Chemical Science International Journal

Volume 33, Issue 6, Page 198-211, 2024; Article no.CSIJ.126793
ISSN: 2456-706X
(Past name: American Chemical Science Journal, Past ISSN: 2249-0205)

Nanotechnology in Enhanced oil Recovery: A Review of Current Research

AKPAN, U.E. [a*] and OKOYE. O. [a]

[a] *Department of Pure and Industrial Chemistry, University of Port Harcourt, Rivers State, Nigeria.*

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/CSJI/2024/v33i6938

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/126793

Review Article

Received: 24/09/2024
Accepted: 28/11/2024
Published: 13/12/2024

ABSTRACT

Nowadays, nanotechnology has emerged as one of the revolutionary approaches in Enhanced Oil Recovery (EOR), having a high capability for solving many of the challenges related to conventional methods. This technology applies nanoparticles to achieve higher recovery through various mechanisms, which include the alteration of wettability, reduction of interfacial tension, and stabilization of emulsion. These different nanomaterials include silica, metal oxides, and carbon-based nanomaterials, which showed great improvement in oil displacement and recovery rates both at laboratory experiments and in field trials. However, there are some problems of nanofluids' stability, economic feasibility, and environmental safety that have to be overcome. This reminds one that the current trend in research is focused on hybrid, biodegradable nanoparticles, integrated nanotechnology with low-salinity water flooding, and smart nanomaterials responsive to reservoir conditions. In essence, since this is a field in continuous evolution, the accomplishment of full potential regarding nanotechnology application for efficient and sustainable oil recovery practices calls for unending research and collaboration.

**Corresponding author: E-mail: uduakobong23@gmail.com;*

Cite as: *U.E., AKPAN, and OKOYE. O. 2024. "Nanotechnology in Enhanced Oil Recovery: A Review of Current Research". Chemical Science International Journal 33 (6):198-211. https://doi.org/10.9734/CSJI/2024/v33i6938.*

Keywords: Nanotechnology; enhanced oil recovery (EOR); nanoparticles; wettability alteration; interfacial tension reduction; emulsion stabilization.

1. INTRODUCTION

Enhanced oil recovery is an important process in petroleum industries for extracting the maximum amount of crude oil from a reservoir [1]. The conventional methods of extracting crude oil, namely primary recovery by natural pressure and secondary recovery by water or gas injection, recover merely 20-40% of the original oil in place [2]. Of these, EOR techniques include thermal, gas injection, and chemical methods that can increase recovery rates as high as 30-60% or more, making the process one of the optimization means in oil production amid diminishing resources and increase in energy demand. Recently, the application of nanotechnology in EOR has gained considerable attention, as it is expected to bring significant improvements in recovery efficiency and possibly decrease adverse environmental impacts [3]. Nanotechnology refers to a number of techniques for producing and processing ultrafine powder materials with sizes from 1 to 100 nanometers. Agglomeration, either hard or soft, may give these nanomaterials special physical and chemical properties, different from their bulk states [1]. It has been established that nanoparticles change wettability, reduce IFT, and increase mobility in flow within the reservoir, thus making NPs effective in the EOR process [2].

2. THE ROLE OF NANOTECHNOLOGY IN EOR

Nanotechnology can introduce new ways of solving part of the problems that have prevailed in oil recovery. Wettability alteration has been considered among the first modes of action in nanoparticles' enhancing oil recovery [4]. Many reservoir rocks are naturally oil-wet-a factor limiting water from efficiently displacing oil in the rock. Adding hydrophilic nanoparticles to the reservoir can create such an effect to change the wettability from oil-wet to water-wet and hence increase efficiency in water flooding [3]. This change in wettability is critical for achieving maximum oil recovery, because it allows the trapped oil to be displaced more effectively.

Another important benefit of nanoparticles in EOR is the decrease in IFT between oil and water. Lower values of IFT can mobilize oil droplets more easily through the porous media in the reservoir. This reduction of IFT is highly desirable for heavy oil recovery, where high viscosity is a key barrier against extraction. Nanoparticles can also stabilize emulsions, which may enhance the oil recovery further due to improved flow characteristics of the injected fluids [5].

3. CURRENTS RESEARCH AND DEVELOPMENTS

Recent research has illustrated how different types of nanoparticles can help in enhancing oil recovery. For instance, it was found that silica nanoparticles can alter the wettability characteristics of carbonate rocks very profoundly and hence enhance recoveries of oil [6]. There are hybrid applications involving nanoparticles together with surfactants and polymers, too, in which synergistic effects have been found to further enhance the performances of these EOR methods [7]. These advances prove that nanotechnology faces the various challenges of oil recovery. With these promising results, the application of nanotechnology in EOR is not devoid of challenges [8]. Amongst the vital concerns arising in this connection is the stability of nanofluids under harsh reservoir conditions because nanoparticles may agglomerate or precipitate, hence reducing their efficiency [9].

Furthermore, economic viability concerning large-scale production and deployment of nanoparticles remains one of the key barriers to its widespread adoption [10]. These challenges need further research and interaction between academia and industry.

4. ENVIRONMENTAL CONSIDERATIONS

In addition, environmental impacts of the EOR methods are a great concern for the oil industry. The conventional EOR techniques may have very high greenhouse gas emissions and potential groundwater resources contamination [11]. On the other hand, nanotechnology could develop more environmentally-friendly EOR techniques. It is possible to design biodegradable nanoparticles with a minimum ecological footprint that enhance oil recovery [12]. In fact, this trend of sustainability has become an actual need for the future in the oil industry, as the regulatory pressure and publicity about environmental impacts are on the rise.

In brief, nanotechnology application in the enhanced oil recovery process stands as one of the most prospective approaches toward improvement regarding environmental issues in oil extraction efficiency [13]. Due to the specific properties of nanoparticles, salient improvements can be noticed in such areas as wettability alteration, reduction of interfacial tension, and enhancement of fluid mobility [14]. However, instability, economic feasibility, and environmental impacts are challenges that have to be met for fully capturing the potential of nanotechnology in EOR [15]. As these approaches are continually developed through research, so will their benefits to the oil industry. In that case, more sustainable and efficient ways of recovering oil can be realized [16].

5. FUNDAMENTAL OF NANOTECHNOLOGY

Nanotechnology is an interdisciplinary study that involves the need for manipulation and engineering of materials on a nanoscale, normally in size from 1 to 100 nanometers [17]. At this scale, the material assumes unique physical, chemical, and biological properties remarkably different from their bulk material. This technology has been used to transform many areas of medicine, electronics, materials science, and energy [18]. It explains the basics of nanotechnology in order to understand its potential applications better, especially in some particular sectors like EOR.

Nanotechnology is the design, characterization, production, and application in changing shape and size at the nanoscale. The word "nano" is derived from a Greek word "nanos," which means dwarf, indicating the small size of the material involved. At the nanoscale, because of quantum effects and high surface area-to-volume ratios, materials exhibit novel properties, hence displaying higher reactivity and strength [19].

Nanoscale materials are substances whose at least one dimension measures less than about 100 nanometers. A nanometer is one-millionth of a millimeter, roughly 100,000 times thinner than a human hair. These materials are important because at this scale, they show unique optical, magnetic, electrical, and other properties. Such properties could greatly influence areas to include but not limited to electronics, medicine, and many other fields [20].

Nanotechnology involves the design and application of materials at dimensions of approximately a billionth of a meter-one nanometer (1x10^-9)-and hence are known as ultrafine particles [20]. Fig. 1 shows the size of nanoparticles relative to other living and nonliving things. The chemistry of nanoparticles is different from their bulk counterparts, due to a change in properties [21]. As the particle size reaches to nanoscale, their electronic structure, reactivity, and thermal and mechanical properties may change. Through nanotechnology, one can design materials and devices at the level of individual atoms and molecules. In the last two decades, a number of reports have been published on the natural design of colloids and nanoparticles [22].

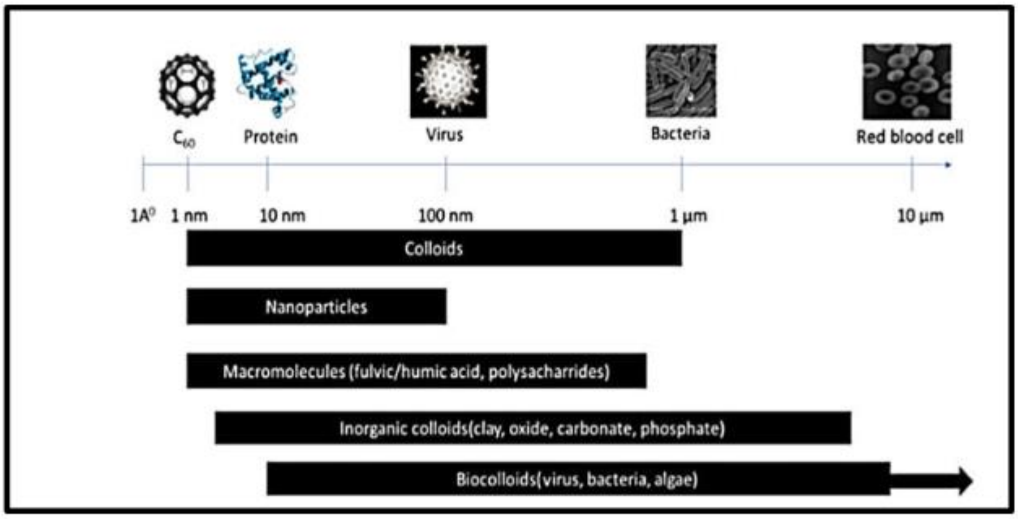

Fig. 1. Size comparison of different structures (living and non-living) [23]

The history of nanomaterials goes back to the time of the Big Bang, when nanostructures formed in early meteorites. Nature developed a lot of other nanostructures in due course of time, like seashells and skeletons. Early humans produced nanoscale smoke particles when they learned the use of fire [24]. However, nanomaterials started being explored much later scientifically. One of the first scientific reports in this field concerned the preparation of colloidal gold particles by Michael Faraday in 1857 [25]. Nanostructured catalysts have been studied for more than 70 years. Since the beginning of the 1940s, precipitated and fumed silica nanoparticles had been manufactured and marketed in the USA and Germany for use as a substitute for ultracarbon black in rubber reinforcement.

Recently, nanomaterials have attracted much attention from researchers due to their nanoscale size and unique physical, biological, and chemical properties compared to bulk materials. NMs are classified according to their size, chemical composition, shape, and sources. Several types of NMs have been synthesized from different materials and, accordingly, are categorized into different categories. Many NMs are produced in bulk quantities for industrial application purposes. The main sources of NMs are synthetic methods and naturally occurring nanoparticles. This chapter will explain the types and classifications of NMs, focusing on those from natural and synthetic sources [26].

6. TYPES OF NANOMATERIALS

Different types of nanomaterials are being produced for specific applications, it is important to have an appropriate classification of these materials. Most nanomaterials are solids, and size and dimensions can be defined with acceptable precision by various methods. A classification of nanomaterials was attempted by a scientist in the year 2000 on the basis of crystalline forms and chemical compositions of nanomaterials. This was not a broad approach since it did not consider the dimensions of the nanomaterials.

In a different study, scientists proposed a new classification based on dimensions: 0-Dimension, 1-Dimension, 2-Dimension, and 3-Dimension nanomaterials. This classification is mainly dependent on the mobility of electrons within the nanomaterials. In 0-Dimension nanomaterials, the presence of electrons is usually fixed, while in 1-Dimension nanomaterials, electrons can move freely along the x-axis, typically measuring less than 100 nm. Similarly, 2-Dimension and 3-Dimension nanomaterials have larger electron mobility along the x-y and x-y-z axis, respectively. The predictive precept of nanomaterial properties is another factor for classification of nanomaterials.

On the other hand, the presence of grain boundaries in nanomaterials defines their characteristics, as explained in Gleiter's classification. In addition, according to the classification by Pokropivny and Skorokhod, shapes and dimensionalities are critical in defining the properties of nanomaterials.

Nanomaterials can be categorized based on their dimensionality, composition and functionality:

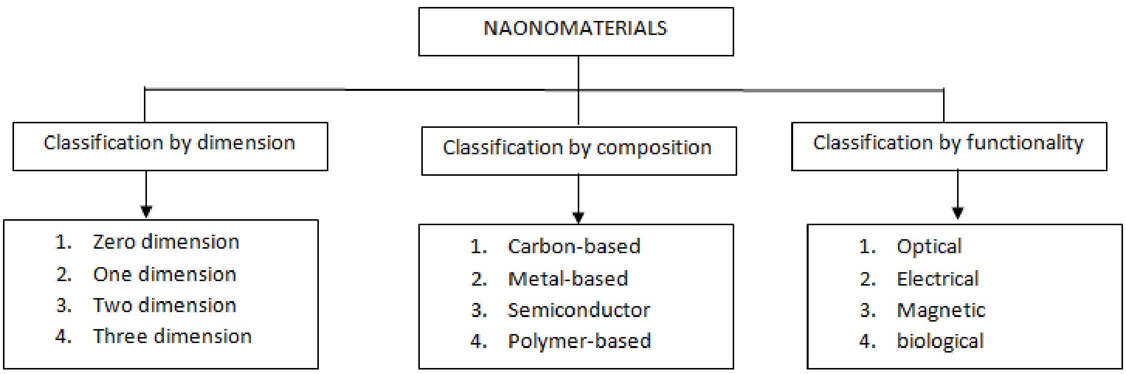

Fig. 2. Categorization of nanomaterials

A. Zero-Dimensional (0D) Nanomaterials: These materials are confined in all three-dimensional space. Examples include some NPs, for instance, those of metals like gold or silver or oxide, for example, silica and titanium dioxide. As the sizes are so small it is possible to be possessed with unique optical electronic and catalytic behavior [27].

B. One-dimensional nanomaterials: One-dimensional nanomaterials have only one dimension in the nanoscale, such as nanowires and nanotubes. The important example is carbon nanotubes (CNTs). Such nanomaterials possess superior mechanical properties, electrical conductivity, and find applications in sensors to energy storage [27].

C. Two-Dimensional Nanomaterials: 2D materials such as graphene and transition metal dichalcogenides, while they extend in two dimensions, have nanoscale thickness. Graphene is one-atom-thin sheet of sp2-hybridized carbon atoms arranged in a hexagonal lattice; it has emerged as one of the hot topics in nanotechnology research due to its exceptional electrical, thermal, and mechanical properties [27].

D. Three-Dimensional Nanostructures: In these materials, even though structured at nanoscale, the dimensions extend beyond this. Examples include nanocomposites, which combine nanoparticles with bulk material to improve mechanical, thermal, or electrical properties [27].

7. NATURAL NANO-MATERIALS

Natural nano-materials may be generated from biological systems such as microbes and plants, and also from human activities. Their generation is an easily accessible process because they are widely distributed throughout the hydrosphere, atmosphere, lithosphere, and biosphere. Indeed, our planet possesses naturally occurring nanomaterials in rivers, groundwater, oceans, lakes, rocks, soils, magma, and lava, and within microbial organisms and humans [26].

8. SYNTHESIS OF NANOMATERIALS

Synthetic method is by far the most common way to create nanomaterials because this provides a way in which to make nanomaterials using biological, physical, chemical, and hybrid technique [25]. The main reasons behind making synthetic nanomaterials is that large numbers of such materials can easily be fabricated having different shape and size. In synthetic approach it is also feasible to conjugate or link the chemicals or reagents specifically to nanomaterials. However, a huge challenge for synthetically designed nanomaterials is whether existing knowledge is sufficient to predict their performance. In addition, the environmental behaviors of synthetically produced nanomaterials also differ from those of their natural counterparts [21]. Currently, there are many types of nanomaterials being fabricated from various sources for different biological purposes.

In general, the synthesis of nanomaterials can be conceived to fall into two major approaches: the top-down and the bottom-up methods.

A. Top-Down Approaches: In top-down processes, larger bulk materials are subsequently reduced into nanoscale particles. Techniques include mechanical milling, lithography, and etching. While these methods can often produce high-purity nanoscale materials, they often give a wide size distribution and may not take full advantage of the unique properties of nanoscale materials (Cheraghian et al., 2013).

B. Bottom-Up Approaches: Bottom-up methods will build the nanoscale structures from molecular or atomic building blocks. Common techniques are CVD, sol-gel synthesis, and self-assembly. These methods may result in materials of higher uniformity and specificity of properties, and thus of potentially novel applications.

9. CHARACTERIZATION TECHNIQUES

Characterization of nanomaterials is an important aspect for understanding their properties and behaviors. Some of the various techniques include the following:

Transmission Electron Microscopy, TEM: generally offers high-resolution images of nanostructures, whose size, shape, and morphology are directly observable.

Scanning Electron Microscopy: provides detailed topography of the surface and detailed information on the composition.

Atomic Force Microscopy: measures forces and surface topography at the nanoscale, hence used to obtain insight into mechanical properties.

DLS (Dynamic Light Scattering): This technique is used for the determination of the size distribution of nanoparticles in suspension. XRD (X-ray Diffraction): This analysis characterizes the crystalline structure of nanomaterials.

10. UNIQUE PROPERTIES OF NANOMATERIALS

Their reduced size and increased surface area-to-volume ratio give nanomaterials unique properties.

A. Optical Properties: Some nanomaterials exhibit size-dependent optical properties, including quantum confinement effects. Quantum dots are semiconductor nanoparticles whose size determines the wavelength of the emitted light and are being used in displays and biomedical imaging [28].

B. Mechanical Properties: Mechanical strength in the case of nanomaterials is usually higher than that of bulk materials. For example, carbon nanotubes have very high tensile strength and elasticity, which enable their application as reinforcing materials in composites [28].

C. Chemical Reactivity: High surface area increases the rate of reactivity in nanomaterials, thereby increasing the catalytic activity. This attribute finds a useful application in various fields like catalysis and environmental remediation.

11. APPLICATIONS OF NANOTECHNOLOGY

Nanotechnology spans a wide fan of fields due to its versatility:

A. Medicine: The use of nanoparticles in medicine is done in drug delivery systems, imaging agents, and diagnostic tools. It can target specific cells. It may do less collateral damage, thereby allowing a minimization of side effects [29].

B. Electronics: Nanotechnology has completely revolutionized the field of electronics. It has become possible to miniaturize components which have led to faster and more efficient devices. Some nanoscale electronic devices include nanoscale transistors and memory devices [30].

C. Energy: Nanomaterials have important applications in energy industries relating to solar cells, fuel cells, and batteries, among others. In fact, the improved conductivity and reactivity of such materials may lead to the improvement of energy conversion and storage efficiencies [29].

D. Environmental Remediation: Nanotechnology provides novel opportunities for solving environmental problems, especially those concerning water treatment and soil remediation. Thus, nanoparticles efficiently can perform degradation of organic pollutants or contaminant adsorption [30].

12. CHALLENGES IN THE APPLICATION OF NANOMATERIALS

Despite all the brilliant prospects, nanotechnology also has its challenges, which should be pursued:
Safety and Environmental Issues: Toxicity and environmental impact would be fully studied for safe use in nanomaterials.

Economic Feasibility: Production cost and scaling up of nanomaterials remain so high that the development of more economic methods of synthesis is urgently needed.

Regulatory Framework: The establishment of transparent regulation and standards regarding the use of nanotechnology will help gain public confidence about safety concerns. Nanotechnology represents the frontier of the latest developments in science and engineering, offering transformational solutions within a wide array of fields. Having gained an understanding of the basics regarding nanomaterials, especially types, synthesis, characterization, and unique properties, it should be easier to work with such materials with the ultimate aim of coming up with interesting applications. As advancements continue, addressing the associated challenges will be crucial for realizing the full benefits of nanotechnology in fields such as enhanced oil recovery and beyond [30].

13. APPLICATION OF NANOTECHNOLOGY IN ENHANCED OIL RECOVERY (EOR)

The role of EOR techniques becomes indispensable in present times when the efficiency of conventional methods is sharply falling. Nanotechnology has cropped up as a promising approach towards EOR processes' improvement using nanoparticles and nanomaterials to increase the efficiency of oil recovery. This application of nanotechnology addresses several challenges related to high interfacial tension, wettability issues, and the need for more effective surfactants in traditional EOR methods [29].

14. MECHANISMS OF NANO-TECHNOLOGY IN EOR

Nanotechnology can enhance oil recovery through several modes of action, including the following:

A. Wettability Alteration: Wettability is a term that can be used to explain the spreading of a liquid on or adhesion to a solid surface. Most reservoir rocks are oil-wet, which negatively impacts the effectiveness of water in displacing oil. Nanoparticles can cause changes in the wettability of reservoir rocks from oil-wet to water-wet, a process that cannot help but improve the efficiency of water flooding. For instance, hydrophilic nanoparticles might be injected into the reservoir and modify the surface properties of the rock to allow for an improved displacement of oil by water [29].

B. Reduction of Interfacial Tension IFT: Nanoparticles can significantly reduce the interfacial tension between oil and water, which is an important phenomenon for mobilizing the trapped oil droplets. A lower IFT value will help the oil to move more easily within the porous media in a reservoir. Some research has illustrated those different types of nanoparticles, such as silica and titanium dioxide, can lower IFT with very positive effects on oil recovery rates [31].

C. Emulsion Stabilization: Emulsions are mixtures of oil and water that have an improved flow characteristic injected. The emulsions are stable with nanoparticles, allowing the oil dispersion in water to persist as a function of creating dispersed oil droplets in water, which enhances the recovery during flooding with the so-dispersed droplets [31].

D. Improved Mobility Control: Nanotechnology can improve the mobility of fluids within the reservoir. The addition of nanoparticles can modify the viscosity of the injected fluids, allowing better displacement of oil. This is particularly helpful in heavy oil recovery because high viscosity is usually one of the major obstacles to extraction [29].

15. TYPES OF NANOMATERIALS USED IN EOR

Various nanomaterials were explored in EOR applications as shown in Table 1 below.

Others include: Magnesium oxide, Iron oxide, Nickel oxide, Tin oxide, Zirconium oxide, Silane treated silicon oxide and Hydrophobic silicon oxide

A. Silica Nanoparticles: Of all the different nanomaterials used in EOR, silica nanoparticles have been studied the most. They are capable of changing wettability and reducing IFT, hence enhancing oil recovery. Research indicates that heavy oil recovery can be improved by silica nanoparticles through changes in the injected fluids' flow characteristics [31].

B. Metal Oxide Nanoparticles: Other metal oxides nanoparticles like titanium dioxide (TiO2) and zinc oxide (ZnO) have also been checked for EOR applications. These nanoparticles can reduce IFT and stabilize emulsions thus turning out to be suitable for enhanced oil recovery applications [31].

C. Carbon-Based Nanomaterials: Carbon-based nanomaterials like carbon nanotubes and graphene exhibit some unique properties that are useful in the EOR process. High surface area with mechanical strength makes them effective for modifying the properties of reservoir fluids, hence improving oil recovery efficiency [32].

Table 1. Different types of Nanomaterials used in Enhanced oil Recovery

s/n	Nanomaterials	Researchers
1	SiO2	Reported in 2017 by Lu et al.
2	TiO2	Reported in 2008 by Sohel et al.
3	MoS2	Reported in 2020 and 2021 by Qu et al.
4	Al2O3	Reported in 2020 by Rezvani et al.
5	CuO	Reported in 2019 by Bahraminejad et al.
6	ZnO	Reported in 2018 by Alnarabiji et al.
7	Graphene	Reported by AfzaliTabar et al. in 2017

D. Polymer Nanocomposites: There is growing interest in the application of polymer nanocomposites, comprising nanoparticles combined with polymers, for EOR applications. This is due to their potential to enhance the viscosity and stability of injected fluids, which could result in improved oil displacement and recovery rates [32].

16. RECENT ADVANCES IN NANO-TECHNOLOGY FOR EOR

Recent studies indicated the effectiveness of nanotechnology for enhanced oil recovery through various experimental works and field trials.

A. Laboratory Studies: Many laboratory experiments are showing the prospect of nanoparticles in enhanced oil recovery. For instance, the work presented by Nezhad et al. [8] considered the application of hydrophilic silica nanoparticles during the course of polymer flooding processes. Results showed there was a significant increase in oil recovery rates due to changes in wettability and IFT reduction provided by the nanoparticles.

Another study by Aliabadian et al., [4] focused on the application of graphene oxide nanosheets to heavy oil recovery. The results presented that the addition of graphene oxide enhanced the flow behavior of the injected fluids, which improved oil recovery accordingly [8].

Nanoparticles are one of the promising *In-situ* agents for reservoir engineering problems. The types of nanoparticles that could be used include oxides of aluminum, zinc, magnesium, iron, zirconium, nickel, tin, and silicon. The study of the effects of these nanoparticle oxides on oil recovery is vital since oil recovery is the main objective of the oil industry. EOR experiments were done using these nanoparticles under surface conditions using distilled water, brine, ethanol, and diesel as dispersing media.

Two rounds of experiments were conducted by Ogolo et al., [33]. The first involved displacing injected oil with nanofluids; the second involved soaking the sands in nanofluid for 60 days before injecting the oil and displacing the same with low salinity brine. Overall results showed that the use of nanofluids during oil displacement was more feasible.

The experimental results showed that aluminum oxide and silicon oxide are effective agents for EOR. Among these, aluminum oxide nanoparticles were found to be more effective in oil recovery with distilled water and brine as dispersing agents. In the tests conducted with ethanol, the highest rate of recovery throughout the experiments was obtained with silane-treated silicon oxide, while hydrophobic silicon oxide in ethanol also showed very good performance. Aluminum oxide contributed to the reduction of oil viscosity, whereas silicon oxide changed rock wettability and reduced interfacial tension between oil and water because of the presence of ethanol.

When diesel was used as a dispersing fluid, the miscibility of diesel and crude oil complicated the determination of actual crude oil recovery; however, overall results with aluminum, nickel, and iron oxides were favorable. On the other hand, the permeability problems developed in magnesium oxide and zinc oxide dispersed in distilled water and brine. In general, the dispersions prepared with distilled water reduced the oil recovery. These again emphasized the importance of the dispersed fluid besides the nanoparticles while developing different oil recovery characteristics in oil reservoirs.

17. SILICA NANOPARTICLES IN THE MIDDLE EAST

In various oil fields throughout the Middle East, silica nanoparticles have been used to boost oil recovery. These nanoparticles primarily serve to alter wettability and reduce interfacial tension. Field trials have indicated significant enhancements in oil recovery rates, with some instances showing increases of up to 15%. By modifying the wettability of reservoir rocks and decreasing interfacial tension, silica nanoparticles improve water imbibition and oil displacement, leading to greater recovery efficiency.

17.1 Polymer-coated Nanoparticles in North America

In Canadian heavy oil reservoirs, polymer-coated nanoparticles have been applied to enhance the efficiency of steam-assisted gravity drainage (SAGD). These nanoparticles improve thermal stability and heat distribution within the reservoir, optimizing the effectiveness of thermal recovery methods. Field applications have demonstrated considerable increases in oil recovery rates, with polymer-coated nanoparticles facilitating smoother oil flow and better sweep efficiency.

This results in higher oil production and improved operational efficiency in heavy oil reservoirs.

17.2 Iron Oxide Nanoparticles in India

Iron oxide nanoparticles have been utilized in Indian oil fields to catalyze chemical reactions that produce in-situ gases, assisting in oil displacement and recovery. Field trials have shown encouraging results, including increased oil production and reduced operational costs. These nanoparticles catalyze reactions that enhance the mobility of oil in the reservoir, leading to improved sweep efficiency and higher recovery rates. This application highlights the potential of catalytic nanoparticles in enhancing EOR processes and maximizing production from existing reservoirs.

17.3 Surfactant-Coated Nanoparticles in Offshore Reservoirs

Offshore reservoirs face unique challenges for oil recovery due to complex geological formations and harsh conditions. Surfactant-coated nanoparticles have been introduced in these environments to reduce interfacial tension and improve oil mobility. Field applications have demonstrated significant enhancements in oil recovery rates, with these nanoparticles promoting smoother oil flow and better sweep efficiency. This application illustrates the versatility of nanoparticles in tackling various challenges associated with offshore oil recovery operations.

Overall, case studies and field applications provide strong evidence of the practical advantages of nanotechnology in improving oil recovery efficiency across different regions and geological settings. From the Middle East to North America and India, nanoparticles have proven effective in enhancing sweep efficiency, increasing oil recovery rates, and optimizing reservoir performance. These case studies emphasize the transformative potential of nanotechnology in addressing global energy needs and maximizing the use of existing oil reserves. As research and development in nanotechnology progress, its integration into EOR practices is expected to become increasingly important for the sustainable development of the oil and gas industry.

Field tests have also been conducted to assess the effectiveness of nanotechnology in EOR. For instance, one of the pilot projects undertaken in the Middle East utilized silica nanoparticles in the process of water flooding. The results indicated clearly that the oil recovery ratio was greater compared to conventional methods, proving that the use of nanotechnology is practically viable in the field [31].

17.4 Effect of Nanoparticles on Oil Recovery

A combination of surfactants and NPs facilitates releasing the oil droplets trapped in narrow throats and micro-channels of reservoir rock for improved oil recovery. These processes are associated with various factors that enhance oil recovery, such as changes in wettability of reservoir rocks, formation of spontaneous emulsion, variations in the interfacial tension between reservoir fluids, and flow property changes of porous media. Over the years, various types of NPs have been tested and studied regarding enhanced oil recovery. Among others, the addition of TiO_2 NPs increased oil recovery by 80%, as Ehtesabi et al. claimed, in oil-wet sandstone. Shah carried out experiments with CuO NPs. He also reported an increase in oil recovery-as high as 71%. Kanj et al. carried out the flooding performance of surface-modified carbon nanoparticles and reported an increase in the oil recovery factor for carbonate reservoirs of more than 96% by carbon-based fluorescent NPs. To study emulsion stability as well as polymer solutions at reservoir conditions, several researchers have prepared different NP-modified polymers. Wang et al. studied the effects of Na–Mt particles and hydrolyzed polyacrylamide on the stability of emulsions by examining the interfacial properties of water–oil, dilatational viscoelasticity, IFT, and zeta potentials. It was reported that at increasing concentrations of NPs, IFT, the zeta potential of oil droplets decreased while it increased in dilatational viscoelasticity. More precisely, while the dilatational viscoelasticity and the IFT increased with the concentration of NP, the zeta potential reached its saturation value above 250 mg/L. During EOR in heavy oil reservoirs, pH conditions could be influenced by nanoparticles coated with polymers.

Hendraningrat et al. performed an extended laboratory experiment on hydrophilic silica dioxide nanoparticles for EOR under different wettability conditions and different temperatures of the reservoir (oil-wet, intermediate-wet, and water-wet). They examined how temperature, initial wettability, extra oil recovery, and the process of nanofluid flooding-or nano-EOR-interact. Experimental results demonstrated that these NPs were stable at high temperature, which, in turn, hindered particle aggregation in porous media. In all, their findings provided a critical review of nanofluid properties for EOR within a wide range of reservoir conditions.

Recently, several systematic studies have been done on the effects of NPs on surfactant flooding. Recently, Zargartalebi et al. conducted a study on surfactant flooding with nanoparticles. It was demonstrated that NPs can enhance oil recovery, especially at an equal concentration of NPs and surfactants. Besides, hydrophobic NP-modified surfactants exhibited higher efficiency compared to their hydrophilic counterparts.

In one recent study, a new type of polymer nanocomposite was prepared with nano-silica and free-radical polymerization in order to enhance properties for the polymer flooding system. Properties such as oil displacement efficiency, mobility control, salt and temperature tolerance, and rheological characteristics were studied in different states. The results showed that the studied polymer nanocomposite exhibited excellent performances as a chemical agent for strong mobility control, high temperature tolerance, and good rheological properties for polymer flooding. Other important work by Hendraningrat also illustrated that polymeric nanospheres have enormous potential in the recovery of residual trapped oil within porous media. His findings demonstrated that NPs reduce water permeability and mobility ratio, which enables the polymer solutions to reach the unswept zone of oils and thereby recover them. Moreover, NPs have an important role in changing the oil displacement mechanism and wettability.

18. CURRENT RESEARCH TRENDS IN THE APPLICATION OF NANOTECHNOLOGY IN ENHANCED OIL RECOVERY (EOR)

18.1 Hybrid Nanomaterials

The interest in using hybrid nanomaterials comprising more than one type of nanoparticle to enhance properties and performances is presently in the learning curve. For example, nanoparticles of silica combined with a polymer result in better stability and improved viscosity of injection fluids and hence may yield better results in oil recovery. The trend aims at combining strengths of different materials for efficient EOR methods [34].

18.2 Biodegradable Nanoparticles

Much emphasis is being placed on the development of biodegradable nanoparticles with less environmental impact. With this in mind, fundamental research using naturally derived materials, for example, chitosan or starch-based nanoparticles, is done, and these materials turn out to be effective in altering wettability through a reduction of interfacial tension with minimal environmental impact, showcasing an increasing awareness of sustainability within the EOR practice [35].

18.3 Nanotechnology in Low Salinity Water Flooding

Recent research has focused on the combined synergistic effects of nanotechnology with low-salinity water flooding techniques. By adding nanoparticles to low-salinity water, there is an attempt to enhance oil recovery through better wettability alteration and reduction of IFT. This may provide an economical and environmentally friendly approach toward enhanced oil extraction [35].

18.4 Smart Nanomaterials

Therefore, smart nanomaterials will come into the light that can sense the environmental stimuli such as temperature, pH, or salinity and would release certain agents or alter the properties at pre-specified conditions along the reservoir. This will dynamically help in enhancing the process of EOR. The current trend in research is focused on modifying nanomaterials according to specific features of the reservoir [17].

18.5 Advanced Characterization Techniques

The improved understanding of the nanoparticle interactions with the reservoir rocks at the nanoscale is now possible thanks to advances in various characterization techniques, including high-resolution microscopy and spectroscopy. Enhanced characterization will help in designing nanomaterials for intended applications and achieving better EOR performance.

18.6 Field-Scale Applications and Pilot Studies

There is more emphasis on scale-up from lab studies to field-scale applications and pilot projects. The researchers are focusing on the effectiveness of nanotechnology under realistic conditions, performance evaluation of nanoparticles under different reservoir conditions, and data on their economic viability [35].

18.7 Collaboration between Industries and Academia

Currently, the bridging between fundamental research and applied research is increasingly being done through collaboration of research efforts among academia, industry, and governmental organizations. Such collaborations will result in knowledge exchange that will promote innovative nanotechnology solutions for EOR [34].

18.8 Computational Modeling and Simulation

Computational modeling and simulation have also become important methods to predict nanoparticle behavior under reservoir conditions. Researchers applied advanced modeling techniques to investigate nanoparticles interacting with crude oil and reservoir rocks, allowing them to design and optimize EOR processes [35].

18.9 Emphasis on Safety and Environmental Impact

Safety and environmental concerns in the application of nanomaterials in EOR are also increasingly being put under research. Testing toxicity and ecological effects of different nanoparticles are being conducted so that their applications do not harm human health or create environmental hazards [34].

These trends are a reflection of the dynamism of the research landscape into the application of nanotechnology in enhanced oil recovery. In fact, as the field continues to evolve, further innovation and collaboration will be integral in harnessing the full potential of nanotechnology toward even more efficient and sustainable oil recovery practices.

19. CHALLENGES AND LIMITATIONS

Despite such promising results, the following challenges have to be resolved for the effective deployment of nanotechnology in EOR:

A. Stability of Nanofluids: The most important factor is the stability of nanofluids under hostile reservoir conditions. This can lead to aggregation or sedimentation of nanoparticles, reducing their effectiveness. Further research is required to formulate a stable formulation that can survive the harshest conditions of oil reservoirs [35].

B. Economic Feasibility: The final major barrier to nanoparticle application is a basic economic one: manufacture and deployment at appropriate scales is expensive. Expensive synthesis methodologies and studies of economic viability in regard to nanotechnology-based EOR processes are essential to develop if commercialization is ever to be pursued [34].

C. Environmental Impact: The application of nanomaterials in EOR practices needs a comprehensive environmental impact analysis. The knowledge on the toxicity and ecological impacts of nanoparticles will help design safe and sustainable oil practices [34].
Future Directions

The future of nanotechnology in EOR has tremendous scope and areas that could be pursued:

A. Advanced Nanomaterials: Further investigation of new nanomaterials, including hybrid nanoparticles and biodegradable nanoparticles, may lead to much more effective and environmentally acceptable EOR applications. Synergetic effects of various combinations of nanoparticles may also lead to significant improvements in the recovery rates [36].

B. Integration with Other Technologies: The combination of nanotechnology with other EOR methods, such as MEOR or low-salinity water flooding, could even further improve the overall efficiency of recovery. It is these types of multidisciplinary approaches that may yield the innovative solutions being searched for to solve some of the multidimensional problems in oil recovery [37].

C. Regulatory Framework: Obviously, clear legislation and directives on the application of nanotechnology in EOR will be required for safety and public confidence. Responsible utilization of nanotechnology in the petroleum industry will involve researcher-industry-regulator cooperation in formulating a proper code that addresses all the potential risks posed by nanotechnology [38].

20. CONCLUSION

Nanotechnology-enhanced EOR techniques presently engage nanoparticles to alter wettability and reduce interfacial tension. Nanoparticles can also be used as emulsions stabilizers. All this helps in improving oil displacement and an increase in oil recovery ratios. The main materials involved in EOR are silica and metal oxide nanoparticles, which so far are effective in both laboratory and field studies. In spite of such advancement in this field, issues related to stability of nanofluids, economic viability, and environmental safety are yet to be sorted out. Current research trends include hybrid and biodegradable nanoparticles, nanotechnology combined with low-salinity flooding, and intelligent nanomaterials which are sensitive to reservoir conditions. All in all, still promising, the successful implementation of nanotechnology in EOR calls for continued research and agreement among the parties involved to ensure efficiency and sustainability. Nanotechnology can indeed play a great role in enhanced oil recovery processes by providing solutions to many problems that traditional EOR methods have been facing. Nanoparticles might improve oil recovery efficiency by altering wettability, reducing interfacial tension, and emulsion stabilization. Quite a few laboratory and field trials in recent times have reported encouraging oil recovery rates with different nanomaterials, including silica nanoparticles, metal oxides, and carbon-based materials. However, their viable applications need to be complemented by stability issues, economic feasibility, and environmental concern. Eventually, when research will be continually upgraded, the incorporation of nanotechnology with EOR could help in introducing different sustainable and economical methods for the extraction of oil.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/126793