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Recent Developments and Future Prospects of Nanomaterials in the Petroleum Industry: Enhancing Upstream Operations and Addressing Sustainability Challenges

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Abstract: Nanomaterials are being employed to enhance the performance and durability of equipment such as pipes and drilling bits. They are used as smart additives in drilling fluids, cementing, and fracturing operations. Owing to their exceptional mechanical, electrical, and thermal properties, a wide range of nanomaterials has been applied across multiple domains. Research on these materials has progressed beyond laboratory and simulation studies, with several successful field implementations reported worldwide. However, as the use of engineered nanoparticles expands rapidly, it is essential to assess their potential risks to human health, ecosystems, and the environment. While nanotechnology holds significant promise for the upstream oil industry, establishing clear standards and sustainable infrastructure is necessary to minimize potential harm and ensure economic feasibility. In this review, we explain the current applications of nanotechnology in upstream operations, assess its effectiveness through laboratory and field data, and highlight the major challenges and future prospects for its industrial deployment.

Introduction

The world today faces significant challenges in meeting energy demands, driven by rapid population growth, accelerated industrialization, and widespread desires for improved living standards. Consequently, the exploration of diverse energy sources to satisfy this demand is of paramount importance.[1] Green energy sources, including solar, wind, hydroelectric, geothermal, and biomass, have garnered considerable attention due to their environmental friendliness and absence of carbon dioxide emissions. However, these sources in aggregate are still insufficient to meet global energy needs. At present, and likely for the coming decades, the oil and gas industry continue to be the primary source of energy supply.[2] Therefore, the exploration and development of unconventional alternative resources is crucial for significantly enhancing oil production. It is estimated that a substantial 75% of unconventional reserves are unrecoverable. Moreover, even in conventional reservoirs, despite the application of various enhanced oil recovery (EOR) techniques, an average of over 40% of the original oil in place remains trapped and unproducible.[3] Thus, the utilization of cutting-edge technologies and scientific advancements is essential to overcome existing challenges and maximize energy production from the oil and gas sector. Nanomaterials represent a relatively novel class of materials that have made a dramatic entry into numerous global industries in recent decades, yielding significant and valuable impacts.[4] As illustrated in Fig. 1, research and studies focused on nanotechnology in the upstream and downstream oil industry have become increasingly prominent, with major oil companies filing numerous patents in this domain. Furthermore, these investigations are not confined to laboratory settings; numerous projects have been defined and executed at a large-scale field level.[5-7]

Nanomaterials have played a crucial role in various areas, including exploration monitoring, equipment quality enhancement and upgrading, modifing drilling fluids, mitigating formation damage, and synergizing enhanced oil recovery (EOR) mechanisms in recent decades.[8,9] In order for better understanding, Fig. 2 illustrates a word cloud highlighting the applications of nanomaterials in the upstream oil industry, which demonstrates their wide-ranging applications. However, it is important to note that this technology is not without challenges. While it is effective in various applications, nanomaterials can have significant side effects. For example, environmental concerns, material sourcing difficulties, and limited economic feasibility studies are among the complexities that may hinder the widespread implementation of these materials in the near future.[10]

This article discusses different types of nanomaterials and their unique properties, evaluating their efficiency across various applications. In addition, this article examines real-world applications and operational challenges to clearly define the current status and role of nanotechnology in the oil industry.

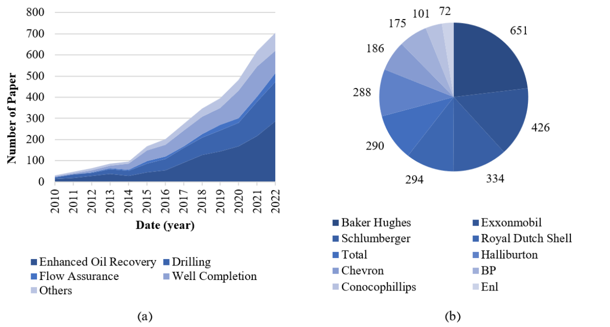


Fig. 1. a) Research papers on the application of nanomaterials in the oil industry, categorized by application type (based on Sciencedirect articles from 2010 to 2022); b) Patents filed by major oil companies related to nanotechnology in the oil industry up to 2023

Fig. 2. Word cloud of nanotechnology applications in the upstream oil and gas industry

1- Nanotechnology

Nanotechnology is defined as the science of studying, developing, and applying materials at the nanoscale (less than 100 nanometers or 0.1 micrometers). At this extremely small scale, the properties and behavior of materials undergo significant changes. As such, nanotechnology primarily focuses on analyzing and optimizing the structures and characteristics of materials at this dimensional scale.[11] Today, few industries remain untouched by the capabilities of nanotechnology. This technology has found widespread applications across various sectors including electronics, biotechnology, tissue engineering, drug delivery, and the food supply chain.[12] The oil industry is no exception, and alongside the widespread adoption of this technology, major private and state-owned oil companies have incorporated research and development activities centered on nanotechnology into their agendas. Nanomaterials come in a wide variety of forms, and there are multiple methods for their synthesis. Broadly speaking, there are two main approaches for producing nanomaterials: top-down and bottom-up methods, which can be selected based on their intended applications.[13] Fig. 3 schematically illustrates the processes involved in each method, along with other key details such as material sources, types of nanoparticles, and their morphologies. Additionally, the figure highlights the usage percentages of the most prominent nanoparticles in upstream oil operations, with silicate and aluminum oxide recording the highest utilization rates.[14] The applications of nanotechnology in upstream industries have been categorized into eight distinct groups, which are illustrated in detail in Table. 1.[15]

Table. 1. Types of nanomaterials and nanotechnologies used in the petroleum industry

Nanomaterial Type	Applications
Nanoparticles	• Drilling fluids • Wellbore cementing (casing-cement bonding) • Underbalanced drilling • Prevention of multiphase flow in wells and pipelines • Foam injection for coning control
Nanocoatings	• Nanocomposite coatings for drill bits • Casing perforation • Turbine drilling systems
Nanosensors	• Seismic exploration for oil/gas reservoirs • Well logging for reservoir characterization • Logging while drilling (LWD) • Mud logging • Formation evaluation and wear monitoring in drill bits • Top drive systems • Flow path detection in production monitoring
Nanocomposites	• Directional and horizontal drilling • Coiled tubing applications • Hydraulic fracturing operations • Pipeline pigging for maintenance and integrity • Steel nanocomposites for well casing • Polymer nanocomposites for EOR
Nanocrystals	• Casing perforation
Nanofluids	• Reservoir pressure equalization
Nanofilters	• On-site oil/water/gas separation
Nanoinformatics	• Seismic data processing for exploration

2- Applications of Nanotechnology in Upstream Oil Industry

Drawing upon peer-reviewed research and scholarly publications in recent years, it is unequivocally evident that nanotechnology has permeated all facets of the oil industry. Corroborating this assertion is the utilization of sophisticated sensors for oil reservoir characterization and the augmentation of data acquisition in well testing and logging procedures.[16] Nanoparticles demonstrate their most salient utility in oil and gas well drilling, ranging from fortifying drill bits and drill strings to refining the attributes of drilling fluids and cementing operations. Within Enhanced Oil Recovery (EOR), these materials would exert their most profound influence through diverse mechanisms, encompassing wettability modification and synergistic effects in chemical and thermal methodologies.[17] Nevertheless, the purview of nanotechnology within this industry extends beyond these domains. The subsequent sections will delve into the expansive applications of nanomaterials in the upstream oil sector.

3- Advanced Sensors in Oil & Gas Recovery

Despite the use of modern technologies in oil and gas production, typically more than 40% of resources remain underground after primary, secondary, and even tertiary recovery. To address this challenge, a multi-million-dollar research consortium called the Advanced Energy Consortium has been established at the University of Texas, with the primary goal of developing smart micro and nano sensors capable of mapping the reservoir's three-dimensional space. For this purpose, nano sensors are injected into the reservoir, and after determining its 3D structure, the recovery of both new and existing hydrocarbon resources will significantly increase. Consequently, in the future, the results of this research are expected to provide a better understanding of subsurface resources and fluid behavior.[18] Furthermore, the use of nano tracers in reservoirs has found special applications. These tracers are used to determine the connectivity between wells, identify the behavior of the injected fluid, and detect fractures and cracks in pipes. Nano sensors and tracers have been employed cumulatively in several large-scale industrial projects by being deployed underground for these purposes.[19,]

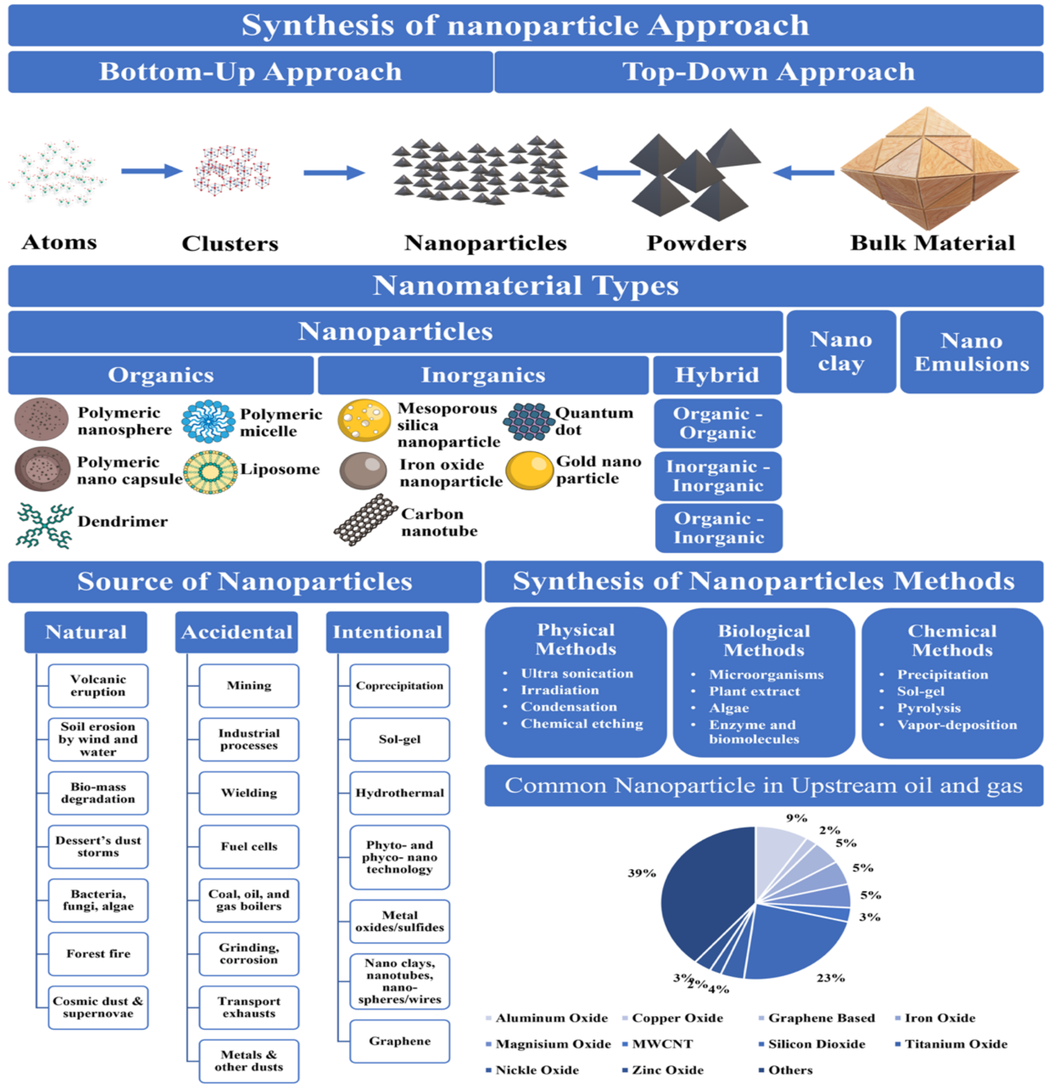


Fig. 3. Supply sources, synthesis methods, and morphologies of the most prominent nanomaterials in the upstream oil and gas industry

4- Seismic Survey Operations

In seismic exploration, a carefully orchestrated sequence of detonations is initiated at predetermined geolocations, whereupon specialized instrumentation quantifies the intensity and amplitude of the resultant seismic waves. The acquired seismic data furnishes valuable insights into the Earth's subsurface architecture, delineating reservoir boundaries, and characterizing fluid types. Data acquisition in seismic surveys is executed utilizing sophisticated sensor technologies.[21] Leading multinational corporations within this sector, such as BP and Shell, have integrated nanotechnology to optimize 4D seismic surveys for the identification and extraction of hydrocarbons from underexplored geological formations. Furthermore, entities like Texas Instruments have harnessed nanotechnology to engineer Micro-Electro-Mechanical Systems (MEMS) devices, thereby facilitating enhanced precision and fidelity in seismic data acquisition.[22] These sensor modalities procure information by quantifying magnetic, biological, thermal, chemical, mechanical, and optical phenomena within the operational environment. In the ensuing analytical phase, electromechanical apparatuses, augmented with artificial intelligence algorithms, scrutinize the acquired datasets and modulate actuators based on pre-defined parameters encompassing displacement, tuning, and filtering to realize the stipulated objectives. Significantly, the incorporation of nanotechnology has yielded a marked enhancement in data fidelity whilst concurrently diminishing equipment dimensions without compromising measurement accuracy.[23]

5- Drilling Fluids

Drilling fluids, with their specialized compositions, are essential components of well drilling operations. In fact, successful drilling would not be possible without an effective mud system. Initially, it was thought that drilling fluids were solely used to remove drill cuttings from the bottom of the well, essentially serving as a cleaning agent. However, as the industry has advanced, it has become evident that drilling mud performs several critical functions. These include cooling and lubricating the drill bit, controlling subsurface pressures, stabilizing the walls of the wellbore, forming a mud cake, preventing corrosion of the drill string, and transmitting hydraulic power from the pumps to the drill bit.[24] To achieve these objectives, drilling fluids must be carefully tailored with various additives to suit specific geological conditions. Research indicates that the incorporation of different nanomaterials as additives can significantly enhance the key properties of drilling fluids. The primary goals of using nano-additives include reducing costs by minimizing material consumption, improving rheological properties for optimal viscosity and density, enhancing resistance to thermal and environmental stress, and decreasing fluid loss and filtration.[25,26] The latest findings on the application of nanoparticles in drilling fluids, organized by fluid type and nanomaterial type (emphasizing particle size) are summarized in Table. 2.

Table. 2. Application of Various Nanomaterials in Enhancing Fluid Properties

Year	Drilling Fluid Composition	Nanomaterial	Size (nm)	Description	Reference
2020	Water - Bentonite - Xanthan gum - KCl - HEC or PAC	TiO_2	250	Nanoparticle synergy with PAC and HEC, alongside beneficial filtration reduction, improved thermal stability and rheological properties. Nanoparticles dispersed on mud cake surface, filling nano/micro-sized gaps, reducing filtration rate.	[27]
2020	Fresh water - Caustic soda - Soda ash - KCl - PAC.LV - PHPA - Glycol - Limestone	SiO_2	12, 22, 54	Addressing shale formation challenges where oil-based fluids are impractical due to cost, environmental impact, and logging interference. Glycol-based water mud with amorphous silica nanoparticles enhanced shale stability, showing optimal performance at 22nm/10% concentration.	[28]
2021	Water - NaCl - XCP - PAC.LV - Polyamine - PHPA - Soda ash - MCC	ZnO	40-50	Non-damaging drilling fluid with superior shale inhibition. 1wt% nanoparticles increased thermal stability >100°C and reduced fluid loss by 49%. CFD simulations confirmed stable linear pressure drop across temperatures.	[29]
2022	Deionized water - Calcium bentonite - Sodium carbonate - PAC	PAC-DDAS-SiO_2	20	High-temperature/calcium/salt-resistant fluid for deep/ultra-deep wells. Maintained rheology at 260°C with only 8mL filtration. Anionic groups in copolymer formed H-bonds/ionic bonds with clay, preventing Na^+/Ca^{2+} penetration.	[30]
2022	Fresh water - Soda ash - CMC - Bentonite	ZnO/TiO_2/U-MWCNTs/F-MWCNTs	40-50	Poly(AN-co-VP) composite with nanoparticles enhanced bentonite mud. 0.5g F-MWCNTs increased yield point by 250%. Improved PV, YP, and filtration volume with thermal stability.	[31]
2022	Water - Caustic soda - Bentonite - PAC.LV - Xanthan gum - Barite - Defoamer	ZnO	28	1wt% nanoparticles increased YP/gel strength by 61.54%/125% at 40°C. At 0.5wt%/80°C, improvements were 60%/50%, showing better efficacy at low concentrations/high temps.	[32]
2023	Water - Bentonite - Barite - PAC - CTAB	SiO_2	68	Cationic surfactant-modified nanoparticles for geothermal wells. Optimal 2wt% CTAB yielded stable viscosity, reducing fluid loss by 29.5% and cake thickness by 28.7%. Zeta potential correlated with performance.	[33]

6- Drilling Cement

Cementing oil and gas wells involves mixing cement, water, and necessary additives and pumping it into the annular space between the casing pipes and the wellbore wall. This process aims to prevent fluid movement behind the casing, reduce the risk of formation fracturing, prevent potential blowouts from high-pressure zones, and protect the casing itself.[34] It is worth noting that cement is also used to plug and abandon wells that have reached the end of their productive life. For example, in the Gulf of Mexico alone, over 19,000 abandoned wells are planned for future sealing due to potential environmental concerns.[35] A suitable cement must have low viscosity for injectability, controllable setting time, strength and durability under stress and over time, and effective sealing between the casing and the formation. These properties can be enhanced using nanomaterials with unique quantum-related characteristics. Nanomaterials such as SiO_2, MgO, TiO_2, Fe_2O_3, Al_2O_3, and graphene oxide have been explored as potential additives to improve cement properties. Among these, silicate is the most widely used nanoparticle in cementing operations due to its abundance, affordability, ease of access, and promising results.[36] The effectiveness of nano-additives in cement slurry design depends on their reactivity and compatibility with the cement. Various studies have shown that nanomaterials interact differently with different cement types (Class A, Class G, Class H, etc.), meaning the same concentration of nano-additives may yield conflicting results with different cement type.[37] In addition to nano-additives, nano-engineered cement has significantly improved compressive strength, corrosion resistance, and other relevant properties under challenging well conditions.[38] However, the current state of nanotechnology in cementing operations remains experimental, and there is a pressing need for economic studies to enable field-commercial applications.

7- Manufacturing Drilling Tools and Equipment

The most critical component in well construction is the drill bit. These vital tools are positioned at the bottom of the drill string and are responsible for crushing rock formations and advancing drilling operations. Nanotechnology has contributed to the development of drill bits with longer service life and higher crushing efficiency through the use of nanocoatings.[39] Additionally, researchers have developed nanocomposite pipes for other drilling equipment, such as casing and tubing, which exhibit exceptional corrosion resistance and thermal insulation properties, performing remarkably well under high-pressure and high-temperature conditions. Recent advancements in nanotechnology have also led to the production of nanocomposites and nanostructured coatings with superior architectures that enhance the lifespan of components.[40] Some of these coatings are designed to interact with the fluids flowing through the pipes, forming extremely strong and dense protective layers that can both prevent corrosion and reduce friction. Finally, nanostructured coatings made from combinations of metals and ceramics offer unique properties, including high hardness, low friction coefficients, and excellent thermal and electrical conductivity. Overall, nanotechnology has significant potential to improve efficiency in this sector.[41,42]

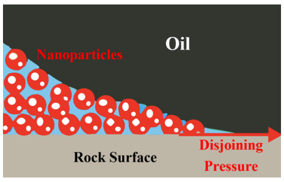
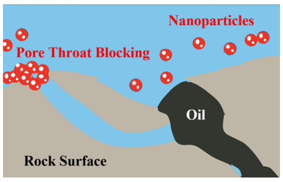
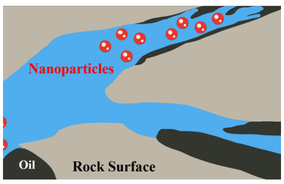
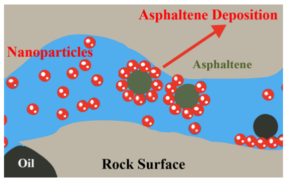
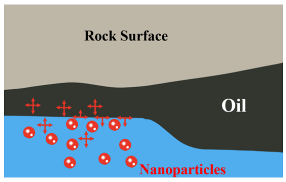
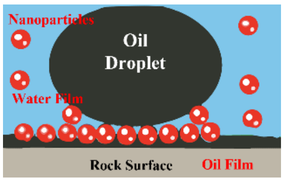
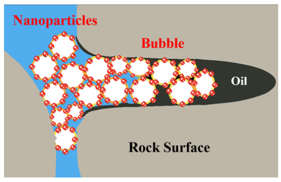
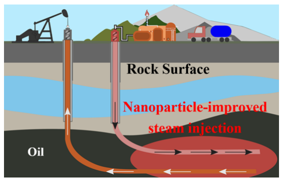
8- Well Stimulation

Well stimulation methods are used to reduce reservoir damage and enhance well productivity. The two primary stimulation techniques are acidizing and hydraulic fracturing. Both aim to effectively treat damaged zones, allowing restoration of permeability to its ideal state or even higher. This can significantly improve the productivity index or injectivity of the well.[43] Nanotechnology has various applications in hydraulic fracturing for oil and gas reservoirs, breaking traditional patterns and providing notable advancements. By incorporating nanomaterials into water-based, polymer-based, foam-based, and viscoelastic surfactant (VES) fracturing fluids, the rheological properties, proppant-carrying capacity, thermal stability, and other characteristics can be effectively enhanced. This improvement is achieved through cross-linking between nanomaterials and polymers, the formation of reversible structures with micelles, and synergy with surfactants. As a result, this leads to higher-quality hydraulic fractures during well stimulation.[44] Moreover, nanomaterials can modify the surface properties of proppants using various methods, such as coatings, which significantly improves attributes like compressive strength. In particular, when proppants are derived from industrial waste (e.g., fly ash), nanoparticles can serve as effective reinforcements, increasing the volume of reservoir stimulation and creating high-conductivity channels for oil and gas flow. Nanomaterial-based hydraulic fracturing completion tools demonstrate desirable properties, including low density, high strength, and temperature resistance. These tools are typically insoluble in fracturing fluids and dissolve only in the flowback fluid, leaving no residue after fracturing. This simplifies operations and greatly improves efficiency.[45] Compared to conventional fracturing fluid treatment methods, techniques such as nanophotocatalysis and membrane separation can more effectively remove contaminants, achieving deep purification of flowback fluids. Additionally, magnetic nanoparticles can be mixed with proppants and injected to track their distribution within fractures, allowing for real-time monitoring of the fracturing process. In this context, the emerging FracBot technology is designed not only to enhance the efficiency of hydraulic fracture monitoring but also to enable more precise morphological mapping of hydraulic fractures in reservoirs, thanks to its high integration and multifunctional capabalities.[46]

9- Enhanced Oil Recovery (EOR)

Given the maturity of most global oil reservoirs and the numerous challenges associated with drilling and production from unconventional reservoirs, there is a constant need for optimized enhanced oil recovery (EOR) methods to extract remaining oil. Currently, nanotechnology has gained significant attention for improving reservoir recovery rates.[47-50] The nanoparticles commonly used in EOR such as silica (SiO_2), titanium oxide (TiO_2), and aluminum oxide (Al_2O_3)—are smaller than reservoir pore sizes, allowing them to pass through without damaging the formation or clogging pores, thereby enhancing recovery. Another key advantage of nanoparticles is their exceptionally high surface-area-to-volume ratio, owing to their minuscule size, making them highly effective for chemical EOR operations. To optimize and properly utilize nanomaterials under various operational conditions, a thorough understanding of their mechanisms in improving oil recovery is crucial.[51] Table. 3 briefly reviews the primary proposed mechanisms by which nanomaterials enhance oil production.[52,54.]

Table. 3. Proposed Mechanisms for Nanotechnology Applications in Enhanced Oil Recovery

Disjoining Pressure		Nanoparticles in injected water can form a wedge-shaped layer and create osmotic pressure, detaching oil droplets adhered to rock surfaces and thereby increasing oil production. Key factors: Nanoparticle type, concentration, and size; ions in water; rock properties; temperature.
Pore Throat Blocking		Nanoparticles block fine pore throats through two mechanisms: Mechanical trapping: Pores are smaller than nanoparticle size, leading to clogging. Jamming effect: Nanoparticles temporarily aggregate, sealing pores and redirecting flow to other paths, increasing pressure differential and production. Once oil is drained from other paths, pressure drops, and the blocked pore reopens. Key factors: Nanoparticle type, size, and concentration; injection flow rate; pore throat radius; rock porosity
Mobility Ratio Reduction		Nanoparticles increase injected fluid viscosity, reducing the mobility ratio. This promotes piston-like displacement, improving sweep efficiency. Studies show a 100x viscosity increase in CO_2 with less than 1% nanoparticles. Key factors: Nanoparticle type, size, and concentration; temperature; shear rate.
Asphaltene Deposition Prevention & Control		Asphaltene deposition, caused by thermodynamic instability, is a major issue in reservoirs, wells, and facilities. Nanoparticles adsorb onto asphaltene molecules, preventing aggregation and stabilizing them in the oil phase. Key factors: Nanoparticle type, size, and concentration; asphaltene structure; water ion content; contact time.
Interfacial Tension Reduction		Certain nanoparticles act as surface-active agents, reducing interfacial tension (IFT); a key mechanism in chemical EOR. Some nanoparticles enhance surfactant performance, further lowering IFT and enhancing oil recovery.
Wettability Alteration		Wettability alteration is crucial in EOR. Nanoparticles adsorbed on rock surfaces can shift rock preference from oil to water or gas, overcoming capillary forces and improving injection efficiency. For gas reservoirs, making surfaces gas-wet reduces liquid condensation near wellbores, enhancing production.
Foam/Microemulsion Stabilization		Nanoparticles form a protective layer at fluid interfaces, increasing surface elasticity and stabilizing foams/microemulsions. Their high resistance to temperature and salinity allows foam use in harsh reservoir conditions.
Enhancing Thermal EOR Efficiency		Nanoparticles improve thermal EOR methods (e.g., steam injection, in-situ combustion) by: Increasing thermal conductivity of injected fluids or oil. Upgrading heavy oil via chemical reactions, reducing viscosity and lightening oil for higher recovery.

10- Industrial and Semi-Industrial Applications

Recent advancements in nanotechnology have enabled its large-scale application in the oil industry. Currently, various countries have utilized these materials for diverse purposes, with the highest diversity of projects implemented in Colombia. Since 2012, significant strides have been made in using nanomaterials in various sectors, such as addressing formation damage, heavy oil production, improving drilling and fracturing fluids, and EOR on a field scale.[55,56] In China, over 8,000 projects have employed nanomaterials for improved water injection into reservoirs and separation processes. Additionally, given the importance of drilling, several countries, including Canada[57], Brazil[58], and Iran[59], have utilized nanomaterials in large-scale projects to enhance drilling fluids, reduce filtrate loss, and mitigate formation damage. Hungary has used nanomaterials to reduce water cut, the U.S. for gas injection, and Saudi Arabia has employed them as tracers to better understand reservoir conditions.[60] Figure 4 illustrates some ongoing or completed industrial-scale projects involving nanomaterials in different countries, along with the types of nanoparticles used.[61] Although real-world projects over the past decade demonstrate the significant progress in industrializing these materials, a more meaningful collaboration between industry and academia is essential to further advance this technology effectively.

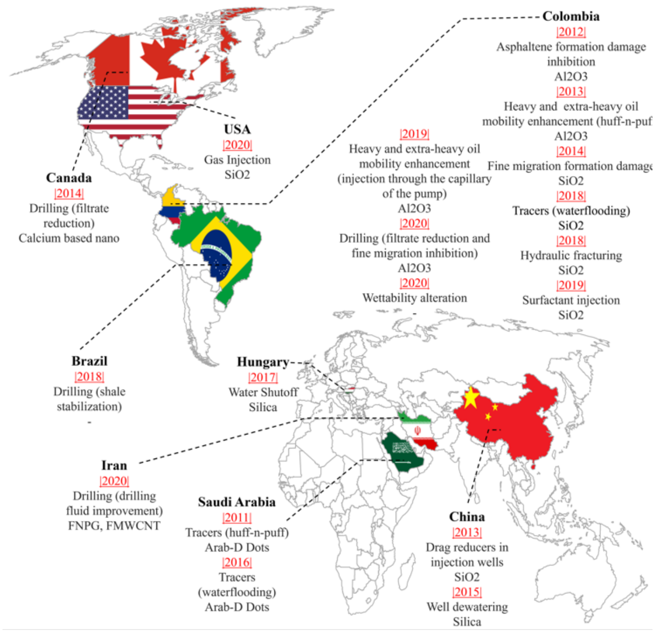


Fig. 4. Industrial Applications of Nanomaterials Worldwide

11- Challenges and Limitations

One of the most significant challenges in applying nanotechnology to the oil and gas industry is related to the production methods of nanomaterials and the energy required for their synthesis. Large-scale industrial production of nanomaterials is not economically feasible due to the traditional synthesis techniques used. In fact, this non-standardized production approach is the primary reason for the high cost of nanomaterials. Therefore, for industrial applications, it is necessary to explore cheaper and simpler methods for producing these materials, and adequate resources must be allocated for research in this field. On the other hand, comparing the number of real-world projects implemented by industry players with the patents and research papers published by academics reveals that, despite the high success potential demonstrated at the laboratory scale, widespread implementation at the industrial and field levels has not yet occurred. There remains a degree of uncertainty and operational risk in scaling up these technologies. The question arises: Can these nanomaterials maintain their efficiency at larger scales and become economically and technically viable alternatives to conventional materials? Thus, further research in pilot and semi-industrial projects could be a crucial step toward operationalizing these materials.[60]

Finally, the most critical issue concerning the use of nanomaterials is their impact on health, safety, and the environment (HSE). Figure 5 illustrates the hazards associated with some of the most widely used nanoparticles. Given their high potential for inhalation or even absorption through human skin, several standards, such as those set by the EPA, ASTM, and ISO, have been established to mitigate potential risks, and strict adherence to these guidelines is essential. However, for large-scale applications, it is necessary to further prove the capabilities of these materials in various fields while making modifications or developing new types of nanomaterials with lower risks to humans and the environment to minimize these concerns.[61]

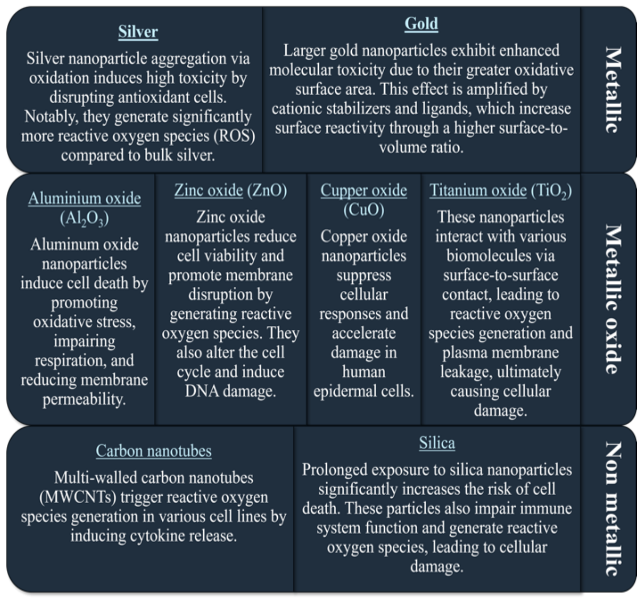


Fig. 5. HSE (Health, Safety, and Environment) Challenges of Nanoparticles in the Oil Industry

Conclusion

Nanotechnology is a significant cutting-edge technology with applications across various industries, including oil and gas. Studies have investigated the use of nanomaterials like nanoparticles, nanocoatings, nanosensors, and nanocomposites in upstream and downstream operations. The findings suggest that these materials have the potential to enhance or upgrade various applications in the industry. Nanomaterials offer high resistance and flowability, making them effective as sensors and tracers in reservoir exploration and assisting in assessing rock and fluid properties. Their use in drilling, well completion, and stimulation is becoming increasingly valuable. Nanotechnology has enhanced equipment like drill pipes and bits through nanocoatings and nanocomposites, improving properties such as corrosion resistance and thermal performance under extreme conditions. It has optimized drilling fluids and cementing operations, enhancing rheological properties and reducing fluid loss. Research suggests that an optimal nanoparticle concentration of 0.5% to 1% by weight yields the best results. While studies on nanoparticles in drilling cement have been inconclusive, materials like silicon oxide, manganese, aluminum, and graphene show promise in enhancing compressive strength and corrosion resistance. Nanomaterials also show substantial effectiveness in fracturing fluids used for well stimulation. Observations suggest that nanoparticles can modify and improve rheological properties, proppant transport, thermal stability, and the surface properties of proppants.

One of the most significant applications of nanomaterials in the oil and gas industry is their role in enhanced oil recovery (EOR). Their potential to improve recovery rates, both independently and in conjunction with other additives, has been thoroughly documented in various studies. These nanomaterials operate through multiple mechanisms such as disjoining pressure, which can help improve the interaction between oil and water; pore throat blockage, which reduces the passage of fluids and optimizes flow; mobility ratio reduction, which balances the movement of oil and water to enhance recovery efficiency; and wettability alteration, which modifies the interaction of fluids with rock surfaces to facilitate extraction. The exceptional stability of nanomaterials makes them particularly valuable in bolstering the stability of foams and emulsions, crucial for maintaining optimal conditions during oil recovery processes. Moreover, they play a vital role in the removal of stubborn asphaltene deposits that can hinder flow, and enhance filtration techniques to ensure smooth flow assurance in production systems. Ultimately, the integration of nanotechnology into EOR not only helps to mitigate formation damage but also addresses negative changes in permeability, paving the way for more efficient and sustainable oil recovery practices. Countries like Colombia, China, Iran, Saudi Arabia, and the United States have led in nanotechnology, implementing promising field-scale projects. However, there is limited information on the identification and management of health and environmental risks posed by nanomaterials. Additionally, traditional production methods can present challenges to feasibility. Strengthening collaboration among academia, industry, and government is essential to overcome these obstacles and optimize performance in the upstream oil sector. Further research and development are crucial for realizing the potential of nanotechnology in the oil and gas industry.

Conflicts of interest

There are no conflicts to declare.

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