' surface-to-volume ratio frequently leads to aggregation and accumulation and irrevocably changes their unique features.[81] To improve the nanomaterials' chemical characteristics and surface topology and to create PGNs, polymer molecules are attached to the surfaces of organic, inorganic, or nonmetallic nanoparticles.[82] Covalent bonds are formed when the hydrophilic groups on the surface of the nanoparticles react chemically with the organic, long-chained polymer.[83] Due to the nanoparticles' penetration of the surface and their usually low molecular weight, the grafted macromolecular chain fills the nanoparticles' interstitial volume, prevents their aggregation through steric hindrance, and interacts with their active sites (see Figure 9).[84]

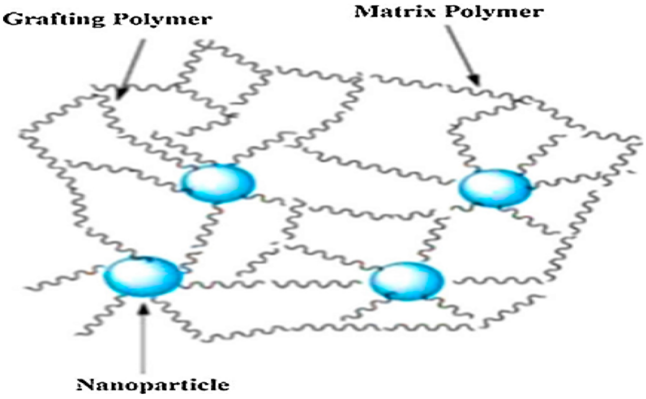


Figure 9. Diagrammatic representation of PGN.[85]

The grafting of nanoparticles with polymer is primarily accomplished by two mechanisms, namely, the "grafting to" and "grafting from" ways.[86,87] In the former, end-functionalized polymer chains and the surfaces of nanoparticles interact chemically. As shown in Figure 10, the latter involves initiator-terminated self-assembled monolayers, which simultaneously involve polymer chains on the surface of nanoparticles. The "grafting from" approach is tougher. Functional groups are first added to the surface of nanoparticles, acting as an initiator in the reaction between molecules and particles. To create the final product, the molecules begin polymerization processes using one of the following methods: cationic, anionic, free-radical, frontal, and ring-opening polymerization. The processes achieved are nitroxide-mediated polymerization (NMP), surface-initiated polymerization (SIP), reversible

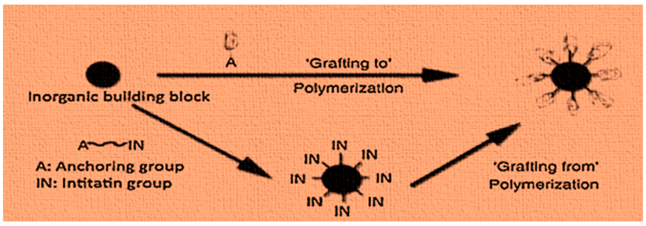


Figure 10. PGN via "grafting to" and "grafting from" process.[85]

addition−fragmentation chain transfer (RAFT), and atom-transfer radical polymerization (ATRP).[88] Barrera et al. used the "grafting to" method to graft different molecular weights of poly(ethylene glycol)-silane onto iron oxide magnetic nanoparticles to study the effects of electrostatic and steric interactions on particle stability. Jiemvarangkul et al. improved the transport of nanoscale, zerovalent iron in porous media by using poly acrylic acid (PAA), poly(vinyl alcohol)-*co*-vinyl acetate-*co*-itaconic acid (PV3A), and soy proteins.[89] To stabilize the nanoparticles in highly concentrated brine and at high temperatures, Worthen et al. grafted zwitterionic sulfobetaine and 3-[dimethyl(3-trimethoxysilyl)pro-pyl]-ammonio)propane-1-sulfonate into SiO_2.[90] Ge et al.,[91] on the other hand, created PGNs using the "grafting from" method using copolymers of acrylic acid (AA) and crotonic acid (CA) and magnetite Fe_3O_4 nanoparticles modified with 3-APS. Additionally, by emulsion copolymerizing AM, AMPS, and triethoxy(vinyl)silane-functionalized nano-SiO_2, Xin et al. created a new water-soluble PGN.[92] A hyperbranched PGN was created by Li et al.[93] using atom-transfer radical polymerization (ATRP) on silica surfaces to create self-condensing vinyl polymerization (SCVP). PGN suspensions were created using both techniques, resulting in better-performing ones.

3. CONTROLLING FACTORS FOR THE SUCCESS OF NANOFLOODING

Concerning oil emulsification, wettability modification, and foam stability, laboratory data indicate that nanoflooding approaches outperform traditional flooding techniques. Nanomaterials must be evaluated to effectively conduct an improved oil recovery operation without damaging the reservoir. The quality of nanoflooding may be influenced by numerous variables: Nanotechnology has the potential to play a significant role in enhanced oil recovery. However, there are still a number of challenges that need to be addressed before nanotechnology can be widely deployed in the field. One of the biggest challenges is developing more accurate and reliable nanoparticle transport and retention models. Another challenge is the need to develop better engineering methods to produce nanoparticles with the optimal properties for nanoflooding. In addition, more research is needed to assess the environmental impact of nano-EOR and to design green nanoparticles. By addressing these challenges, we can accelerate the commercialization of nanotechnology for enhanced oil recovery.

3.1. Developing Nanoparticle Transport and Retention Models. Nanoparticle transport and retention models must be developed to predict nanoflooding performance accurately. These models need to consider the nanoparticles' size, shape, surface chemistry, and the characteristics of the reservoir rock and fluids. A number of nanoparticle transport and retention models have been developed, but these models are still in their early stages of development. More research is needed to develop more accurate and reliable models that can be used to predict nanoflooding performance in a variety of reservoir conditions.[94,95]

3.2. Engineering Nanoparticles for Optimal Suspension and Flow in Reservoirs. Nanoparticles need to be engineered for optimal suspension and flow in reservoirs. This can be done by controlling the nanoparticles' size, shape, and surface chemistry. For example, smaller nanoparticles are more likely to be suspended in the reservoir fluids and to flow through the reservoir more easily. Nanoparticles with a hydrophilic surface are also more likely to be suspended in the reservoir fluids. More research is needed to develop engineering methods to produce nanoparticles with the optimal properties for nanoflooding.[96]

3.3. Toxicity Studies on Nano-EOR's Environmental Impact and Designing Green Nanoparticles. Toxicity studies need to be conducted to assess the environmental impact of nano-EOR. These studies need to evaluate the potential impact of nanoparticles on human health and the environment. In addition, more research is needed to design green nanoparticles for nano-EOR. Green nanoparticles are nanoparticles produced from sustainable sources and are biodegradable. By developing green nanoparticles, we can reduce the environmental impact of nano-EOR.[86,97]

3.3.1. Nanomaterial Structure. An issue with nanoparticles in EOR is material swelling. It damages unmodified clay nanoparticles with multilayer structures that may intercalate with formation water. Water interacts with exchangeable ions inside clay structures to hydrate and extend layered clay material d-space. The cause of significant formation damage is a 60 to 3800% rise in d-space. Swelling inhibitors (such as K^+) or exfoliated clay materials may help reduce material swelling and damage. According to Gonzalez et al.,[87] swelling inhibitors may reduce edema by up to 60%. A variety of lamellar clay materials have been researched in exfoliation and delamination.

3.3.2. Nanomaterial Morphology. The pore throat size physically limits nanoparticle-aided EOR. Effective nanoflooding requires good morphology. Pore neck creation harm occurs when particle size exceeds the pore throat size. Log-jammed particles cannot pass through pore throats even if they are smaller. Log jamming is often caused by particle retention and entrapment. To avoid possible formation damage, particle size must be managed to flow easily down the throat.

Particle hydrophobicity, fluid ion strength, and formation conditions must be considered to prevent jamming. Retention and entrapment are also affected by particle-to-pore ratio and fluid velocity. Nanoparticle entrapment has been studied experimentally and conceptually. The above studies linked particle shape and size to particle retention. Particle-stabilized emulsions, also known as Pickering emulsions, are gaining popularity as oil emulsion aids. Aspect ratio, particle shape, and surface wettability affect interface stability. De Folter et al.[98] found Pickering emulsions containing cubic and peanut-shaped particles obtained 90% surface coverage greater than spherical particles. Gao et al.[99] numerically examined the surface activity of Janus particles. They discovered that although spheres and rods have just one equilibrium state, discotic forms have two: reverse orientation and inversion. Madivala et al.[100] found a strong link between particle aspect ratio and emulsion stability.

3.3.3. Formation Salinity, Temperature, and pH Value. The formation's salinity, temperature, and pH may influence

Table 2. Some Properties of Different Nanoparticles for CEOR

NP	method/polymerization	PNF conc. (wt %)	rock type/media	contact angle	contact angle after treatment	ref
SiO_2	PAM	0.1	glass	112	20	115
SiO_2	PEG	1	carbonate	108	24	109
SiO_2	poly(AMPS)	0.5	capillary tube rock	73.51	21.98	116
SiO_2	PGN	0.6	sandstone	87	28	56
SiO_2/TiO_2	SDS/HPAM	0.1	glass	137	60	117

nanoflooding performance and inorganic material stability due to the compatibility of nanomaterials with the formation circumstances (salinity, temperature, and pH). McElfresh's latest study evaluated the effect of temperature and salinity on nanoparticle durability and described multiple historical occurrences of nanoparticle dispersions with acid for asphaltene cleanup.[101] The effects of these variables on organic molecules grafted on inorganic templates may be complex. Surfactants have optimum salinities and pH levels where interfacial tension is lowest. An IFT screening test usually measures salinity and pH. A low IFT value drastically boosts the oil recovery ratio. Aside from salinity and pH, temperature and interfacial tension have also been examined for molecular surfactant systems. These predicted nanoparticle surface alterations are due to chemical and electric stability impacts. A comprehensive surface chemistry compatibility test is advised.

3.3.4. Nanomaterial Surface Modification. Surface chemistry governs dispersion, wettability, emulsion/foam stability, and particle retention. However, material surface properties can be modified to regulate material surface characteristics. Surface modifications can reduce particle hydrophobicity and adhesion. Particle retention causes formation damage and should be reduced. Dehghan Monfared et al.[102] explained particle retention and surface charge change. A second-order model for silica nanoparticle adsorption on calcite was created. Nanoflooding is a possible Janus particle application, for example, grafting hydrophobic and hydrophilic polymers on both sides of particles. The interfacial stability of heterogeneous and amphiphilic nanoparticles was improved in the study of Janus silica nanoparticles by Takahara et al.[103] on water/oil contact with silane-created particle formation. The surface tension of the final product was measured by grafting gold nanoparticles onto silica nanoparticles' hydroxyl groups. Glaser et al.[104] discovered that when Au/Fe_3O_4 was applied to the hexane−water interface, the interfacial tension was lower in Janus particle systems. Other studies supported these findings, including Fernandez and Rodriguez's study on homogeneous and Janus gold nanoparticles.[105] Janus particles outperformed homogenized gold particles overall. Desiccation may help displace residual oil formation. Emulsification can be reversed by altering the solution's surface. Delivering reagents underground requires precise regulation of emulsification and demulsification.

3.3.5. Intrinsic Material Properties. Using material characteristics effectively may aid oil recovery. Electrical, magnetic, rheological, and thermal characteristics are examples. A potential approach for heavy oil recovery was shown by Yahya et al.[106] using cobalt ferrite nanoparticles and electromagnetic waves. High-frequency electromagnetic waves heat the magnetic particles. In this way, nanoparticles reduce viscosity and increase oil recovery. Paramagnetic materials are suspended in a ferrofluid. Studies have also suggested and tested ferrofluid for improved oil recovery (EOR).

3.3.5.1. Change in Wettability. "Wettability" refers to a fluid's capacity to occupy a porous solid surface while other immiscible fluids are present. When discussing reservoir rock, wettability is directly tied to how fluids interact with the solid or one another.[107] This feature can be determined via unconstrained ingestion, contact angle estimates, zeta potential estimations, and surface imaging studies. Ju and Fan created a theoretical model to investigate how nanoparticles impact wettability.[56]

As a result of modifications in wettability, selective nanoparticle adsorption on pore surfaces and increases in oil-relative porosity were achieved.[68,108] Wasan and Nikolov employed video microscopy in their research to demonstrate how an immiscible fluid spreads through solid surfaces when nanoparticles are present.[109] Surface wetting is brought on by an increase in the nanofluids' spreading coefficient, an increase in the film pressure toward the wedge's vertex, and an increase in the separate auxiliary weight.[110,111] The presence of a polyacrylamide solution, which improves the hydrophilicity of the SiO_2 NP surface, was attributable to the decrease in the contact angle.[112] The flow component on the shake surface was regarded as an auxiliary disjoining weight. Following flooding with PGNs, the contact point of the oil stage changed from 16.49° to 68.02°, suggesting that the wettability of the rock surface changed from oil-wet to water-wet.[113] van der Waals, electrostatic, and solvation capabilities found in PGNs and PNS are additional components that can influence disjoining and fundamental disjoining pressure.[114] Table 2 illustrates some properties of different nanoparticles for CEOR.

3.3.5.2. Rheology. Research in fluid flow and deformation is called rheology. An evaluation of the viscoelastic nature of fluids relies heavily on the rheological characteristics of the fluid in question. In EOR applications, they are critical for determining and planning the best infusion fluid concentrations. A sufficient comprehension of the viscoelastic behavior of injections ensures that the required portability proportion in permeable media may be maintained to predict or fulfill thick-fingering marvels. There are two types of permeability and thickness for a water flood, and the ratio between them is known as the "Kwo/Kow" mobility ratio. The mobility ratio (M) is the displacing fluid's portability ratio to the displaced fluids. When water is displaced, the subscript w stands for the displacement stage (water), while o stands for the displaced stage (oil). $M \leq 1$ is preferable to avoid viscous fingering phenomena.[118] Enhanced bridging-activated nanoparticle flocculation improves the rheological performance of polymeric nanofluids at increasing temperatures. This behavior may result from the interaction between polymer and nanoparticles via the assembly of nanoparticles within the polymer framework and their multivalent connections, forming a modern structure. This shows that nanoparticles function as the cross-linking operators of polymer chains, resulting in a more stable nanoparticle−polymer lattice.[119] The new structure form is governed by a balance between entropic and enthalpic influences, which rely on the framework temperature and improve as the framework temperature increases,[120] decreasing polymer framework corruption. Thus, the molecule–polymer interaction provides a polymer solution with improved salt and temperature resistance.

Hu et al.[107] investigated polymeric nanofluids' pushed-forward rheological features at HTHS settings using Fourier-change infrared (FTIR) spectra data. An advanced polymeric nanofluids arrangement was formed by the hydrogen bond arrangement between the carbonyl groups in polymer (HPAM) and the silanol functionalities on the surface of SiO_2 nanoparticles. This hypothesis was confirmed by Zhu et al.[121,122] and Maurya.[115] In conclusion, for advanced rheological properties and subsequent EOR by polymeric nanofluids, particularly at HTHS, a combination of ion-exchange reactions, the protective effects of the nanoparticles on the polymer, and the formation of a more grounded bond between the hydroxyl group of the nanoparticle and the hydrophobic group of the polyelectrolytes are required. Lai et al. discovered comparative behavior when they examined the shear stability of PGNs synthesized from the same components from the standpoint of rheological behavior. They noticed and developed the macro-rheological properties and dynamic viscoelasticity of sheared and unsheared PGNs compared to HPAM solutions.[108] Using functionalized SiO_2 nanoparticles synthesized on-site by free-radical polymerization and molecules of acrylamide-based polymer, Liu et al.[123] continued their rheological investigation of a novel core–shell PGN. The rigid inner core–shell structure and multibranched morphology of the described HBAPAM molecules improved their viscoelastic conduct, notably under HTHS circumstances. When tested at 110 °C, HBAPAM maintained a viscosity of 77% and a salinity of 18 wt %, while HPAM maintained a viscosity of 30% under the same conditions. Liu and colleagues later observed the better rheological properties of a new, starlike PGN produced using simple water FRP of SiO_2 NPs and an amphiphilic MeDiC8AM polymeric chain. Because of the protective effect of the nanoparticles on the polymer atom and the arrangement of hydrophobic microdomains by the polymeric nanofluids, the synthesized SHAPAM had much better and improved dress and viscosity properties, resulting in better, improved thickening efficiency even in harsh conditions.[124]

In addition, Ye et al.,[125] Pu et al.,[126] and Ponnapati et al.[127] collated rheological estimates of the PGN, and their results showed that the PGN was remarkably resistant to shear debasement, exhibited attractive salt resistance, and was temperature-resilient. To see how nanoparticles slowed down the pace of polymer arrangement execution when salt was present, Maghzi et al.[128] undertook a series of polymer-flooding studies in a quarter-five-spot glass micromodel submerged in heavy oil. Polymer flooding of heavy oil is studied by injecting varying salinities of PNS to see how silica nanoparticles affect polyacrylamide performance. Viscosity measurements were utilized to evaluate the outcomes of the polymer-flooding studies. The oil recovery values at various salinities were determined by analyzing the continuously acquired photos during displacement testing. On the basis of the test findings, the consistency of PNS was greater than that of the polyacrylamide arrangement at the same saltiness. Increasing the silica nanoparticles' concentration made the viscosity increase more perceptible. Hu et al.[107] developed a novel, aqueous, hydrolyzed, polyacrylamide-based SiO_2 nanosuspension for EOR, and they investigated the rheological properties of the PNS under varying salinities, temperatures, and aging durations. According to their investigation findings, adding silica nanoparticles significantly improved the consistency qualities of the acrylamide-based polymer, especially under high-temperature and high-shear conditions (HTHS).

Furthermore, the hybrid suspension proved superior thermal soundness to the normal polymer solution. Surprisingly, the Wavering test revealed that adding nanoparticles to the polymer solution increased cross-links between polymer molecules, making the hybrid solution more flexible and overpowering. Table S1 summarizes points of interest in polymeric nanofluid rheological research.[107,108,123,127−132]

3.3.6. Oil Displacement/Flooding Experiments Using Polymeric Nanofluids.

The results of core flooding for EOR utilizing polymeric nanofluids are provided in Table S2 to evaluate and encourage validation of the improved performance of polymeric nanofluids in demanding settings compared to traditional polymers.[56,88,109,115,116,128,133−135] Experiments using core flooding are commonly utilized in the petroleum industry to examine the impact of infusing fluids and calculate oil recovery under particular store conditions. In accordance with the provided figures, more oil was collected under HTHS conditions due to the consolidation of polymer and nanoparticles. After confirming their starlike polymeric nanofluid's better stability and adsorption, Liu et al.[136] saw a 20% increase in oil recovery over conventional HPAM during core-flooding trials in sandstone cores. Berea sandstone cores treated with polymeric nanofluids increased oil recovery by 19.5%, according to a study by Ponnapati et al.,[127] and 16.3%, according to Pu et al.[126] Maghzi et al.[128] reported that shifting the wettability of the glass surface from oil-wet to water-wet resulted in enhanced polymeric nanofluid oil recovery compared to an HPAM solution. Oil recovery was increased by 10% according to their micromodel flooding data, suggesting that the PNS suspension was responsible for the oil displacement. Cheng et al.[135] tested these for oil displacement after observing their wettability in a capillary tube and on a carbonate rock surface. The results showed a recovery rate of 23.22%.

For more information on the efficacy of Pickering emulsions made from polymeric nanofluids, Kumar et al.[112] performed a flooding exploration in sandpack. The investigation findings showed an increase in oil recovery of nearly 24%. It was found by Maghzi et al. in 2014[128] that raising the salt concentration during polyacrylamide flooding reduces oil recovery. A 10% increase in the oil recovery factor was observed during flooding with polymeric nanofluid because of the nanofluid's improved rheology.[114,137] Furthermore, Rezaei Abiz et al.[94] noted that actuating clay nanoparticles into a polymer solution increased the oil recovery factor 33% more than standard polymer flooding, enhancing rheological behavior. Finally, Khalilinezhad et al.[133] demonstrated that using a polymeric nanofluid as the injectant rather than a normal polymer solution enhanced cumulative oil recovery, water cut, and breakthrough time using three-dimensional simulations and a verified model of a NAP field pilot.

4. NANOPARTICLES' ENVIRONMENTAL IMPACT

Nanotechnology has shown that it has a bright future in a lot of different fields, such as transportation, agriculture, energy, and health, where it can make things more efficient. People are excited about the potential benefits of nanotechnology for things such as health and the environment (for instance, water sanitation). If the exploited features (such as high surface reactivity and the ability to cross cell membranes) also harm human health and the environment, there could be more toxicity. Nanomaterials and their biodegradability have raised concerns regarding long-term consequences and safety. Many nanomaterials have entered the market in the previous 15 years, affecting society directly and indirectly. However, long-term evidence on nanomaterial exposure effects on human health and the environment is limited. Other research has raised concerns regarding the impact of these nanoparticles.

Moreover, little is known regarding nanomaterial production, use, disposal, and the dangers of their exposure. Nanomaterials also lack suitable detection, measurement, analysis, and tracing techniques.

A new and demanding chemical technique, heavy oil recovery, has been studied as an adsorbent/catalyst for nanoparticles. To fully comprehend the utilization of nanoparticles, various hurdles must be overcome. Injecting nanoparticles into the formation results in some being deposited inside the porous medium for years. No long-term environmental effects of nanocatalysts have been studied yet. Others are recovered with enhanced oil. Experimental and modeling analyses should examine all aspects of nanomaterial use. On the operational side, nanocatalyst contamination of groundwater should be considered. Sustainable nanocatalysts should have greater activity, selectivity, recovery efficiency, durability, and recyclability. This should lessen the environmental effect. The development of sustainable nanoparticles, which have a lower environmental effect than synthetic or commercial nanoparticles, is now underway.

5. OPPORTUNITIES AND CHALLENGES

Increased upstream productivity uses nanomaterials in EOR. The techniques for synthesizing various nanomaterial morphologies are well-developed now. These tools are well-established, although more development is welcome.

However, the exact process of nanoflooding is yet unknown. Nanomaterials, rock surfaces, and oil/water contact should be studied more thoroughly. Until now, researchers have seldom used Pickering emulsions or foams to improve oil recovery. Encapsulated breakers and tracers are now the most effective nanomaterial in the oil sector. Only in laboratories has nanoflooding been successful. Because we do not know enough about how nanoparticles move oil and how they behave down in the well, we think nanoflooding is not yet very mature. Other things that make it hard for nanomaterials to be used in the oil field are their cost and risk to the environment and formation.

6. ASPECTS OF THE FIELD

To ensure that NPs work well in the field, we need to know everything about how things work. The difference between the field and the lab must be examined, which can help to scale up lab experiments. Nanoparticles in EOR have not received a lot of attention in the past because of a lack of understanding about how they work, high chemical costs, and low crude oil prices. A lot more people are now writing about how to use NPs in EOR. Most publications are about screening and evaluating NPs by looking at how well their wettability, IFT, and rheological measurements work. Some experiments have been performed to determine how much oil can be extracted from different rocks in the ground. Carbonates and sandstones were some of the rocks used in these experiments.

Unpublished data on EOR with NPs do not exist. NPs surfactants and polymers may be future EOR candidates due to the increasing number of papers and positive laboratory results. While NPs have shown promise in the laboratory, there are still issues to overcome before they can be used in oil fields. Recent laboratory studies revealed that NP dispersions are stable at low temperatures and salinities. The stability of NPs under difficult reservoir conditions is one of the primary concerns in EOR. However, extreme temperature and salinity conditions were not addressed. According to our lab's findings, NPs distributed in water-soluble polymers, such as polyacrylamide, are stable for a long time. Combining polymer and NP flooding can address NP dispersion stability issues. Polymer coatings may also increase the stability and surface characteristics of NPs for EOR. Most of the examined NPs are customized and pricey. One of the primary obstacles to in-field deployment is finding low-cost NPs with strong EOR characteristics. Producing NPs in large quantities at low cost is the next challenge. Some of the NPs are also harmful to people. The mechanism of NP adsorption on various rocks is unknown. Nobody knows how adsorption affects rock type, temperature, and salinity. Finally, scaling up NP laboratory research to field applications is difficult. Many desirable features, such as decreased IFT and increased viscosity, may be achieved using cost-effective nanoparticle formulations with lower adsorption and less aggregation. Nano-EOR has the potential to play a significant role in improving oil recovery. However, there are still a number of challenges that need to be addressed before nano-EOR can be widely deployed in the field. Some of the biggest challenges include better correlation between laboratory tests and field performance, addressing expertise gaps, and fostering international collaborations. By addressing these challenges, we can accelerate the commercialization of nano-EOR for enhanced oil recovery.

6.1. Major Nano-EOR Field Trials. A number of major nano-EOR field trials have been conducted in recent years. These field trials have demonstrated the viability of nano-EOR for improving oil recovery. Some of the most notable nano-EOR field trials include the following. (i) Petronas Carigali's field trial in Malaysia: This field trial demonstrated that nano-EOR can increase oil recovery by up to 15%. (ii) Saudi Aramco's field trial in Saudi Arabia: This field trial demonstrated that nano-EOR can be used to recover oil from unconventional reservoirs. (iii) ConocoPhillips' field trial in the United States: This field trial demonstrated that nano-EOR can be used to improve oil recovery from mature reservoirs. These field trials demonstrate that nano-EOR has the potential to be a viable technology for improving oil recovery in a variety of reservoir conditions.[29,138]

6.2. Laboratory Tests and Field Performance. There is need for a better correlation between laboratory tests and field performance for nano-EOR. Laboratory tests are often conducted under ideal conditions, which do not represent the real-world conditions encountered in the field.

As a result, it can be challenging to predict how well a nano-EOR technology will perform in the field based on laboratory test results. More research is needed to develop laboratory tests that better represent the real-world conditions encountered in the field.[139,140]

6.3. Bibliometric Analysis of Nano-EOR Publications. The bibliometric analysis of nano-EOR publications provides insights into nano-EOR publication trends. However, additional perspectives on expertise gaps and potential international collaborations could aid research and development.

For example, the bibliometric analysis could be used to identify countries and institutions that are leading the way in nano-EOR research. This information could then be used to identify potential international collaborators.[141,142]

6.4. Expertise Gaps and Potential International Collaborations. There are a number of expertise gaps in nano-EOR. For example, there is a need for more research on the following topics: (i) nanoparticle transport and retention in porous media, (ii) engineering nanoparticles for optimal suspension and flow in reservoirs, (iii) toxicity studies on nano-EOR's environmental impact, and (iv) designing green nanoparticles for nano-EOR.

International collaborations could help to address these expertise gaps. By bringing together researchers from different countries and institutions, we can accelerate the pace of nano-EOR research and development.

7. CONCLUSIONS AND RECOMMENDATIONS

An alternative to existing EOR technologies, nano-EOR has emerged as a viable option for increasing ultimate oil recovery. For nano-EOR, a variety of advantages come from using particular nanomaterial process: (1) high surface-area-to-volume ratio nanoparticles create good porous rock mobility; (2) the ability to improve fluid performance can be achieved with only a small amount; (3) more efficient transfer of heat and mass can be achieved even at high temperatures; (4) the ability to combine other materials, such as surfactants and polymers, can be achieved in novel ways; (5) nanoparticles such as SiO_2 and TiO_2 show promise in the recovery process; (6) when a semiconductor nanoparticle is used, it helps to minimize the interfacial tension (IFT), and as a result, each nanoparticle contributes significantly to higher oil output; and (7) nano-EOR possesses a number of unique features, including wettability alteration, improved oil mobility, enhanced sand consolidation, and a reduction in interfacial tension (IFT). In nano-EOR, concentrations of NPs, size, temperature, wettability, and salinity affect nanofluid flooding performance. Dispersion of NPs in water, alcohols, surfactants, and polymers has yielded high EOR performance in various nanofluid, nanoemulsion, and nanocatalyst formulations of NPs. An additional 20% OOIP can be recovered using silica NPs, among the most commonly used and most effective NPs available. Disjoining pressure, wettability change, IFT reduction, and mobility ratio were some of the nano-EOR mechanisms discussed in this overview. The performance of a nanofluid can be affected by a number of factors, such as the NPs' size, type, concentration, temperature, salinity, and dispersion medium. The following need to be accomplished: (i) Develop more accurate and reliable nanoparticle transport and retention models: These models need to consider the size, shape, and surface chemistry of the nanoparticles, as well as the characteristics of the reservoir rock and fluids. This will help better predict the performance of nano-EOR in different reservoir conditions. (ii) Develop better engineering methods to produce nanoparticles with the optimal properties for nanoflooding: This includes developing methods to produce nanoparticles well-suspended in the reservoir fluids that can flow through the reservoir easily. This will help to improve the effectiveness of nano-EOR and reduce the cost of nanoparticle production. (iii) Conduct toxicity studies to assess the environmental impact of nano-EOR: These studies need to evaluate the potential impact of nanoparticles on human health and the environment. This information is essential for developing safe and sustainable nano-EOR technologies. (iv) Design green nanoparticles for nano-EOR: Green nanoparticles are biodegradable and produced from sustainable sources. By developing green nanoparticles, we can reduce the environmental impact of nano-EOR. (v) Conduct more field trials to demonstrate the viability of nano-EOR in various reservoir conditions: These field trials need to be conducted in collaboration with industry partners. This will help to identify the challenges and opportunities associated with implementing nano-EOR in the field.[13]

7.1. Key Areas for Future Research. There are some key areas for future research, which include the following. (i) Developing new nanomaterials for EOR: New nanomaterials with improved properties, such as higher stability and lower toxicity, need to be developed for EOR. For example, nanomaterials that can be used to develop more effective surfactants or reduce oil viscosity could be very beneficial. (ii) Investigating the synergistic effects of nanoparticles with other EOR methods: Nanoparticles can be combined with other EOR methods, such as thermal and chemical EOR, to improve the overall effectiveness of EOR. For example, nanoparticles could enhance emulsions' stability or reduce the chemicals required for EOR. (iii) Developing new methods for EOR monitoring and evaluation: New methods need to be developed to monitor and evaluate the performance of EOR in the field. This is important for ensuring that EOR is implemented effectively and optimizing EOR operations. (iv) Developing EOR technologies for unconventional reservoirs: Unconventional reservoirs, such as shale oil and tight oil reservoirs, are becoming increasingly important sources of oil and gas. However, EOR in unconventional reservoirs can be challenging. More research is needed to develop EOR technologies specifically tailored for unconventional reservoirs. (v) Reducing the cost of EOR: EOR can be expensive, especially compared to conventional oil production methods. More research is needed to develop more cost-effective EOR technologies.[140]

7.2. Addressing Technological Gaps, Environmental Risks, Field Implementation Challenges, and Recommended Future Research Directions. By addressing these technological gaps, environmental risks, field implementation challenges, and recommended future research directions, we can accelerate the development of new and improved EOR technologies. This will help us to produce more oil from existing reservoirs and to extend the life of oil and gas fields.

7.2.1. Technological Gaps. Some of the technological gaps include the following. (i) Develop more accurate and reliable nanoparticle transport and retention models: These models need to consider the size, shape, and surface chemistry of the nanoparticles, as well as the characteristics of the reservoir rock and fluids. This will help better predict the performance of EOR in different reservoir conditions. (ii) Develop better engineering methods to produce nanoparticles with the optimal properties for EOR: This includes developing methods to produce well-suspended nanoparticles in the reservoir fluids that can flow through the reservoir easily. This will help to improve the effectiveness of EOR and reduce the cost of nanoparticle production. (iii) Investigate the synergistic effects of nanoparticles with other EOR methods: Nanoparticles can be combined with other EOR methods, such as thermal and chemical EOR, to improve the overall effectiveness of EOR. For example, nanoparticles could enhance emulsions' stability or reduce the chemicals required for EOR. (iv) Develop new methods for EOR monitoring and evaluation: New methods need to be developed to monitor and evaluate the performance of EOR in the field. This is important for ensuring that EOR is implemented effectively and optimizing EOR operations.

7.2.2. Environmental Risks. Several of the environmental risks include the following. (i) Conduct toxicity studies to assess the environmental impact of nano-EOR: These studies need to evaluate the potential impact of nanoparticles on human health and the environment. This information is essential for developing safe and sustainable EOR technologies. (ii) Design green nanoparticles for EOR: Green nanoparticles are biodegradable and produced from sustainable sources. By developing green nanoparticles, we can reduce the environmental impact of EOR.

7.2.3. Field Implementation Challenges. There are multiple field implementation challenges that include the following. (i) Develop better methods for injecting nanoparticles into reservoirs: Injecting nanoparticles into reservoirs can be challenging due to their small size and tendency to aggregate. New methods need to be developed to inject nanoparticles into reservoirs in a way that is effective and cost-efficient. (ii) Develop new methods for monitoring and evaluating the performance of nano-EOR in the field: New methods need to be developed to monitor and assess the performance of nano-EOR in the field. This is important for ensuring that EOR is implemented effectively and optimizing EOR operations.[143] (iii) The following are recommended future research directions: (a) Develop new EOR technologies for unconventional reservoirs: Unconventional reservoirs, such as shale oil and tight oil reservoirs are becoming increasingly important sources of oil and gas. However, EOR in unconventional reservoirs can be challenging. More research is needed to develop EOR technologies specifically tailored for unconventional reservoirs. (b) Reduce the cost of EOR: EOR can be expensive, especially compared to conventional oil production methods. More research is needed to develop more cost-effective EOR technologies.[144]

8. BIBLIOMETRIC STUDY

From the documents available on the database Web of Science during the period between 2010 and 2023, the search was performed using the following search fields: Title, Abstract, Author keywords, and Keywords Plus. A combination of the keywords used in the search was made using AND/OR as follows: ("chemical-enhanced oil recovery" OR "oil recovery") AND ("nanotechnology" OR "nanoparticles"). Results were evaluated by their titles and abstracts for compliance with the theme and the core topic of the article. The study was carried out using the Bibliometrix package (R core team 2022) and VOSviewer software, and graphs were created using Microsoft Excel software and the line graph maker tool in the Web site rabidtables.

For every document, the following information was extracted: (1) the number of documents per year and the cumulative number of documents for each year, (2) average citations of articles per year, (3) author keywords and most used words in titles, (4) journals in which every article was published, (5) science categories, (6) most cited articles, (7) authors and coauthors of every article, (8) H-index for top 10 authors, (9) affiliation of the authors and coauthors, (10) countries of the authors, (11) H-index for top 10 journals, and (12) correlation between countries, journals, and affiliations. Bibliographic maps were created using the VOSviewer software for the following data: (1) co-occurrence between keywords, (2) co-authorship map for countries, and (3) bibliographic coupling for countries and affiliations.

The total number of results that were initially found is 1880 documents, out of which 1634 were found to be correlated with the theme of the study. Filtered results were categorized as follows: research articles, 175 review papers, 48 proceedings papers, and 51 for all other documents categories. The total number of sources is 323, the number of keywords is 3126, and the average number of citations per document is 19.03.

Retrieved publications had an average annual growth rate of 44.71%; the most significant increase was between 2016 and 2020 (Figure 11). The most publications were in 2022, with 330 (Figure 12). The highest average citation per year was in 2012, with a mean total citation per year of 8.54 (Figure 13). This specific year had only 4 articles. The article "Wettability Alteration in Carbonates using Zirconium Oxide Nanofluids: EOR Implications" (Karimi, A., 2012) had the highest of citations with 286 citations, followed by "Amphiphilic Nanohybrid Catalysts for Reactions at the Water/Oil Interface in Subsurface Reservoirs" (Drexler, S., 2012) with 66 citations. The total citations per year keep decreasing annually due to increased publications. The article "A coreflood investigation of nanofluid enhanced oil recovery" (Hendraningrat, L., 2013)

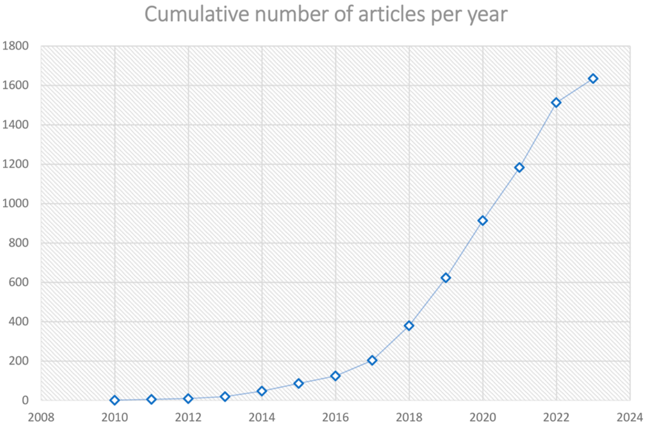


Figure 11. Cumulative number of articles each year.

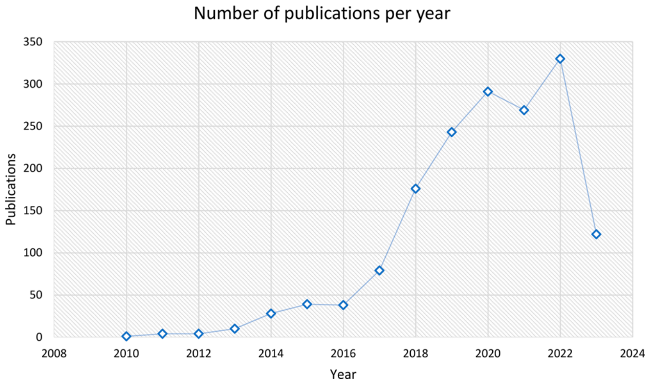


Figure 12. Number of articles per year.

https://doi.org/10.1021/acsomega.3c06206

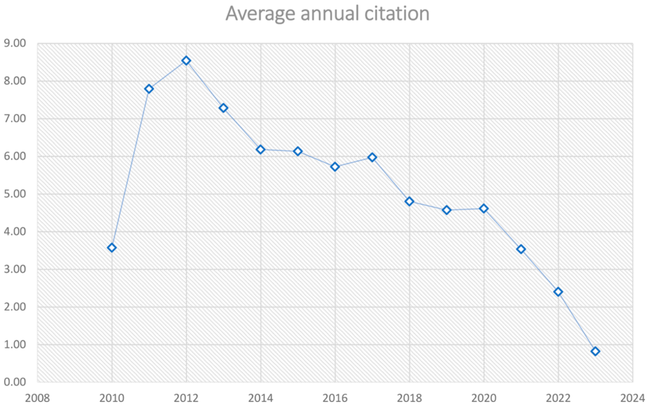


Figure 13. Average citation per article each year.

had the highest citation score with 319 citations. It was published in the Journal "Journal of Petroleum Science and Engineering," followed by the article "Nanofluid for enhanced oil recovery" (Hendraningrat, L., 2011) with 288 citations. It was also published in the Journal "Journal of Petroleum Science and Engineering."

The Journal "Journal of Petroleum Science and Engineering" presented the highest number of articles with 156 articles, followed by the Journal "Energy \& Fuels" with 129 articles, and the Journal "Journal of Molecular Liquids" came third with 107 articles (Figure 14a). While Figure 14b shows journals' dynamics over the years, the journal "Energy \& Fuels" was the most popular journal until the year 2021, when the journal "Journal of Petroleum Science and Engineering" took its place with a cumulative number of articles of 110. As for the H-index of journals, "Energy \& Fuels" had the highest H-index with a score of 34, followed by "Fuel" with an H-index of 33 and "Journal of Petroleum Science and Engineering" also with an H-index of 33 (Figure 15). Concerning scientific categories, 614 articles fell under the category of energy and fuels, followed by chemical engineering with 491 articles and physical chemistry with 323 articles (Figure 16).

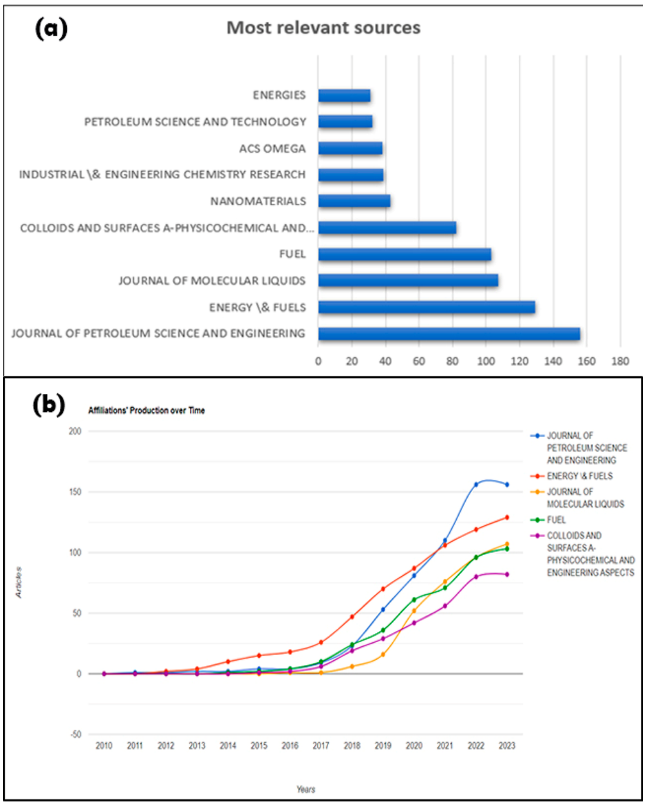


Figure 14. (a) Top 10 journals based on the number of articles. (b) Journal production per year.

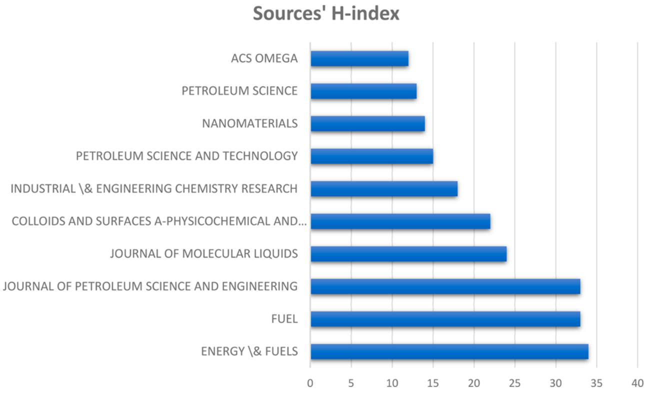


Figure 15. Top 10 journals based on H-index.

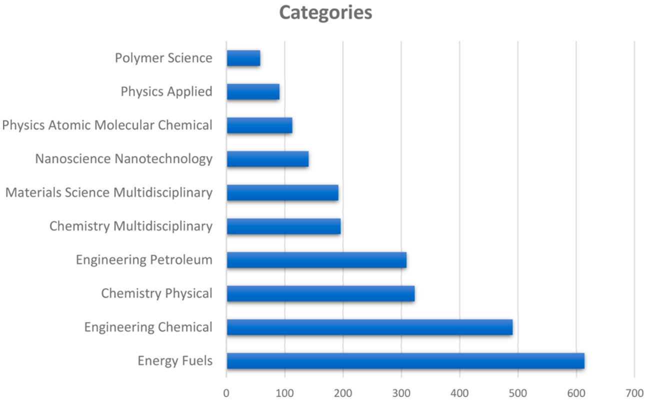


Figure 16. Top 10 areas of concentration.

The articles had a total number of authors and coauthors of 3645; the number of authors of single-authored docs was 27, corresponding to 35 single-authored articles, and most articles had between 4 and 5 authors. "Cortes FB." had the highest number of articles, with 41 articles, and "Franco, CA" came in second with 40 articles, followed by "Wang X" with 37 articles (Figure 17). As for the authors' H-index, "Cortes FB" had the highest H-index with a score of 20, followed by "Franco CA" with an H-index of 19 and "Cheraghian G" with an H-index of 18 (Figure 18). "Hendraningrat L" had the highest local citations of 334 citations, followed by "Cheraghian G" with 317 citations and "Junin R" with 264 citations (Figure 19).

The total number of keywords used in the articles was 3126. The most used keyword was "enhanced oil recovery," which was used 370 times, followed by "nanoparticles" with 247 occurrences and "wettability alteration" with 120 occurrences (Figure 20). As for words used in the titles of the articles, the word "oil" was used 942 times, followed by "recovery" with 734 occurrences and "enhanced" with 523 occurrences (Figure 21).

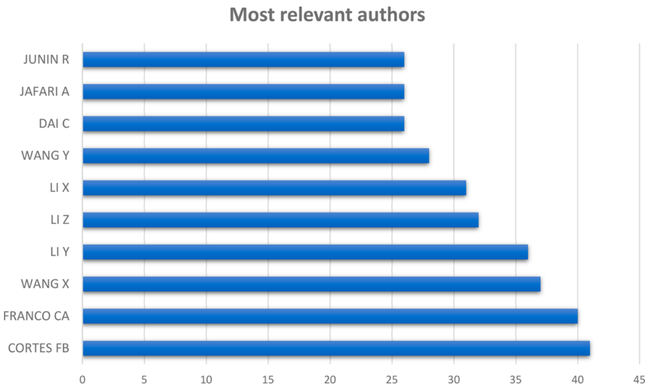


Figure 17. Top 10 authors based on the number of articles.

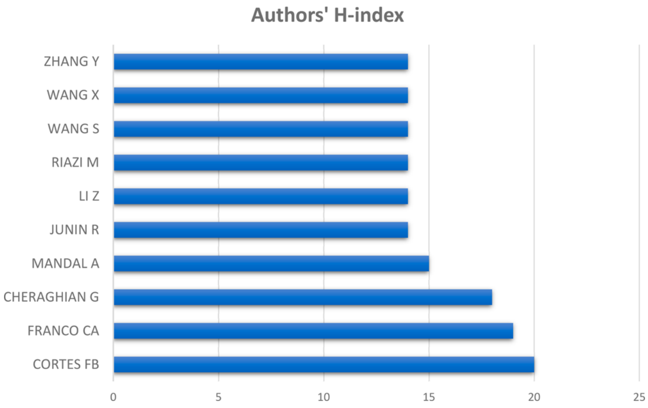


Figure 18. Top 10 authors based on local citations.

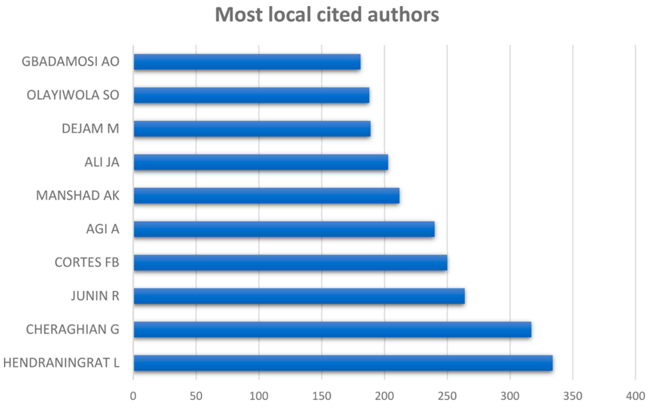


Figure 19. Top 10 authors based on H-index.

China represented the most productive country with a total number of publications 480; it had the strongest connections with almost all journals (Figure 22) and the strongest connections with other countries (Figure 23). Iran came second with 363 publications, and the USA placed third with 212 publications (Table 3). The most productive affiliation was "China Univ Petr East China" with 341 articles, followed by "Univ Teknol Petronas" with 203 articles and "China Univ Petr" with 197 articles (Figure 24a). In contrast (Figure 24b) shows affiliations' dynamics based on the number of cumulative articles.

9. CHALLENGES AND FUTURE RESEARCH

Nano-EOR faces a long road of challenges before it can reach its full potential. The petroleum sector's most significant

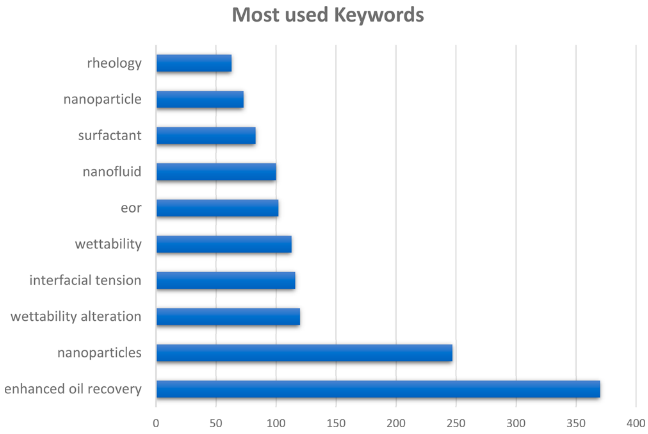


Figure 20. Top 10 used keywords.

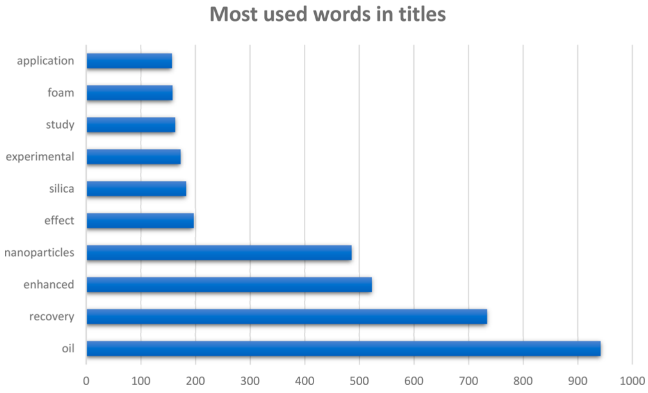


Figure 21. Top 10 used words in titles.

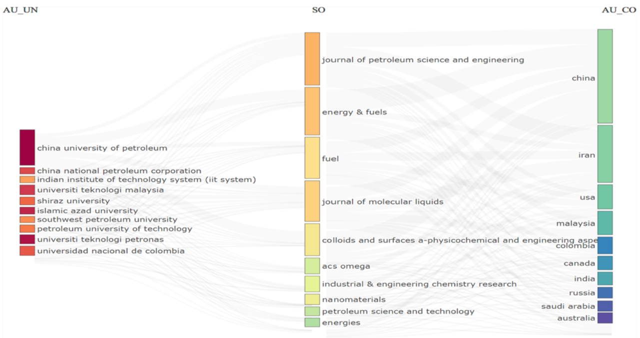


Figure 22. Correlation between countries, journals, and affiliations.

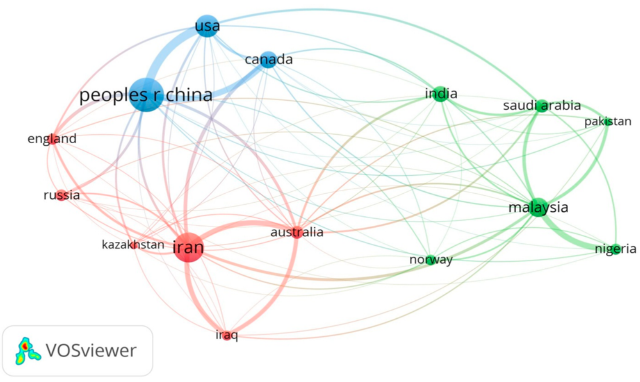


Figure 23. Co-authorship map of the top 15 countries.

Table 3. Most Productive Countries

country	number of articles
China	480
Iran	363
USA	212
Malaysia	151
Canada	123
India	105
Saudi Arabia	74
Australia	68
Colombia	64

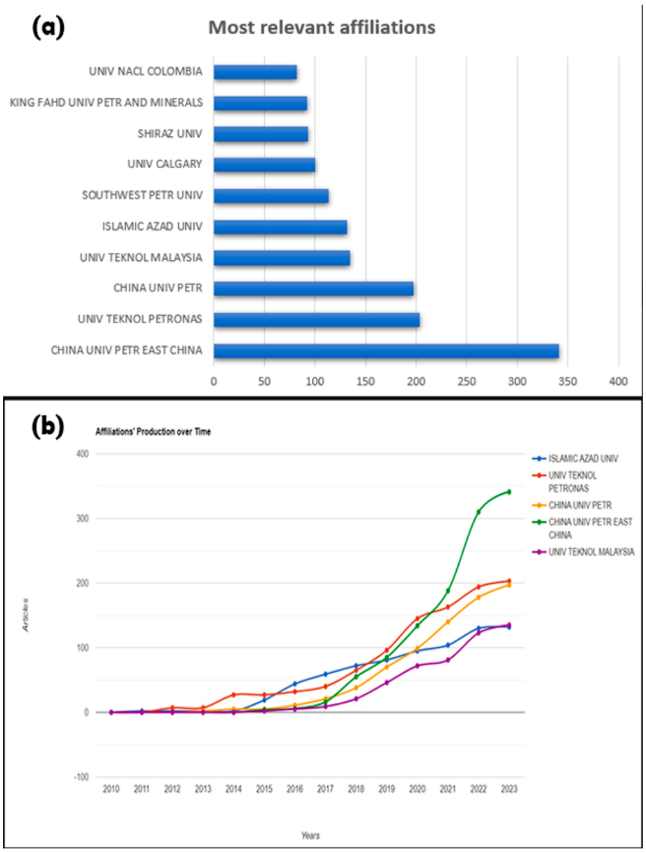


Figure 24. (a) Top 10 affiliations based on the number of articles. (b) Affiliations' production over time.

obstacles are economic, technological, environmental, and health problems. NPs have been shown to increase oil recovery in numerous studies, but they have been limited to laboratory scales. For now, they are not ready for widespread use in the field. Therefore, further study needs to be performed to fill in the gaps between lab results and real-world applications. For the eventual implementation of PNPs in EOR processes, the following must be addressed. (1) Nano-EOR pilot projects must be carried out. These initiatives will help researchers understand how nano-EOR works in the real world. Studies on nano-EOR parameter optimization are also recommended to improve recovery and cost-effectiveness. (2) Due to their tendency to clump together in reservoir conditions, preparing homogeneous NP suspensions is challenging (high temperature, pressure, and salinity). Consequently, large-scale production of stable nanofluids must take into account economic considerations. (3) Stabilizing a foam or emulsion requires the same energy as injecting it into cores, typically requiring 10 feet per day or more flow rates. Different types and functionalities of polymers should be studied to reduce the energy needed for nanoparticle adsorption at the fluid−fluid interface and foam/emulsion stability. (4) In accordance with previous research, nanoparticles coated with polymers do not alter their wettability. As a result, the disjoining pressure near an inner contact line can be affected by various effects on the energy and entropy of the system (structural, electrostatic, hydrophobic, and other effects), which alters the rate of wettability alteration caused by such PNPs. (5) In nano-EOR, there are numerous ways to increase recovery. These mechanisms and the factors that influence them are not completely known. There has to be more research performed on NPs and rock surfaces. (6) There is a lack of knowledge about nano-EOR at the most basic level. Insufficient theoretical and numerical research into nano-EOR appears to be a contributing factor. The colloidal particle model, commonly used in numerical studies, does not perfectly capture NPs' behavior. There is no consideration of chemical interactions in the models, restricting it to NPs and physical interactions only. (7) Because of nanotechnology's rapid advancements, health and safety studies lag. An important barrier to the advancement of NPs is the dearth of data on the effects of various nanoparticles on human health. Inhalation of NPs into the lungs is possible due to their small size at the nanoscale. (8) Many NPs have been shown to have other EOR characteristics and mechanisms. However, no studies have yet been performed on nanofluid mixtures. Combining the properties of two or more nanofluids could open up new possibilities for application and performance. (9) Adsorption and desorption behavior during NPs' flow must be experimentally confirmed. Adsorption mechanisms such as reversible and irreversible adsorption must be better understood experimentally and theoretically to ensure that NPs are delivered to the correct location.

A PNP polymer coating that minimizes the undesirable effects (adsorption, aggregation, etc.) and maximizes the desirable effects (increased viscosity, emulsion generation, and reduced interfacial tension) may be achieved by addressing these challenges. NPs may threaten human health and the environment unless comprehensive research into their safety and health implications is conducted.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.3c06206.

(Table S1) Rheological studies of polymeric nanofluids and (Table S2) oil recovery from displacement and flooding tests of polymeric nanofluids (PDF)

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Conceptualization, R.H., A.A., and A.E.S.; methodology, R.H., A.Z., A.A., and A.E.S.; software, A.A. and A.E.S.; validation, R.H; formal analysis, R.H., A.A., and A.E.S.; investigation, R.H.; resources, R.H.; data curation, R.H., A.A., and A.E.S.; writing—original draft preparation, R.H., M.F.M., and M.F.H.; writing—review and editing, R.H., A.A., A.E.S., and M.F.H.; visualization, R.H.; supervision, R.H., M.R., and M.A.Z. All authors have read and agreed to the published version of the manuscript.

Notes

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■ ABBREVIATIONS

APTES	amino propyl tri ethoxy silane
CDG	nano-sized colloidal dispersion gels
CNT	carbon nanotube
CSS	cyclic steam simulation
DCMS	dichlorodimethylsilane
EOR	enhanced oil recovery
nano-EOR	nano-enhanced oil recovery
E	layer thickness
GPTMS	glycidyloxy propyl tri methoxy silane
HEMA	hydroxyethyl methyl methacrylate
HLPN	hydrophobic and lipophilic polysilicon nanoparticles
HLP	hydrophobic and lipophilic polysilicon
HAPAM	hydrophobically associated polyacrylamide
IFT	interfacial tension
Kro	permeability of the oil phase
K	absolute permeability
K_{rw}	relative permeability of the water phase
LHPN	lipophobic and hydrophilic polysilicon nanoparticles
LHP	lipophobic and hydrophilic polysilicon
MMA	methyl methacrylate
MWNT	multiwall carbon nanotubes
NPs	nanoparticles
NWP	neutrally wet polysilicon
NWPN	neutrally wet polysilicon nanoparticles
OOIP	original oil in place
PVP	poly vinyl pyrrolidone
PSNP	polysilicon nanoparticle
PDMS	poly-di-methyl-siloxane
PG	propyl gallate
PEG	polyethylene glycol
PNP	polymer-coated nanoparticles
PAMNP	polyacrylamide microgel nanospheres
RF	resistance factor
SSGD	steam-assisted gravity drainage
SEM	scanning electron microscope
SPE	society of petroleum engineers
% SOr	% residual oil saturation
TMPM	tri methoxysilyl propyl methacrylate
PGN	polymer-grafted nanoparticles

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