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Review article

Unveiling the revolutionary role of nanoparticles in the oil and gas field: Unleashing new avenues for enhanced efficiency and productivity

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ABSTRACT

Prominent oil corporations are currently engaged in a thorough examination of the potential implementation of nanoparticles within the oil and gas sector. This is evidenced by the substantial financial investments made towards research and development, which serves as a testament to the significant consideration given to nanoparticles. Indeed, nanoparticles has garnered increasing attention and innovative applications across various industries, including but not limited to food, biomedicine, electronics, and materials. In recent years, the oil and gas industry has conducted extensive research on the utilization of nanoparticles for diverse purposes, such as well stimulation, cementing, wettability, drilling fluids, and enhanced oil recovery. To explore the manifold uses of nanoparticles in the oil and gas sector, a comprehensive literature review was conducted. Reviewing several published study data leads to the conclusion that nanoparticles can effectively increase oil recovery by 10 %–15 % of the initial oil in place while tertiary oil recovery gives 20−30 % extra initial oil in place. Besides, it has been noted that the properties of the reservoir rock influence the choice of the right nanoparticle for oil recovery.

The present work examines the utilization of nanoparticles in the oil and gas sector, providing a comprehensive analysis of their applications, advantages, and challenges. The article explores various applications of nanoparticles in the industry, including enhanced oil recovery, drilling fluids, wellbore strengthening, and reservoir characterization. By delving into these applications, the article offers a thorough understanding of how nanoparticles are employed in different processes within the sector. This analysis may prove highly advantageous for future studies and applications in the oil and gas sector.

1. Introduction

Over the past 20 years, global energy consumption has been gradually increasing. That aside, exploration of hydrocarbon resources in low-risk geological circumstances is increasingly becoming rare. As a consequence, exploration challenges in various locations keeps on increasing for there is a larger chance of mishaps or natural disasters. Due to those challenges, meeting the needs of a growing population energy demand is becoming even harder as energy extraction costs rises [1]. It is noteworthy to bear in mind that most recently discovered oil and gas formations are situated in high-pressure and high-temperature conditions. Exploration and production under such environments are costly and challenging. That's why getting access to these resources may be challenging and costly. The economic viability of these resources may be hampered as a result [2]. To circumvent these issues, researchers have looked into nanoparticles as potential answers [3,3,4]. Ever since its inception in the latter half of the 1980s, nanotechnology has played a pivotal role in bringing together a multitude of scientific disciplines [3], including physics, chemistry, materials science, biology, electronics, and mechanics [3,4]. This convergence has paved the way for the creation of innovative frameworks that have enabled technological advancements to tackle complex challenges [5]. The wide field of nanotechnology has inspired researchers to investigate and improve materials' atomic-level characteristics. Basically, the properties of materials between 1 and 100 nm at the nanoscale provide new

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insights on how to improve existing materials successfully and effectively construct unique ones with eye-catching attributes. Nanomaterials can be either particles, rods, sheets, or crystals, and have special optical, electrical, and mechanical properties that make them useful in a variety of industrial fields [6][6] The study of physical properties of innovative nanoparticles opens up new horizons in science and engineering by establishing concepts and theories. In microelectronics, manufacturing, biology, chemistry, energy, and agriculture, the new properties of nanoparticles have been used to produce superior products with spectacular performance [6,7]. The idea of nanotechnology was stimulated by Richard Feynman's 1959 California Institute of Technology lecture titled, "*There's Plenty of Room at the Bottom*," in which he highlighted the possibility that one day, scientists may be able to manipulate single atoms and molecules and he believed that materials at that level will have unique properties [8]. The development of nanotechnology over the past two decades has greatly advanced scientific and technical research and created many new opportunities [10]. Through increased productivity and superior products created at lower overhead costs, which boosts demand, nanoparticles has had a clear and significant impact on society in many fields. Nanoparticles are therefore crucial to contemporary lifestyles. Nanotechnology has shown that nanoparticles outperform similar macro- and micro-materials in terms of their chemical, physical, thermal, mechanical and tribological capabilities [9][9],[10]. Several industries, including but not limited to electrical, electronics, communications, medicinal, and coating, have already embraced nanotechnology and produced important technological breakthroughs nanoparticles [11]. One of these sectors is the upstream and downstream segments of the oil and gas industry, where the revolution of nanoparticles applications encompasses various domains [9]. Numerous scholars have put forth the application of nanotechnology within the oil and gas sector, encompassing the mitigation of viscosity in heavy crude oil [12,13], wireless H_2S sensors based on nanoparticles to augment safety in oil and gas facilities [14], smart cement and cement additives for oil and gas operations [15], the increase in cuttings transport, decrease the average slip velocity of the sludge particles, and the reduction of pressure using nanoparticles in the drilling fluid [16–18], minimizing water invasion in shale using nanoparticles [19], enhanced oil recovery using nanoparticles [20] and many other applications that are going to be reviewed under the current work. When for example a flooding system contains nanoparticles, the injected fluid becomes more viscous, which improves the mobility ratio and increases displacement efficiency, which in turn helps to create a large volume of oil [21–23]. The dispersion of nanoparticles can change the wettability [24–26].When considering a novel application of nanoparticles in the oil and gas industry, many concerns are often raised, such as why nanoparticles? What distinguishes nanoparticles from the standard approach? Large surface area to volume ratios, high reactivity, and tunable optical and electrical properties are only a few of their special qualities that set them apart from bulk materials [27]. Large surface area to volume ratios allows for more interactions with molecules per unit mass, which can result in increased reactivity and other features [17]. They have high reactivity because the surface atoms of nanoparticles are more likely to come into contact with air and water molecules, which can then interact with them [18]. By modifying the size, composition, and optical and electrical properties of nanoparticles, their qualities are also affected and, in most cases, superb [5]. They are therefore desirable for a range of applications, including sensing, imaging, and catalysis [7]. Additionally, due to the nanoparticles' small size, they may easily pass through the formation's tiny pores, allowing the employed nanoparticles to circulate freely within them [6]. Due to the above-mentioned special qualities of nanoparticles, their application in the oil and gas industry can be justified. Size, shape, physical, chemical, and mechanical properties are used to categorize nanoparticles [28,29]. As a result, each nanoparticle has distinct physical, chemical, and mechanical properties [29,30]. They can remain free or be tied together depending on the attractive and repellent factors present. Nanoparticles have a strong chemical reactivity and a greater surface-to-volume ratio [31,32]. In oil and gas reservoirs with high salinity and temperature, nanoparticles are also resistant to deterioration [32]. They are ideal for a variety of enhanced oil recovery techniques because of these qualities. Different nanofluids are used in enhanced oil recovery (EOR) techniques such as chemical, thermal, miscible, polymer and microbiological flooding [33,34]. Nanoparticles are added to fluids to create nanofluids. With this technique, fluid characteristics are enhanced and improved at low volume proportions of the dispersion medium [35,36]. Silica nanoparticles have been the subject of the most in-depth research and have demonstrated encouraging EOR outcomes [37,38]. In addition to SiO_2 nanoparticles, which have been employed for more than a decade already, recent research has examined the potential of Al_2O_3, MgO, and Fe_2O_3 in EOR applications [35,39]. Disjoining pressure is one of the main EOR processes for nanoparticles. Other important EOR mechanisms include injection fluid viscosity increase, asphaltene precipitation and prevention, interfacial tension, and wettability changes [40]. They are used as nano-catalysts, nano-emulsions, nanocomposites, and nanofluids [1,19,20,43–48].

2. Aim of this review and its novelty

Nanoparticles have gained significant attention in the oil and gas sector due to their unique properties and potential applications. The novelty of an in-depth analysis of how nanoparticles are used in the oil and gas sector lies in its comprehensive review of the various ways nanoparticles are being utilized in this industry. This review work delves into the specific types of nanoparticles being employed, their functions, and the impact they have on enhancing processes within the oil and gas sector. Furthermore, it provides insights into the latest advancements and innovations in nanoparticle technology as applied to this particular industry. The review work also explores the challenges and opportunities associated with the use of nanoparticles in the oil and gas sector, shedding light on potential areas for further research and development. By critically analyzing the current state of nanoparticle utilization in this industry, it offers valuable perspectives for researchers, engineers, and professionals seeking to leverage nanotechnology for improved efficiency, sustainability, and environmental impact within the oil and gas domain.

A comprehensive assessment of the utilization of nanotechnology, highlighting its potential and practical implications.

Integrated circuit technology that are lighter, with reduced size, and superior than ever before have been made possible by nanotechnology. Not only that but also in the medical field the development of medicinal treatments that target certain cells and tissues have been made possible [41,42]. The technology has also made it possible to make materials at a scale that is much smaller than before, as a consequence materials application in our daily life has expanded [41,42]. Akin to the mentioned fields, the oil and gas field is anticipated to see a successful expansion in the application of nanotechnology [43].

In the review, we'll pay close attention to numerous studies done by researchers about the use of nanotechnology in the oil and gas sector. To evaluate the possibilities of this technology in the sector, we will carefully examine the studies' findings. We will also examine the risks and difficulties that come with using nanotechnology to the oil and gas sector. Finally, based on our research, we will come to some conclusions and offer some suggestions.

The use of nanomaterials and nanotechnology for oil and gas operations, drilling, and production has been extensively studied in recent years. For instance, the performance of oil-based muds, which are used in drilling operations and to stabilize the wellbore, is being improved by the use of nanomaterials such as nanofibers, nanoclays, and nanocomposites [44–46]. Long before nanomaterials were created, ancient Romans utilized many naturally occurring nanoscale particles [47,48]. These particles were employed in a variety of products, including food, medicine, and cosmetics [49]. Engineered nanomaterials can also have special qualities that are not present in nature, such as reactivity, physical characteristics, and electrical conductivity, in addition to their distinctive chemical features [47,48]. This is caused by the fact that nanoparticles have a high surface area to volume ratio and that they can interact with their surroundings in ways that bigger materials cannot. They are appealing for a range of applications, including medicine delivery, sensors, and catalysts due to their distinctive features [50]. The nanotechnology revolution has been sparked by this discovery. The aforementioned elucidates that the fundamental factor in the advancement of nanomaterials has been the manipulation of existing materials at the nanoscale level, resulting in novel properties and functionalities that cater to specific needs. Carbon black, nano-clay, carbon nanotubes, polymeric, metal nanoparticles (NPs), and quantum dots are among the various types of engineered nanoparticles.

3. Nanoparticle utilization in the oil and gas industry

This section presents a comprehensive examination of the latest applications of nanoparticles in the oil and gas industry, encompassing water treatment, enhanced oil recovery (EOR), drilling fluids, cementing, nano membrane, and well stimulation. The discourse entails a tabulated synopsis of the utilized nanoparticles, the scrutinized parameters, and their efficacy in augmenting the desired parameters.

3.1. Application of nano-particles in water treatment

Oil and gas field operations may be classified into two distinct sectors, namely upstream and downstream. The upstream sector pertains to the exploration and production of oil, while the downstream sector is primarily concerned with the refining, processing, purification, marketing, and distribution of the resulting products. Both upstream and downstream sectors employ water in accomplishing its activities, such as in drilling fluids, enhanced oil recovery/improved oil recovery (EOR/IOR), and in oil refinery processes, which significantly taint the huge volume of the produced waters [51,52]. Treatment of contaminated water is essential but increasingly difficult due to the negative environmental effects of industrial water pollution [53]. Physical, chemical, and biological techniques like adsorption, chemical precipitation, flocculation, and membrane treatment can be used to remove pollutants from effluent from the oil industry. However, using nanomaterials for water treatment and purification processes demonstrates appealing qualities [53–56]. Cellulose nano-fibers or nanocrystals are a compelling substitute for adsorbents in wastewater treatment applications due to their exceptional specific surface area, economical cost, abundant natural availability, and eco-friendliness [56,57]. It has been reported that the heavy metal ions and organic impurities can be removed using cellulose nanoparticles as adsorbents, and also the surface functionalization may improve the effectiveness of the pollutants' binding to the cellulose nanomaterials [58–62]. Literatures report that adding succinic acid groups to cellulose nanocrystals (CNCs) dramatically improved their ability to bind Pb^{2+} and Cd^{2+} out of aqueous solutions [63–68]. Additionally, heavy metal ions, organic solvents, and crude oil can all be removed using cellulose-based nanocomposites as adsorbents [69,70]. It has been reported that silane-treated, cross-linked polyvinyl alcohol (PVA) and cellulose nanofibril (CNF) hybrid organic aerogels exhibit excellent absorption for heavy metal ions (such as Pb^{2+} and Hg^{2+}) and crude oil [71]. Akin to that, the report also reveals that functionalized cellulose nanofibril aerogels with oleophilic coatings like titanium dioxide can result in the formation of a selective oil-absorbing material capable of floating on water [72–75]. This material can be used again after washing, recycled, or incinerated along with the absorbed oil [72]. Researchers in their curiosity trying to enhance the surface area of the adsorbents presented a hydrophobic and nano-porous chitosan-silica composite aerogels with an exquisite oil absorbency efficiency and which can be re-used multiple folds up to ten times [76]. That aside, there have been another promising form of water treatment reported, the nanofiltration separation process, the technique can be used to purify and desalinate injected water for EOR processes, water produced in oil fields, and water used in refineries. Nanofiltration (NF) membranes have evolved tremendously since their creation in the late 1980s [77]. NF membranes, possessing properties that lie midway between those of reverse osmosis (RO) and ultrafiltration (UF), have been utilized in a multitude of fascinating applications, such as desalination, water treatment, and wastewater treatment [78]. Comparing nanofiltration membranes to traditional technologies, they are more effective at eliminating pollutants from small adjourned oil droplets and dissolved substances [79–81]. Not only that, but a tubular ultrafiltration (UF) membrane made of an Al_2O_3-poly (vinylidene difluoride) nanocomposite has been also reported. This membrane performed incredibly well in the treatment of oily wastewater [82,83]. From that results it was noted that the addition of nano-sized Al_2O_3 particles improves membrane anti-fouling performance. Water from the oil sands process, which is mostly produced during the oil sands production process, can also be cleaned using reverse osmosis and nanofiltration membranes [80,84,85]. In their experiment, the water that had been impacted by the oil sands process was pretreated using the coagulation-flocculation-sedimentation (CFS) method prior to nanofiltration and reverse osmosis, yielding an efficient desalination of 98.5 %. Therefore, nanofiltration membranes can be applied in the oil and or water separation, gas purification, and wastewater treatment. More details are presented in Table 1 underneath with details of the types of the nanoparticles, parameters considered, and the reference considered.

3.2. Enhanced oil recovery applications of nanoparticles

Enhanced oil recovery techniques have been employed to extract the residual percentage of original oil from areas that are not amenable to water flooding. As a result of the fact that a substantial proportion of the oil reserves remain untapped following primary and secondary recovery methods, amounting to two-thirds of the total oil in place, extensive research has been undertaken to enhance oil recovery techniques [95]. These techniques, collectively known as enhanced oil recovery (EOR), encompass chemical injection, thermal recovery, and gas injection, and have demonstrated a marked increase in oil recovery rates as depicted in Fig. 1 [96]. The conventional chemical EOR method involves the use of polymers, surfactants, or alkaline substances to enhance sweep efficiency and oil displacement efficiency, thereby facilitating the recovery of reserved oil [96,97]. The nanofluids technique holds promise for augmenting production beyond that achieved by traditional chemical EOR, as well as improving injection efficacy, which has garnered global interest [98,99]. In order to further improve the efficacy of EOR methods, numerous studies have been conducted to investigate the potential benefits of incorporating nanoparticles. Table 2 presents a concise overview of the latest research endeavors pertaining to the utilization of nanoparticles for the purpose of augmenting enhanced oil recovery (EOR) techniques, including the specific parameters targeted and the nanoparticles investigated. The primary aim of these investigations is to examine the impact of nanoparticles on enhancing oil recovery by improving a parameter associated with the process. Although using nanoparticles (NPs) to improve some metrics may be advantageous, doing so could potentially have a negative effect on other parameters. Researchers reported that the addition of zinc oxide NPs can result in the creation of bigger particles, which can make injection challenging [100]. Furthermore, when NPs are added to brine or ethanol, recovery rates may be lower than when using brine or ethanol alone. Injection obstruction and settling-related problems have also been mentioned in earlier investigations [101]. It is imperative to acknowledge that the utilization of NPs has the potential to modify permeability up to a specific threshold, beyond which a decrease in porosity and absolute permeability may ensue [102], particularly when all contact surfaces are covered with NPs.

3.3. Drilling fluid applications of nanoparticles

Owing to their distinctive characteristics, nanomaterials possess considerable potential for application and can prove instrumental in enhancing mudcake quality, facilitating film formation, mitigating lost circulation, and [119–122]. Various nanomaterials, including nanocomposite filtration-reducing agents, nanocomposite viscosifiers, nanosized emulsion lubricants, nanometer organoclays, and others, have been introduced, all of which have had a significant impact on the drilling process. Nanomaterials serve a multifaceted purpose in the drilling and completion process, particularly in intricate formations and harsh conditions, such as deep wells with high temperatures [123–125]. The incorporation of nanomaterials into drilling and completion fluids yields numerous benefits. Various additives are employed to augment the distinct characteristics of drilling fluids, including their rheological and filtration properties [126–132]. The development of drilling fluids using conventional additives is subject to certain constraints, such as temperature and particle size limitations of the additives [127–129]. Consequently, nanoparticles have been subject to extensive investigation to assess their potential in surmounting these constraints. The preponderance of proposed applications of nanotechnology in the oilfield can be classified into six discrete domains, specifically: (1) sensing or imaging, (2) enhanced oil recovery (EOR),

Table 1
A summary of the application of nanoparticles in water treatment.

Studied Nano Particles	Parameters attention drowned to	References referred to
Graphene oxide (GO) and reduce graphene oxide (rGO).	Contain best TX-100 adsorption capacity, inhibits anaerobic denitrification, effective tetracycline adsorbents.	[53]
NaP1 zeolites (Na_6Al_6 $Si_{10}O_{32}$, $12H_2O$)	Removal of heavy metals from acid mine wastewaters, remove Cr (III), Ni (II), Zn (II), Cu (II) and Cd (II) from metal electroplating wastewaters.	[86,87]
Electrospun nanofiber membranes (ENMs)	The membranes presented a noteworthy increase in flux while maintaining a comparable rejection rate in comparison to conventional membranes, displayed high capability of removing unwanted wastes from wastewaters.	[88]
Surface-oxidized CNTs using hydrogen peroxide, $KMnO_4$, and nitric acid	Removal of Cd^{2+}, Cu^{2+}, Pb^{2+}, and Zn^{2+} from aqueous solutions, shows a very good adsorbing capacity for oil from water, and it removes organic contaminants from water.	[56,89–91]
Cellulose nanocrystals	Displays an excellent adsorption capacity in removing Pb^{2+} and Cd^{2+}.	[57,92]
Carbon based adsorbent material with Phosphorus doping.	Revealed high efficiency in removing sulfur from the commercial diesel, removal of heavy metals from wastewaters.	[59,93]
The grafting of nanocrystallites of the UiO-66-NH_2MOF on cellulose fibers	Demonstrated rapid and effective removal of model contaminants, dichromate ions containing Cr (VI) and methyl orange (MO),	[61]
Nanofibers membrane with amino-based ionic liquid	Displays a reliable efficiency in removing the heavy metal ions	[62]
Carboxylate-functionalized adsorbent based on cellulose nanocrystals.	The adsorption kinetics of this material align well with the pseudo-second-order model, and thermodynamic analysis has revealed that the adsorption process is both spontaneous and exothermic. Additionally, isothermal study has demonstrated a monolayer adsorption behavior that follows the Langmuir model.	[94]

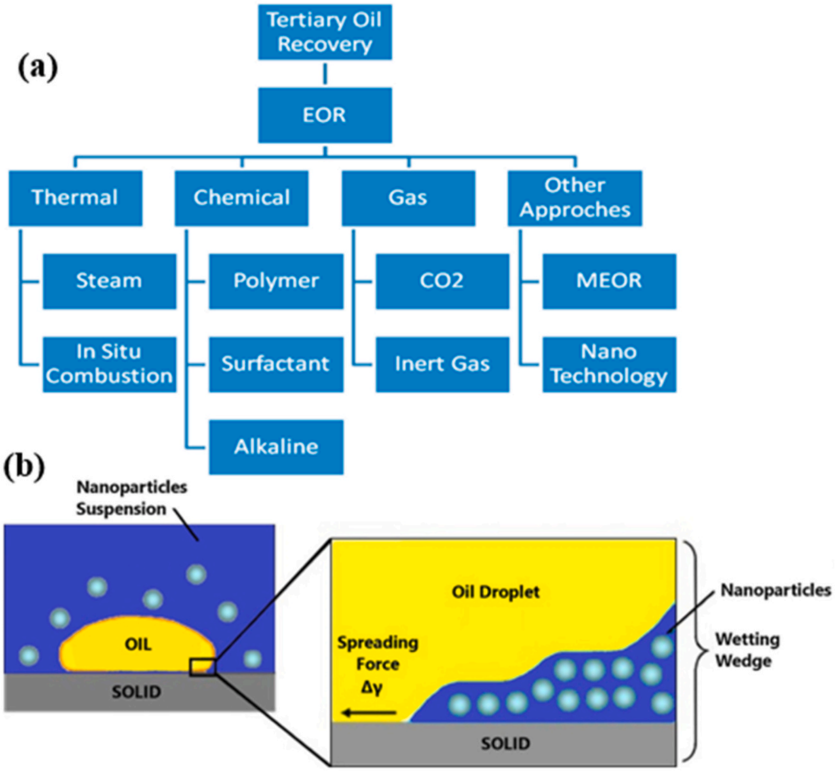

Fig. 1. (a) Types of tertiary oil recovery [103,104] (b) Oil–solid displacement driven by film tension gradient and the role of structural forces [105,106].

Table 2
Application of nanoparticles for EOR.

Studied Nano Particles	Parameters attention drowned to.	References referred to.
Fe_3O_4 (Magnetite)	Reduction of Oil Viscosity.	[107]
ZnO/CNT (carbon nanotube)	Heavy oil viscosity reduction.	[108]
Modified SiO_2 with silane coupling agent KH-560	Enhancing recovery rate.	[109]
Silica nanoparticles/IIT Nanofluid	Crude oil displacement.	[105]
Aluminum oxide	Reducing oil viscosity.	[100]
Aluminum oxide		
Silicon dioxide	Improving the water's rheological characteristics for use in EOR	[110]
Graphene oxide	Reducing oil viscosity.	[111]
Cellulose nanocrystals (CNCs)	Enhancing both the stability of oil in water emulsions and conformance.	[112]
Polyacrylamide polymer + Graphene-based zirconium oxide nanocomposite	Using it as a cross-linker for water shutdown while reducing the generation of extra water.	[113]
Nickel oxide/silicon dioxide	Increasing oil recovery in low-concentration environments.	[114]
Polymer-coated nanoparticle	Enhanced solubility and stability, increased stabilization of foams and emulsions, and easier transport across porous media.	[115]
Nano-suspension (NS) which is Surface-functionalized nanocellulose	NSF (NS flooding) increased oil recovery.	[116]
Hydrogel microspheres consisting of acrylamide (AAm) and acrylic acid (AA) monomers, and silica nanoparticles (SNPs)	Compared to water flooding, hydrogel spheres boost the oil recovery factor more.	[117]
Fe_3O_4/SiO_2	Improved recovery techniques such altering wettability, lowering interfacial tension (IFT), reducing oil viscosity, forming and stabilizing colloidal systems, and reducing asphaltene precipitation.	[118]

Table 3
Application of nanoparticles in drilling fluids.

Studied Nano Particles	Parameters attention drowned to	References referred to.
Aluminum Oxide, Copper Oxide, and Magnesium Oxide	Improving the rheological qualities of drilling fluid that is based on water.	[130]
$ZnTiO_3$ nanoparticles	Enhance the water-based drilling fluid's rheological and filtrate loss characteristics.	[131]
TiO_2 nanoparticle	Increase the drilling fluids' rheology, electrical conductivity, and thermal conductivity.	[132]
Nano-silica and Pure-bore additives-based brine mud (NPBM)	Block the shale pores, mitigate the pore pressure transmission which reduces the rate of permeability as a consequence the enhancement of wellbore stability is influenced, improves shale inhibitory properties as well as enhance the wellbore rheological properties.	[133]
Nano-silica	Enhances the viscosity, stabilize the wellbore and prevent the intrusion of formation fluids into it, improves penetration rate and drilling efficiency.	[134]
Nano-scale ultrasonic curable polymer	Restrict the propagation of fractures, maintain the shale strength, and improve the strength of shale with faults.	[135]
Synthetic based drilling fluids (SBF) modified by nanoclay	Affected the rheological properties by increasing yield point and ultimate shear stress, nanoclay decreased the electrical resistivity of the drilling fluid.	[136]
Silica nanoparticles (SiO_2-NPs) and graphene nanoplatelets (GNPs) [water-based drilling fluid]	Increased the water-based drilling fluid's cutting carrying capacity with only minor effects on its plastic viscosity, provide an adequate plugging network between grain boundaries, resulting in no micro-fractures, and the reduction of the cutting erosion.	[137]
Synthesized α-MnO_2 nanoparticles (MNPs)	Incorporation of nanoparticles into base fluid diminishes the tendency of thermal degradation of drilling fluid properties, improved rheological parameters of mud and reduced filtration loss.	[138]
Sustainable glycol-based drilling fluid plus amorphous silica nanoparticles	Improves the rheological properties of glycol drilling fluid, decreases fluid loss and increases the thermal stability of the drilling fluid, increasing the shale cutting recovery and decreasing the penetration rate of glycol drilling fluid.	[139]
2D nanolayered structures {silicon nano-glass flakes, graphene, MoS_2, disk-shaped Laponite nanoparticles, layered magnesium aluminum silicate nanoparticles, and nanolayered organo-montmorillonite}	The incorporation of 2D nanolayered structures into drilling fluids results in a significant enhancement of their rheological, viscoelastic, and filtration characteristics. Furthermore, this addition contributes to the effective removal of cuttings, as well as the stability and reinforcement of the wellbore.	[140]
TiO_2 nanoparticles	Imparted resistance to thermal degradation in rheological and filtration characteristics of drilling fluids, improves the thermal stability.	[141]

(3) gas mobility control, (4) drilling and completion, (5) produced fluid treatment, and (6) tight reservoir application [27]. Table 3 presents a synopsis of recent research endeavors aimed at enhancing drilling parameters through the utilization of nanoparticles.

3.4. Uses of nanoparticles for well stimulation

The process of well stimulation involves the implementation of treatments with the objective of enhancing well productivity,

Table 4
Application of nanoparticles for well stimulation.

Studied Nano Particles	Parameters attention drowned to	References referred to.
Iron oxide nanoparticles	Increase the reservoir's electromagnetic absorption qualities as a consequence raise in the temperature is experienced due to nanoparticles transport mechanism.	[146]
Nanoparticles based gelled acid system	Prevent acidizing fluid leak-off, lowers the viscosity at the surface, facilitating easy post treatment flow back	[147]
Water-blocking agent – emulsion system with supercharged nanoparticles (ESN)	Makes positive impact on an efficiency of stimulation technique resulting in a redistribution of permeability profile within reservoir thickness and moderation of water-cut under increased fluid rate.	[148]
MgO/ZnO	Improve the thermal stability of viscoelastic surfactant micellar structures in $CaBr_2$ and $CaCl_2$ brines and displays an improved viscosity yield at different shear rates. As a consequence, it enhances the rheological properties of fracturing fluid.	[149]
Silica nanoparticles	Improves the permeability of the unpropped fractures by creating concentration-dependent, non-uniform localized surface etchings.	[13]
Nano-size crystals with unique surface charge (pyroelectric nanoparticles)	Improving the filtration characteristic, as well as the rheological properties of fracturing fluid.	[150]

usually through hydraulic fracturing or matrix acidizing to augment permeability, or by improving well production. The utilization of nanoparticles in the stimulation of wells is presently in its nascent phase, however, it possesses the capability to transform the industry [142]. Recent research has revealed that non-technological methods can also improve well stimulation results, with a particular emphasis on optimizing the filtration and rheological characteristics of fracturing and acidizing fluids. A comprehensive overview of the examined nanoparticles and their corresponding impacts is presented in Table 4.

Research findings summarized in Table 4 noted that nanoparticles with varying chemical structures in completion fluids exhibit a positive dual effect on well stimulation and inhibition of clay swelling damage [143]. Furthermore, it has been observed that the salt concentration significantly impacts the viscoelastic surfactant fracturing fluid, including nanoparticles, and may cause some viscosity instability [13]. The introduction of magnesium oxide nanoparticles results in a reduction in the apparent viscosity of the fracturing fluid [144]. In addition, silicon dioxide acid displays distinct behavior in limestone as compared to shale. The researchers noted that the fracture conductivity of shale rock demonstrated superior enhancements when compared to limestone rock [145]. The study also revealed that there exists an optimal concentration for improving the rheological properties of surfactant-based fluids for hydraulic fracturing applications, and higher concentrations are not recommended [144,145].

3.5. Nanoparticles in oil and gas environmental remediation

One of the most significant predicaments confronting contemporary society is the pervasive environmental pollution and degradation stemming from various origins. Numerous conventional methodologies and instruments are being employed to tackle this predicament. Nanotechnology, acknowledged as the forefront of scientific advancement, has presently being investigation for its potential deployment as a potent tool in combating environmental pollution [151]. In contrast to the partially efficacious conventional techniques and approaches, nanotechnology presents novel prospects in this domain [152,153]. The utilization of nanoremediation techniques presents a promising avenue for the detection and treatment of contaminants in various environmental matrices such as water, soil, sediment, and air [154,155]. The fundamental process of nanoremediation primarily involves the interaction between the contaminant and nanoparticles, wherein the contaminant is first detoxified and subsequently immobilized [155]. Nanoremediation strategies have demonstrated considerable efficacy in disinfection, desalination, elimination of heavy metals and ions, as well as the removal of organic pollutants [156]. This can be attributed to the exceptional surface chemistry and high aspect ratio exhibited by nanomaterials, which endow them with remarkable capabilities for environmental remediation. The nanoremediation technique encompasses the utilization of reactive materials to facilitate the detoxification and conversion of contaminants. These materials play a dual role by initiating chemical reduction and catalyzing the pollutants [157–159]. Consequently, this method serves as a crucial means of safeguarding the environment against diverse sources of pollution. It is imperative to emphasize that this process is not only essential for the preservation of ecological well-being but also for the overall health of the general public [159]. Oil extraction and processing, particularly in accidental situations, can result in the emergence of barely separated mixtures of water, oil, and solid phases, which pose significant environmental challenges. In this part we are going to discuss the application of nanoparticles in the disinfection, removal of heavy metals, desalination, soil, and ions as well as removal of organic pollutants.

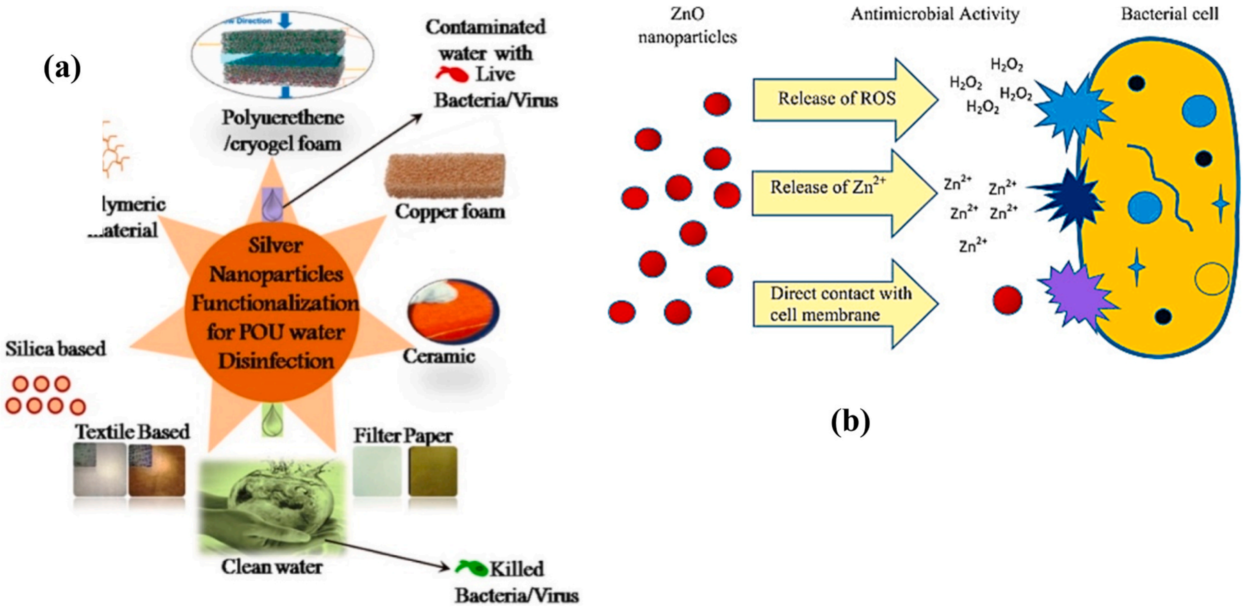

Fig. 2. (a) Silver nanoparticles overview in the antibacterial applications [165], (b) Example of the metal oxide nanoparticles' antibacterial mechanisms [168].

3.6. Nanoparticles for disinfection applications

The drilling process for oil and gas can significantly enhance microbial activity due to the use of chemicals that are biodegradable and serve as a food source for microorganisms. The drilling fluids used to lubricate the drill bit, cool the drill string, and control the pressure in the well can lead to increased microbial activity in the vicinity of drilling operations [128]. Produced water, which is brought to the surface along with oil and gas, contains high levels of nutrients that can stimulate the growth and activity of microorganisms in the subsurface environment [126,127]. Similarly, hydraulic fracturing involves injecting a high-pressure mixture of water, sand, and chemicals into the formation, which can also stimulate microbial growth and activity [121]. This process poses a risk of introducing potentially harmful microbes to the environment. Nanotechnology is used to introduce a method of disinfecting the environment in order to combat the current and anticipated hazard. Nanomaterials possessing antimicrobial properties have the potential to be utilized for the purposes of disinfection and microbial control. Specifically, carbon-based nanomaterials, including carbon nanotubes, fullerenes, and graphene, have gained recognition for their ability to exhibit antimicrobial effects. These carbon-based nanomaterials combat pathogens through either a photothermal mechanism or the production of reactive oxygen species [59]. Carbon nanotubes have demonstrated efficacy against various types of bacteria, pathogens, and protozoa. Furthermore, the functionalization of carbon nanotubes has been shown to enhance their antimicrobial activity, thereby increasing their capacity for disinfection. Conversely, researchers have also investigated the use of graphene-based antimicrobial nanomaterials for the removal of microbes from water, thereby ensuring microbial control. It is worth noting that metals and metal oxide nanoparticles exhibit antimicrobial properties [160,161]. Reports indicate that disinfectants based on nano silver materials (e.g., AgNPs, AgNWs, AgNCs, Ag/PP, Ag/SiO_2, Ag/TiO_2, Ag@ZnO, Ag@Co-NPs, AgNP@SiO_2, Ag/BC etc.) show great promise in enhancing the efficacy of conventional water disinfection methods as illustrated in Fig. 2a [162–165]. Metal oxide nanoparticles, such as TiO_2, ZnO, ZnO–MgO, MgO, CaO, SiO_2, Au/SiO_2, Cu-chitosan nanoparticles, CuO, etc. Are also highly effective in disinfection also illustrated in Fig. 2b [166–170]. Several naturally occurring polymers, including peptides, chitin, and chitosan, have gained recognition for their antimicrobial properties [171–173]. The nanoparticles and other nanostructures derived from these polymers have become extensively utilized due to their affordability and accessibility. In finalizing this aspect, researcher's findings indicate that these nano-based formulations are not only suitable for disinfecting air and surfaces, but also effective in enhancing personal protective equipment, such as facial respirators [159].

3.7. Nanoparticles for the removal of heavy metals discharged from oil and gas production

Heavy metals pose a grave threat to our fresh water reservoirs, and it is imperative that we take action to address this issue. Arsenic, copper, cadmium, chromium, nickel, zinc, lead, and mercury are notorious for their toxic, non-biodegradable, and persistent nature, making them highly detrimental to our environment [161]. The primary sources of heavy metals in the environment, including the air, water, soil, and biosphere, are industrial growth and oil and gas production activities [174]. The high solubility of heavy metals in aquatic environments makes them easily absorbed by fishes and vegetables, leading to their accumulation in the human body through the food chain [175]. To reduce heavy metal concentrations in water and wastewater, several methods have been developed and employed, including membrane filtration, ion-exchange, adsorption, chemical precipitation, nanotechnology treatments, electrochemical, and advanced oxidation processes [176]. Nanoparticles being employed in removing heavy metals from wastewater outperforms other treatment methods due to their improved characteristics. There has been a notable surge of interest in the utilization of nanomaterials for the purpose of degradation and elimination of aquatic contaminants, as indicated by prior research endeavors. This section will examine nanoparticles that have been investigated and demonstrated efficacy in the removal of heavy metals from wastewater. In their recent study, Ituen et al. (2021) presented their findings on the synthesis of walnut husk extract-silver nanoparticles (WHE-AgNPs) with distinct characteristics, including a round shape, uniform size distribution, absence of aggregation, and crystalline structure [177]. These nanoparticles exhibited exceptional adsorption properties. The synthesized WHE-AgNPs demonstrated a remarkable ability to remove Pb, Cr, and Cd ions from petroleum wastewater, achieving removal efficiencies of 72.6 %, 81.3 %, and 88.1 %, respectively, within a 5-h period at a temperature of 25 °C. This efficiency was attributed to the physisorption of various functional groups, such as *C*–N, *N*–H, C═O, C═C, *C*–O, and *O*–H, present on the surfaces of the WHE-AgNPs [177]. In 2023, Bouafia et al. synthesized various nanoparticles, including α-Fe_2O_3, CuO, and ZnO, which exhibited remarkable efficacy (achieving 100 % removal under optimal conditions) in eliminating heavy metals from wastewater [178]. The findings demonstrated that approximately

Table 5
Results of analysis by ICP-MS of the reservoir oily water (OIW) before treatment and after copied from Ref. [178].

OIW after treatment	As = 75 (ug/L)	Be 9 (ug/L)	Cd 111 (ug/L)	Cr 52 (ug/L)	Mn 55 (ug/L)	Mo 98 (ug/L)	Ni 60 (ug/L)	Pb	Sb 121 (ug/L)	Se 82 (ug/L)	Zn 66 (ug/L)
α-Fe_2O_3	1370	0.000	0,406	0.000	71,728	0.000	0,647	2998	0.000	0.000	98,867
Cuo	1212	0.000	0,355	0.000	62,802	0.000	0,428	2399	0.000	0.000	87,992
Zno	1310	0,001	0,392	0.000	69,370	0.000	0,669	0,935	0.000	0.000	327,605
Qtit metals	As = 75 (M	Be 9 (M	Cd 111 (M	Cr 52 (M	Mn 55 (M	Mo 98 (M	Ni 60 (M	PbM	Se 82 M	Sn 118 M	Zn 66 (M
OIW before treatment	2473	0,062	0,546	0,349	92,547	0,206	1009	3601	1706	0,160	113,481

80 % of heavy metal adsorption occurred within 5 and 10 min, respectively, and both ions reached 99.99 % mineralization within less than 30 min. Table 5 summarizes the results, revealing the exceptional performance of the designed nanoparticle systems. In Table 5 the outcomes of the analysis conducted through inductively coupled plasma mass spectrometry (ICP-MS) on the oily water (OIW) present in the reservoir, both prior to and subsequent to treatment, have been presented [178]. Hu et al. (2006) conducted a comparable study with the aim of eliminating heavy metals from industrial wastewater using γ-Fe_2O_3. The results of the adsorption studies indicated that the nanoscale γ-Fe_2O_3 was highly efficient in removing Cr(VI), Cu(II), and Ni(II) from the wastewater, thus demonstrating its potential as a viable solution for heavy metal removal [179]. Abdelmegeed et al. conducted a study in which they developed superparamagnetic multifunctional magnetic nanoparticles (Fe_3O_4, Fe_3O_4/SiO_2, Fe_3O_4/NH_2, and $Fe_3O_4/SiO_2–NH_2$) for the purpose of removing Al^{3+}, Cr^{3+}, Cu^{2+}, Fe^{3+}, and Zn^{2+} from wastewater [180]. The researchers found that the maximum removal capacity was achieved with a dosage of 0.5 g/L after 15 min of utilizing their designed nanoparticles. Furthermore, the $Fe_3O_4/SiO_2–NH_2$ nano adsorbent exhibited a significantly enhanced maximum adsorption capacity (Qm) of 229 mg/g according to the Langmuir model [180]. The adsorption process schematic presentation is depicted in Fig. 3, sourced from Abdelmegeed et al.'s work.

3.8. Nanoparticles in the desalination process

Desalination constitutes a mere 1 % of the global water consumption, yet it is an energy-intensive process, with the majority of operational expenses attributed to energy consumption [181]. Currently, a significant portion of the power required for desalination comes from traditional fossil-fuel-fired power plants, resulting in greenhouse gas emissions and concentrated brine discharge that pose a severe threat to the environment [182]. An example of desalination system is presented in Fig. 4 below. Given the significant impact of climate change, there is a pressing need to develop sustainable desalination processes that address the issues of brine discharge, greenhouse gas emissions, and energy consumption per unit of freshwater produced [183]. Nanotechnology can play a crucial role in achieving specific energy consumption reduction, as nanofluids application increases the overall heat transfer coefficient, enabling the production of more water for the same size desalination plant [184]. Additionally, concentrated brine discharge harms marine ecosystems, necessitating a solution to support the objective of sustainable desalination. In recent years, a number of studies have been undertaken to explore the potential applications of nanotechnology in the fields of desalination, brine treatment, and the integration of renewable energy sources in desalination processes. These investigations have unveiled promising avenues for the development of devices and systems utilizing nanostructured materials, such as carbon nanotubes, nanowires, graphene, quantum dots, superlattices, and nanoshells, among other notable materials [185,186]. Zeolites possess inherent nanopores that effectively accommodate salt ions and water molecules, rendering them highly promising for desalination purposes [187]. However, their practical applications have been significantly hindered by their low permeability [187-189]. Thus far, zeolites have primarily demonstrated successful utilization in the incorporation of surface-active polyamide layers [189]. Carbon nanotubes (CNTs) have garnered significant interest in the field of desalination owing to their exceptional characteristics [190]. Extensive simulation studies have demonstrated that the hydrophobic

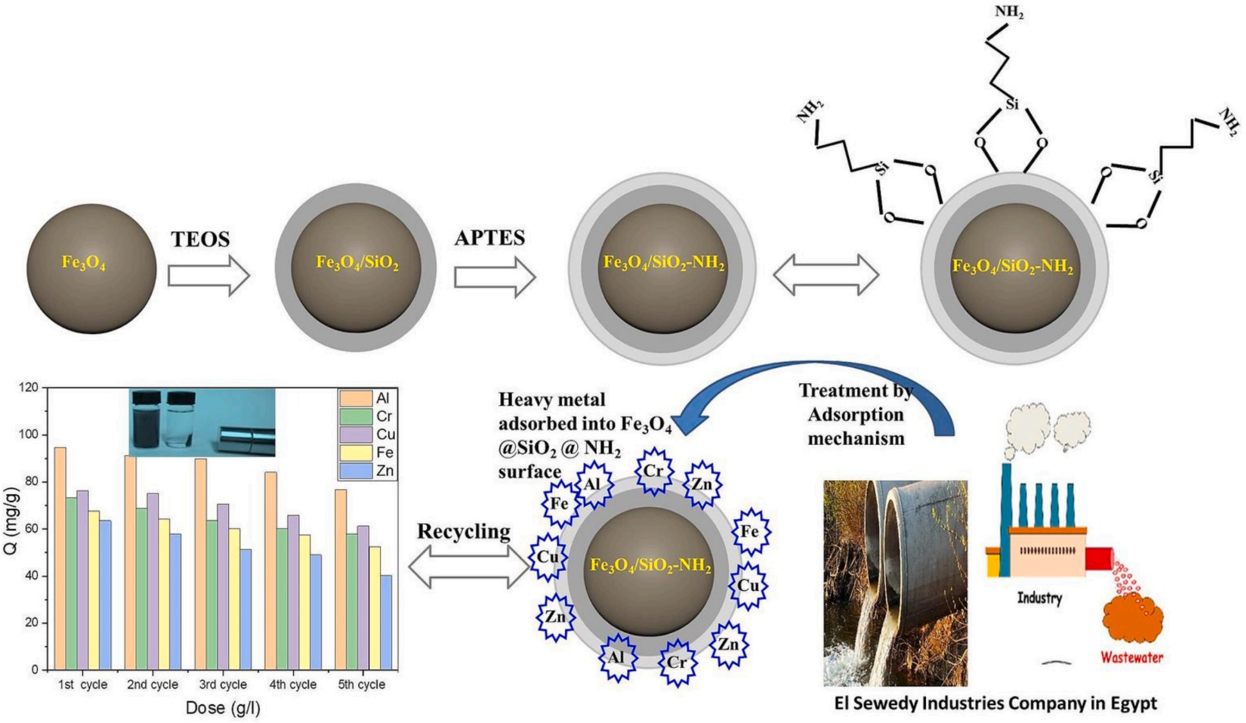

Fig. 3. Schematic presentation of the removal of heavy metals from wastewater using superparamagnetic nanoparticles as sourced from [180].

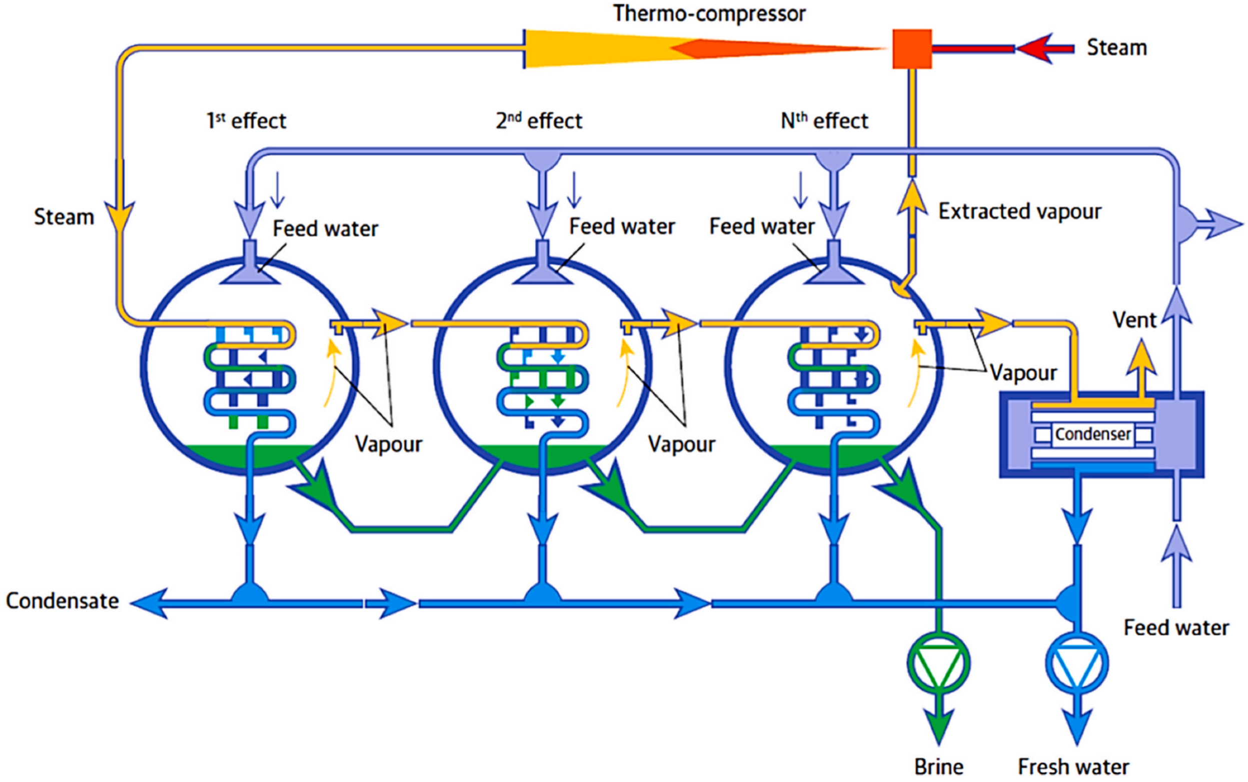

Fig. 4. Schematic presentation of the Multi-Effect Distillation system for desalination sourced from [181].

nature of CNT channels enables the nearly frictionless flow of hydrogenated water molecules, resulting in remarkably high-water flux rates [191]. Furthermore, these materials have also demonstrated their utility in the integration of surface-active layers. Additionally, the ultrahigh water channels present in carbon nanotubes (CNTs) have been found to significantly enhance the water flux of nano-composite polyamide-thin film composite reverse osmosis (PA-TFC RO) membranes [192]. Beside CNTs, graphene, a 2D single-layered nanomaterial with sp2-hybridized carbon atoms in a hexagonal honeycomb lattice, is gaining prominence in materials science [193].

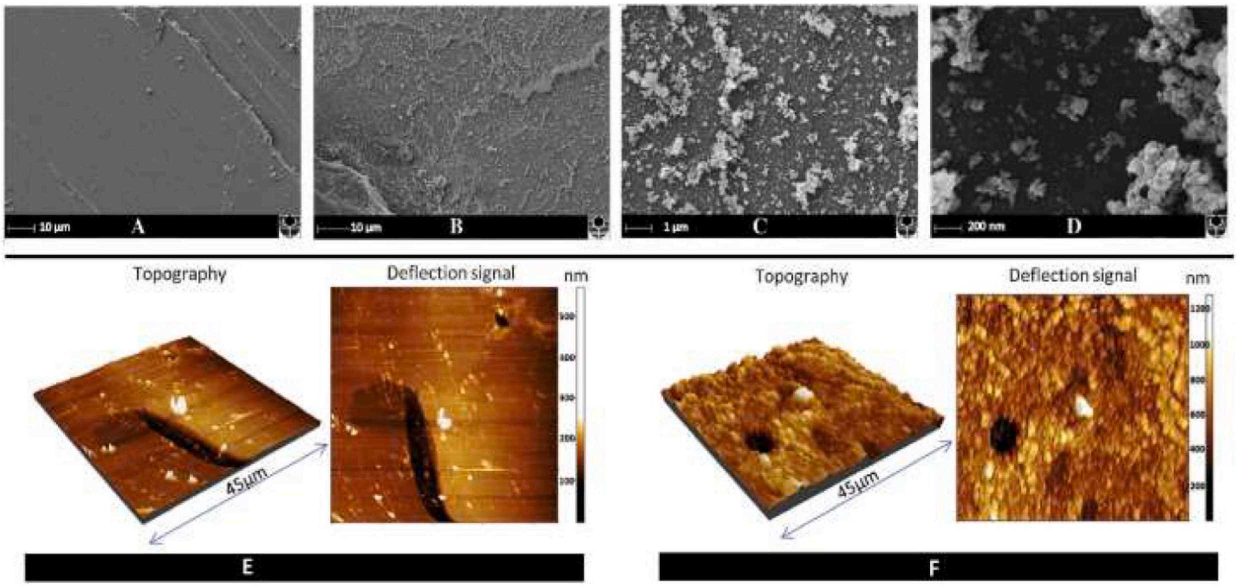

Fig. 5. SEM and atomic force microscopy image of calcite surface. Calcite surface before (a) and after (b) nanofluid treatment; (c) High resolution; (d) Max resolution; Topography picture before (e) and after (f) nanofluid treatment. Adopted from reference [210].

Graphene-based nanomaterials, including graphene, graphene oxide (GO), and reduced graphene oxide (RGO), are captivating due to their exceptional mechanical, thermal, and electrical properties [194]. Graphene's atomic thickness, high mechanical strength, and chemical inertness make it an ideal platform for size-selective membranes [195]. The suitability of these characters for membrane separation processes is evident. Graphene-based membranes, functionalized with nanopores and nanochannels, have potential in desalination [196].

3.9. Application of nanoparticles in wettability alteration, interfacial tension reduction, and adsorption

3.9.1. Wettability

The upstream oil and gas sector finds wettability alteration (WA) of reservoir rock to be an appealing issue for increasing hydrocarbon production. The term "wettability alteration" describes how a surface's affinity for a specific phase (such as a solid, liquid, or gas) changes. Wettability modification is an essential component of improved oil recovery (EOR) procedures in the context of oil recovery [197,198]. In order to improve the effectiveness of oil recovery, the wettability of the reservoir rock is altered from its original state. Numerous procedures, including chemical treatments and surfactant injections, can be used to accomplish this modification [199]. It has been observed that nanoparticles modify the wettability of the surface under study by altering the reservoir rocks' surface roughness, which in turn modifies the rock surface's contact angle with the oil [200–202]. In other words, adding nanoparticles may increase surface roughness, which will reduce the contact angle and increase the system's wettability as depicted in Fig. 5. According to a number of research, the use of nanoparticles modifies the surface of reservoir rocks by adding new functional groups or changing those that already exist, changing the interfacial characteristics between the rock and oil [203–205]. The observed modifications have an impact on the adhesion force and oil spreading on the rock surface, which modifies the wettability. Notwithstanding, through reviewing literatures we have discovered that the use of nanoparticles in reservoirs alters the oil's surface tension and viscosity, affecting the oil's capacity to pass through the rocks and influencing the surface's wettability [206]. Numerous reports reveal that there is a certain improvement in oil recovery when iron nanoparticles are used. Systems with both surfactants and nanoparticles have been shown to improve oil recovery by up to 35 %. This is in contrast to reports of 17 % oil recovery in systems that just contained surfactants [207]. Suleimanov et al. attributed the enhanced oil output to the system's decreased interface tension containing nanoparticles [208]. Other researchers, measured the contact angle and interface tension parameters to investigate the effectiveness of poly-silicone nanoparticles. A decrease in the oil-water interface (from approximately 26 to 2 mN/m^{-1}) and an increase in enhanced oil recovery have been noted with the use of the nanoparticles [209].

3.9.2. Interfacial tension reduction and core displacement

Reducing interfacial tension is essential to improved oil recovery procedures. The force that exists at the interface between two immiscible phases, such water and oil, is referred to as interfacial tension and it is a crucial factor in influencing how fluids behave in different industrial processes [211–213]. It may be challenging to recover oil from porous rock formations when there is high interfacial tension [214]. The interaction between surfactants and nanoparticles in porous media is illustrated in Fig. 6. The presence of nanoparticles enhances the effectiveness of surfactants by reinforcing the underlying mechanisms that govern their performance. Improved oil displacement and recovery are made possible by a decrease in interfacial tension, which also weakens the capillary forces

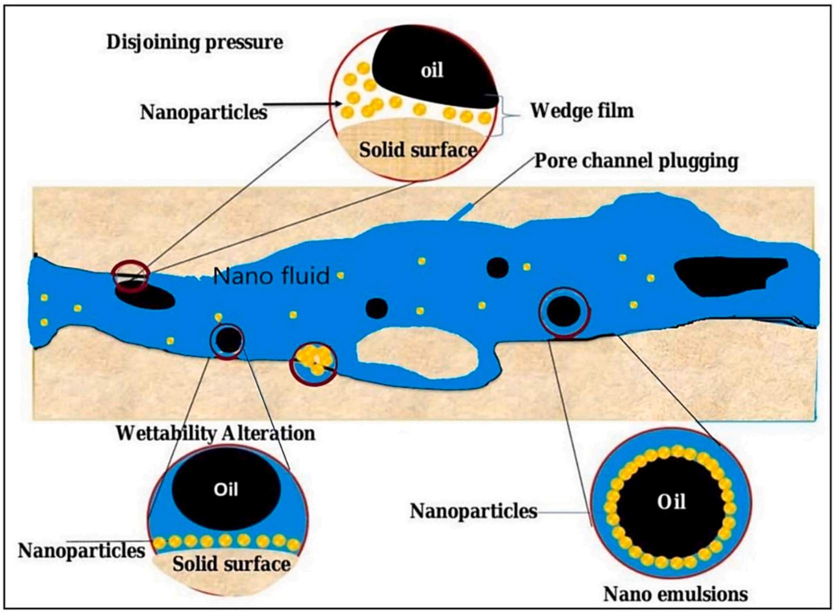

Fig. 6. Surfactants and nanoparticles in porous media adopted from [238–240].

that trap oil inside the pore spaces of the rock [215,216]. In the oil and gas sector, nanoparticles can significantly affect the interfacial tension. By lowering the surface energy between two liquids, nanoparticles can lessen the interfacial tension between them [217-220]. This might happen if the nanoparticles adsorb at the liquid-liquid interface, disrupting the intermolecular interactions that keep the interface together, such as hydrogen bonds [221–223]. Consequently, there is a decrease in the contact angle between the two liquids, which lowers the interfacial tension [224–226]. Because they adsorb at the interface between the two liquids and form a layer of particles that reduces the contact area between the two liquids, nanoparticles can stabilize emulsions by reducing the interfacial tension between the oil and water. As a result, the emulsion is stabilized and the interfacial tension is certain to decrease [227–229]. The interfacial energy is reduced when there is an attractive force between the substrates, while repulsive forces contribute to an increase in the energy of the surface. Young's law is a well-known equation that describes the relationship between interfacial forces in a three-phase system. This equation, represented by $\theta = \frac{\sigma_{sw}-\sigma_{so}}{\sigma_{wo}}$, involves the contact angle (θ) and the interfacial tensions between the solid-water (σ_{sw})), solid-oil (σ_{so}), and water-oil (σ_{wo}) interfaces. It is important to note that Young's equation is applicable under equilibrium conditions and assumes an ideal state of a surface that is perfectly smooth, chemically homogeneous, rigid, insoluble, and nonreactive [21].

Core displacement refers to the process of displacing fluids within porous media, such as rocks or reservoirs, to enhance oil recovery. Gbadamosi et al. conducted a study comparing different fluids, including Al_2O_3 polymeric nanofluid, SiO_2 polymeric nanofluid, and a base polymer without nanomaterial [230]. The addition of nanoparticles to the oilfield polyacrylamide (HPAM) improved rheological properties and prevented polymer degradation in the presence of hardness brine and temperature. The Al_2O_3 polymeric nanofluid, with a concentration of 0.1 wt% nanoparticles in a 2000 ppm HPAM solution, showed superior steady shear performance under various electrolyte concentrations and temperatures. It also reduced interfacial tension between oil and water and changed the wettability of sandstone cores. In sandstone cores, the Al_2O_3 polymeric nanofluid increased oil recovery by 10.6 % compared to conventional HPAM [231]. In their study, Zargar et al. investigated the effects of TiO_2/Quartz-nanofluid (DWN1000) on oil recovery. They found that when the nanofluid, with a concentration of 1000 ppm, was dispersed in distilled water, it led to an increase in oil recovery by 21 % of the original oil in place (OOIP). This improvement was attributed to a significant reduction in interfacial tension (IFT) from 36.4 to 3.5 mN/m. Additionally, the nanofluid enhanced the rheology behavior and altered the wettability towards a stronger water-wet system, as evidenced by a decrease in the contact angle from 103° to 48° [232]. In their study on the rheological properties of guar gum, Bera et al. investigated the impact of silica nanoparticles on the performance of guar gum at different temperatures ranging from 25 °C to 75 °C. The researchers found that a mixture containing 0.2 wt% silica nanoparticles and 4000 ppm guar gum exhibited a higher oil recovery rate of approximately 36 % of the original oil-in-place compared to other test solutions in imbibition experiments. Furthermore, the contact angles between crude oil and sandstone rock were measured in the presence of various substances including 2000 ppm brine, 0.025 wt% silica nanoparticles in water, and a mixture of guar gum (2000 ppm) and silica nanoparticles (0.025 wt%). It was observed that the inclusion of guar gum containing silica nanoparticles effectively altered the contact angle from an oil-wet state (contact angle ~72°) to a water-wet state (contact angle ~115°). Additionally, the addition of silica nanoparticles to the guar gum solution enhanced the effectiveness of the guar gum polymer, resulting in the recovery of 44.3 % of the original oil-in-place [233]. In their study, Asl et al. investigated the impact of silica nanoparticles (NPs) on the performance of two amino-acid surfactants, namely lauroyl-arginine (L-Arg) and lauroyl-cysteine (L-Cys), in enhancing oil recovery. The researchers

Table 6
An overview of prior research on the impact of nanoparticles on interfacial tension (IFT).

NPs	NPs size (nm)	NPs Conc.	IFT (mN/m)		Reference.
			Clean	With NPs	
FNP	7–16	0.05 wt%	16.41	12.61	[238]
CNP	8–75	0.05 wt%	16.41	12.15	[239]
HLP	N/A	0.05 wt%	18.4	5.4	[240]
SiO_2	7–12	1.0 wt%	20	1.87	[241]
SiO_2	20–30	5 wt%	35	10.9	[242]
SiO_2	40	0.05 wt%	19.2	17.5	[243]
TiO_2	21	0.05 wt%	19.2	n.a.	[243]
Al_2O_3	17	0.05 wt%	19.2	12.8	[243]
SiO_2	10–15	10 gr/200 ml	37.5	22.1	[244]
FSPNs	10–15	10 g/200 ml	37.5	13	[244]
Al_2O_3	40	50 mg/L	26.5	18	[245]
TiO_2	10–30	50 mg/L	26.5	17.5	[245]
SiO_2	20	50 mg/L	26.5	17	[245]
Al_2O_3	40	50 mg/L	21.1	13.2	[245]
TiO_2	10–30	50 mg/L	21.1	12.4	[245]
SiO_2	20	50 mg/L	21.1	11.2	[245]
HLP	10–40	4 g/L	26.3	1.75	[246]
NWP	10–20	4 g/L	26.3	2.55	[246]
Al_2O_3	~60	0.5–3 g/L	38.5	2.25	[247]
Fe_2O_3	40–60	0.5–3 g/L	38.5	2.75	[247]
SiO_2	10–30	0.5–3 g/L	38.5	1.45	[247]
SiO_2	12	1–4 g/L	26.5	1.95	[248]
ZrO_2	5–15	10–500 mg/L	48	10	[249]

focused on the reduction of interfacial tension (IFT) and alteration of wettability as key factors. The results revealed that SiO_2 NPs exhibited high stability at a concentration of 1000 ppm when dispersed in surfactant solutions. Additionally, the critical micelle concentration (CMC) values for L-Arg and L-Cys nano-surfactants were determined to be 2000 ppm and 4500 ppm, respectively. The inclusion of $SiO_{,v}$ into the surfactants led to significant reductions of 58 % and 66 % in IFT and contact angle values, respectively. Consequently, the use of nano-surfactant flooding resulted in a higher improvement in oil recovery compared to surfactant flooding, with respective increases of 13.1 % and 11.9 % in original oil in place (OOIP) [234]. Table 6 below displays different researches published pertaining the applicability of nanoparticles and its impacts on the IFT. In spite of their advantages, nanoparticles tend to aggregate in the extreme conditions of the reservoir, such as high electrolyte concentrations or high temperatures [235]. As a result, they are retained in a porous media and separated from the oil/water interface. Dielectric nanoparticles, with their high melting point and thermal characteristics, have been proposed as a more environmentally benign substitute for chemical EOR [236]. These nanoparticles have the ability to polarize in conjunction with low frequency electromagnetic waves, which can rupture the oil/nanofluid interface and enable the release of oil from reservoir rock surfaces and its transit to the production well [237]. On the other hand, a thorough knowledge of the shape and dielectric characteristics of nanoparticles at various calcination temperatures that affect the recovery process is still lacking. Using zinc- (ZnO) and aluminum-oxide (Al_2O_3) nanoparticles with average crystallite sizes ranging from 43.4–47.3 nm to 25–94.3 nm, respectively, Muhammad et al. 2020 studied the dielectric nanofluids in brine with SDBS as a dispersant to close this gap [217]. The crude oil/nanofluids system's IFT measurement showed that rotational polarization which is controlled by the dielectric loss of nanoparticles played a major role in augmenting interfacial disturbance by causing oil droplets to deform. In their study Muhammad et al. 2020 utilized the DROP image software to calculate the interfacial tension ($\boldsymbol{\gamma}$) using the equation $\boldsymbol{\gamma} = \Delta\boldsymbol{\rho}.\boldsymbol{g}.\boldsymbol{R}_0^2/\boldsymbol{\beta}$. This equation considers the density differential ($\boldsymbol{\Delta\rho}$) between oil droplets and nanofluid, gravity constant ($\mathbf{g}$), radius of curvature at drop apex ($\mathbf{R_0}$), and shape factor ($\boldsymbol{\beta}$). The side-view profiles were used to get precise measurements of these characteristics. In their experiment Taylor's proposed lossy dielectric model was used to correlate oil droplet deformation with nanoparticle dielectric characteristics and electric field intensity, as shown in $\boldsymbol{D} = \frac{\boldsymbol{9\varepsilon_0\varepsilon_d\varphi a}\mathrm{E}^2}{\boldsymbol{16}\Upsilon(\boldsymbol{2}+\boldsymbol{R})^2}$ equation where $\Phi = \boldsymbol{S}\left(\boldsymbol{R}^2 + \boldsymbol{1}\right) - \boldsymbol{2} + \boldsymbol{3}(\boldsymbol{SR} - \boldsymbol{1})\frac{\boldsymbol{2M}+\boldsymbol{3}}{\boldsymbol{5M}+\boldsymbol{5}}$ [217]. The equation for the change in droplet shape, indicated as D, can be stated using a variety of factors. The droplet's initial radius ($\boldsymbol{a}$), interfacial tension ($\boldsymbol{\gamma}$), free space permittivity ($\boldsymbol{\varepsilon_0}$), liquid permittivity ($\boldsymbol{\varepsilon_d}$), droplet to nanofluid dielectric permittivity ratio ($\mathbf{S}$), conductivity ratio ($\mathbf{R}$), and viscosity ratio ($\mathbf{M}$).

3.9.3. *Adsorption chemical*

Adsorption plays a significant role in enhanced oil recovery processes. When certain chemicals or surfactants are introduced into the reservoir for EOR purposes, they can adsorb onto the rock surface. This adsorption behavior can influence wettability alteration and interfacial tension reduction. Understanding the adsorption characteristics of these substances is crucial for optimizing their effectiveness in enhancing oil recovery. Chemical adsorption primarily takes place when there is a chemical interaction between the rock surfaces and various types of bonds such as covalent, hydrogen, hydrophobic, and species-specific solvation bonds [250,251]. To prevent these interactions, it is crucial to modify specific events within the system. This is similar to the process of Enhanced Oil Recovery (EOR) chemicals. When surfactant molecules exhibit a higher energy preference towards the solid-liquid interface rather than the bulk phase, surfactant adsorption transpires at this interface [252–254]. This phenomenon occurs when surfactant molecules move from the bulk solution phase to the interface. It is evident that the formation of micelles initiates at higher concentrations of surfactants, leading to the creation of hemimicelles consisting of one or two layers of surfactant molecules [255,256]. After the solid surface has been coated with this layer, the adsorption process continues until a complete bilayer is formed [257–259]. To enhance the adsorption of the surfactant onto solid surfaces, it is essential to anchor the molecules at the interfaces between liquid-liquid or liquid-air [260,261]. By maintaining the surfactant molecules at these interfaces, the presence of nanoparticles in the surfactant solution could potentially impact the adsorption mechanisms and behavior at the interfaces [262,263]. Nanoparticles applied as surface coatings have the ability to significantly alter the behavior of other nanoparticles [264]. When introduced into a slug, these nanoparticles induce a chemical reaction that forms a protective layer on the reservoir rock, thereby reducing the adsorption of chemicals during flooding experiments [265,266]. Numerous laboratory experiments have been conducted to assess the effectiveness of these nanoparticles in enhancing oil recovery [255,257–269]. However, it is worth noting that the adsorption of nanoparticles onto the rock surface is not economically viable for oil recovery. To address this issue, the use of certain chemicals to facilitate the desorption of nanoparticles from solid surfaces is proposed [270–272]. The properties of nanoparticles, such as their hydrophilicity or hydrophobicity, play a crucial role in this context. Various phenomena typically occur during the injection of a nanoparticle suspension into a reservoir rock. These include adsorption, desorption, blocking, transportation, and aggregation of the nanoparticles. A recent investigation has highlighted the potential of nanoparticles to mitigate the adsorption of chemicals onto the surface of the rock. Abbas et al., 2022 conducted a study on the adsorption mechanism of saponin, a natural non-ionic surfactant derived from the Glycyrrhiza glabra plant, in the presence of hydrophilic titanium dioxide nanoparticles (HITNPs) on the surface of carbonate reservoir rocks. The objective of the study was to enhance the recovery of crude oil by mobilizing the remaining oil. The findings revealed that the adsorption process of the GG surfactant and surfactant nanofluid solutions on the adsorbent surface exhibited a rapid adsorption phase followed by a slower adsorption phase [273]. In their experimental study, Amin et al. (2020) discovered that mixtures of CAPB + Na_2CO_3 and CAPB + SiO_2, when used at their optimal concentrations, exhibit great potential as innovative solutions for core flooding experiments conducted under ambient conditions. The researchers conducted adsorption measurement tests and found that the presence of sodium carbonate and silica nanoparticles effectively reduced the adsorption of CAPB on dolomite rock samples by 59.7 % and 35.7 % respectively, compared to the initial CAPB concentration. Additionally, the results of spontaneous imbibition experiments demonstrated that the CAPB + Na_2CO_3 and CAPB + SiO_2 solutions led to 18.2 % and 14.7 % higher oil recoveries from the dolomite rock samples respectively, compared to the synthetic formation water (SFW). Furthermore, the efficiency of these selected solutions for surfactant flooding was evaluated through core flooding experiments on carbonate sister core samples, which resulted in 19.7 % and 12.2 % higher oil recoveries compared to SFW flooding, for the CAPB + Na_2CO_3 and CAPB + SiO_2 solutions respectively [274].

4. Other applications of nanoparticles in oil and gas firms

4.1. Application in the production wellhead

The wellhead is a set of instruments strategically placed at the opening of a well to regulate and monitor the extraction of hydrocarbon derivatives from the subsurface formation. The wellhead is situated atop the actual oil or gas well that extends into the reservoir. Additionally, a wellhead may serve as an injection well, facilitating the reintroduction of gas or water into the reservoir to maintain pressure and levels, thereby enhancing production. The equipment also serves as a safeguard against blowouts resulting from high-pressure formations and prevents the escape of natural gas or crude oil from the well [286], [275,276]. Notwithstanding the implementation of customary failure analysis, the occurrence of corrosion, fracture, cracking, fretting, distortion, and heat damage in this highly crucial component may transpire, leading to substantial detriment [277]. Consequently, oil corporations are allocating a greater amount of funds towards the advancement of nanotechnology research and development [278,279]. Numerous studies have been conducted on nanoparticles with the aim of enhancing the efficiency of wellheads [280]. The results indicate that nanoparticles can effectively seal the wellbore and prevent fluid migration between different formations. Nanotechnology has enabled the development of novel drilling techniques that utilize water-based fluids, which are both cost-effective and user-friendly. These methods have the potential to greatly enhance drilling performance and can also be employed to reduce friction between the production tubing and oil [280], thereby enhancing wellbore efficiency and stability [277]. The efficacy of cementing materials is progressively improving due to the utilization of nanoparticles [281–283]. In order to effectively prevent the migration of fluids between different geological formations, cementing materials are employed to seal the wellbore [282,283]. The efficacy of cementing materials in sealing the wellbore and reducing fractures can be significantly improved through the incorporation of nanoparticles. Furthermore, nanotechnology-based solutions offer a more environmentally friendly alternative to conventional fluid drilling, as they do not contain hazardous chemicals. In order to prevent the formation of a filter cake, which can lead to fluid loss and the development of cracks, nanomaterials can be utilized to seal pores within the shale formation.

4.2. Application in the production and test manifolds stage

There exist two distinct processes under this component, contingent upon whether the process occurs onshore or offshore. In the onshore process, a network of gathering pipes and manifold systems is utilized to convey each well stream to the primary production facilities [284]. The pipelines have been specifically engineered to facilitate the establishment of production “well sets” in order to optimize reservoir utilization, well flow composition (including gas, oil, and waste), and other pertinent factors for a given output level. Conversely, during offshore operations, production manifolds are directly supplied by dry completion wells located at the primary field center, while production risers are supplied by multiphase pipes originating from remote wellhead towers and subsea installations [284,285]. The apparatus responsible for elevating a pipeline to the uppermost portion of a structure is commonly referred to as a riser. This necessitates a method of accommodating weight and motion for floating or edifices [286]. Diluents and heating may be deemed necessary for heavy crude and in the arctic region to reduce viscosity and facilitate flow. The oil and gas industry extensively employs manifolds for the distribution of gases and fluids. These manifolds are designed to either bifurcate a single channel into multiple junctions or converge multiple junctions into a single channel. Simple manifold systems are often utilized to divide a single supply input into multiple outputs, while more advanced systems incorporate inbuilt valves or an electronic network interface [286]. The specific utilization of a manifold is a significant determinant of its features. In the oil and gas sector, various systems are utilized throughout the exploration, development, and production stages, particularly in wells that necessitate surface testing equipment [285]. They possess the ability to execute a diverse array of duties, including but not limited to the redirection of gas or oil to surge or gauge tanks for the purpose of storage or measurement, the guidance of flow towards a production line, or from the separator to the crude oil burner for disposal, and the preservation of flow during testing procedures that necessitate the removal of particular equipment components from operation [286,287]. Despite being in its nascent stage, the utilization of nanoparticles in the production and distribution of oil and gas possesses the capability to revolutionize the entire sector. The incorporation of nanoparticles can enhance the functionality of manifolds, minimize the environmental impact of oil and gas production, and prolong their lifespan [285,288].

Owing to the drilling operation moving from low-risk to high-risk geological locations [289], onshore to offshore locations, and shallow water to deep water [284], currently used conventional tools and fluid systems have functional limitations such as poor physio-chemical stability in acid gas environments, frequent mechanical failure and malfunctioning in complex geological environments, and thermal degradation in high-temperature environments [2]. The constraints of traditional instruments and the various fluid systems utilized by the industry may be resolved through the implementation of nanoparticles in the creation and advancement of specific manifolds and other catalytic materials employed in oil and gas processing for challenging drilling environments [290]. Given the exponential increase in global energy demand and its projected growth in the future, it is inevitable that there will be a gradual transition towards operating conditions that entail higher levels of risk [289]. The industry necessitates tools, equipment, chemicals, and fluid additives that exhibit high reliability, chemical resistance, thermal stability, and mechanical stability to guarantee secure and uncomplicated drilling operations [287,291]. The present tools, equipment, additives, and chemicals are often subject to functional degradation and failure as a result of exposure to exceedingly harsh conditions. The utilization of nanoparticles presents a promising avenue for enhancing the corrosion resistance of manifolds, thereby prolonging their lifespan and reducing maintenance expenses. The superior mechanical, chemical, thermal, electrical, and tribological properties of nanostructured materials and additives have been demonstrated across various fields of inquiry [291,292]. The implementation of certain enhancements can yield significant improvements in the stability and durability of manifolds and equipment, as well as the chemical and thermal stability of additives required for enhanced oil recovery applications. In particular, high molecular weight cross-linked polymer fluids have been utilized to stimulate oil and gas wells in viscoelastic surfactant stimulation fluid. These fluids possess exceptional viscosity, proppant transportability, thermal stability, and fluid leak-off control, which are all highly advantageous. However, the residual polymer left behind by these materials can potentially harm formation permeability and fracture conductivity, thus necessitating the exploration of alternative options. Nanoparticles, due to their high surface morphology and strong surface reactivity, have emerged as a promising substitute. These compounds have the ability to maintain fluid viscosity at high temperatures and generate a pseudo-filter cake of viscous, viscoelastic surfactant stimulation fluid, which reduces fluid loss rates and enhances fluid efficiency. Furthermore, the use of nanomaterials with a hydrophobic surface, such as epoxy paint surfaces, may mitigate the likelihood of scale deposition and prevent the formation of scales within the production tubing. One example of such a substance is the Nano SO_2/epoxy adhesive solution. Another illustration is a nanomaterial coated in the low-surface-energy polymer aminopropyl.

4.3. Application of nanoparticles in the separation process

Before undergoing additional transportation, downstream processing, and refining, hydrocarbon reservoir fluids are subjected to a separation process in surface facilities. This process involves the passage of multiphase fluids through a series of separators, wherein the pressure is gradually reduced. The ultimate objective of this process is to stabilize the final oil product to a certain degree, while separating it from the gas and water components [291,293]. In the event that a well produces a mixture of gas, oil, water, and various impurities, it is necessary to employ separation processes. Among the production separators available in various shapes and designs, the gravity separator is a conventional option. The maximum allowable True Vapor Pressure or Reid Vapor Pressure value is typically specified for this purpose. Surface separation is employed to ensure that the crude oil can be transported through pipelines in a single-phase liquid state without undergoing flashing [292]. Moreover, the reduction of vapor losses is effectively maintained as they near the refining facilities downstream [294]. The occurrence of flashing may result in the generation of fuel gas that can be utilized for the purpose of facilitating refinery operations [295]. Insufficient stabilization of crude upstream may lead to an excessive amount of flashing, ultimately resulting in increased flaring and environmental damage [293,296,297].

The separation stage in an oil and gas field may experience failures due to a multitude of factors. Among the most common causes of separation failure are instances of corrosion, whereby the fluids present within the separation system may cause corrosion, leading to complications such as leaks, blockages, and other related issues [298]. Inappropriate mixing of oil and water molecules can lead to the formation of emulsions, resulting in decreased separation efficiency, excessive pressure loss, and leaks. Mineral deposits caused by scale accumulation can also lead to leaks and reduced system efficiency. Mechanical issues such as cracked pipes, damaged valves, and malfunctioning pumps may also arise. To address these issues, many oil and gas companies are investing in nanotechnology research. Nanoparticles can be utilized in the separation stage of oil and gas fields to enhance the efficiency of the separation process. By increasing the surface area of the separation medium, nanoparticles increase the number of contact points at which oil and water molecules interact, thereby improving separation efficiency. Additionally, nanoparticles reduce friction at the oil-water interface, facilitating the separation of oil and water molecules and further improving separation efficiency [299]. Emulsions, characterized as a heterogeneous mixture of oil and water, pose a significant challenge in terms of separation. However, the utilization of nanoparticles can effectively prevent their formation by enveloping the water and oil molecules, thereby impeding their contact.

4.4. Application of nanotechnology in gas compression

If the gaseous substances emanating from the separators have undergone a substantial reduction in pressure, it is advisable to subject them to recompression prior to their transportation [300]. To enable this feat, turbine compressors consume a mere fraction of the natural gas they compress to generate energy [299]. A centrifugal compressor, equipped with a specific type of fan, can be powered by a turbine to compress and transport natural gas through a pipeline [299,300]. Recompression is deemed unnecessary for gas sourced from a natural gas wellhead, as it possesses sufficient pressure to facilitate its immediate entry into a pipeline transport system. Consequently, there exists a deliberate requirement for the utilization of nanotechnology to augment the performance of the turbine and pump. This can be achieved by regulating the heat transfer between the gas and the compression chamber. The acceleration of heat transfer between the gas molecules and the walls of the compression chamber can be facilitated through the incorporation of nanoparticles [301]. The enhancement of efficiency and prevention of gas overheating can be achieved through the utilization of nanoparticles to improve the wettability of gas molecules to the walls of the compression chamber [300]. The utilization of nanoparticles can yield enhanced efficiency and a reduction in gas sliding. The compression chamber's pressure drop can be mitigated through the incorporation of nanoparticles, leading to a potential decrease in energy consumption and an increase in efficiency. Furthermore, nanoparticles can facilitate the improved separation of gaseous pollutants from liquid and solid contaminants, thereby enhancing the purity of the gas and potentially mitigating the environmental impact of its production.

4.5. Application of nanoparticles in the logging while drilling

The process of acquiring and consolidating data and information during drilling operations is commonly referred to as "logging while drilling" (LWD). This technique employs sensors to collect pertinent data as the drill bit penetrates the rock formation [302]. This data can also be utilized to ascertain the quality of the rock, as well as identify any potential oil and gas reservoirs [303]. The acquisition of data pertaining to directional surveys and drilling mechanics is facilitated by the measurement process that is carried out concurrently with the operation of the drilling equipment [304]. The LWD technology offers measurement capabilities that are comparable to those of wireline measurement. However, it is important to note that there exist several significant differences between the two methods [305]. The LWD system is capable of operating effectively even in the face of challenging conditions. In contrast, wireline measures are characterized by their diminutive size, sensitivity, cable-powered operation, high-speed performance, and susceptibility to the adverse effects of the surrounding environment [306]. The primary advantage of these procedures lies in their capacity to oversee and regulate drilling activities [307]. Various techniques are employed to measure Logging While Drilling (LWD), such as resistivity, sonic and neutron porosity, borehole caliper, natural gamma ray (γ), and resistivity. In contemporary LWD practices, He-3 detectors are predominantly utilized for neutron porosity applications, with the aim of detecting neutrons in their entirety [285,308]. The detectors comprising He-3, exhibit significant advantages in terms of mechanical robustness, high-temperature operability, and compliance with well-logging specifications. Nevertheless, their availability is rather limited, and there exists a possibility of depletion in the foreseeable future [308]. An alternative solution involves the utilization of nanotechnology, specifically nanoparticles, to facilitate the development of sensors that exhibit greater sensitivity and precision compared to conventional sensors. A prime example of this is the Li-6 scintillation detector, which can serve as a viable replacement for the He-3 detector in the context of a logging-while-drilling (LWD) tool [309]. Notwithstanding the fact that Li-6 exhibits a commendable potential as a replacement for He-3 in its bulk form, its efficacy is not as remarkable as when nanotechnology is employed. Nevertheless, the utilization of this technology can be instrumental in augmenting the performance of the detector, thereby rendering it more effective and consequential. In comparison to the existing Li-6 scintillation materials, nanostructured glass-ceramics exhibit a significantly superior performance [310]. The foremost progression in this domain is anticipated to emanate from nano-logging, which is poised to facilitate the succeeding cohort of LWD apparatus, particularly in neutron porosity logging. Furthermore, nanoparticles can be employed to fabricate coatings that safeguard the sensors from damage [311]. Additionally, the utilization of nanotechnology can facilitate the development of drilling fluids that are not only more efficient but also eco-friendly [306]. By reducing heat and friction, these fluids have the potential to enhance penetration and decrease the likelihood of accidents.

4.5.1. Mechanisms of using nanoparticles in drilling

As per the study's report, specific drilling fluids containing nano silica have been designed to tackle water intrusion and seal microcracks in gas shale and Mancos formations [312]. To conduct tests, the researchers generated three samples of mud. The WBM brine used in the first sample, type A, acted as the basic mud. The concentration of nanoparticles in the third sample, type C, was one-third that of the second sample, type B, which contained pure nanoparticles. An experiment with pressure penetration was done to evaluate the effects of these various mud kinds. Based on the findings, it was possible to successfully block the permeability of the formations at higher nanoparticle contents. With a mud permeability of 0.0018 nDarcy and a 98 % reduction in permeability, type B showed the best results. For there was a notable decrease in fluid loss, water invasion, and borehole instability at a range of 10–100-fold reduction [313]. Another study examined the effects of silica and copper oxide nanoparticles on two types of drilling fluids: polyamine-based NDDF and traditional bentonite-based BDF [314]. The researchers prepared nano-based drilling fluids by dispersing nanoparticles at different concentrations. The addition of 0.5 % silica nanoparticles in NDDF resulted in the least degradation in rheological properties compared to other fluids. It also reduced filtrate loss by 31 %. Silica nanoparticles acted as a mud

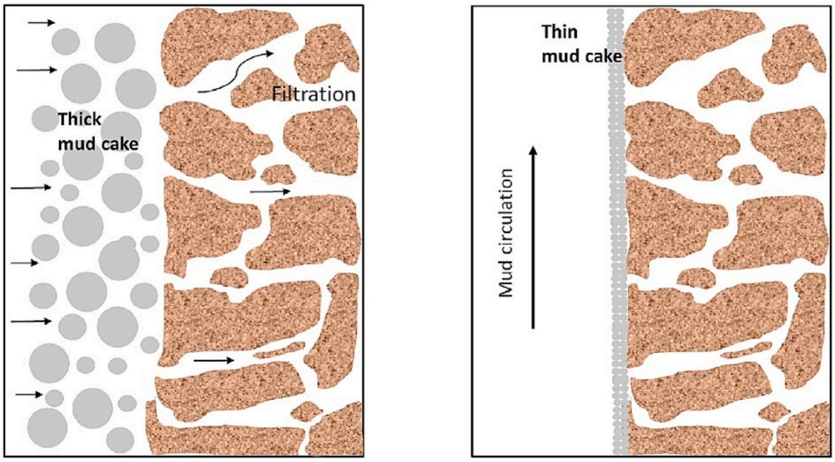

Fig. 7. An image demonstrating the loss of drilling fluid when using nanoparticles (right) and LCM (left) [313,317].

thickener when used in conjunction with BDF, but they also functioned as a mud thinner when used with NDDFs. Copper oxide nanoparticles acted as a thinner in both drilling fluids, with the highest reduction in plastic viscosity observed at a concentration of. 0.8 % in BDF. Higher concentrations of copper oxide nanoparticles resulted in greater thinning qualities but decreased control over fluid loss, with the exception of a 0.5 % concentration that demonstrated a 31 % reduction in fluid loss for both drilling fluids [314]. A fascinating discovery was presented by Borisov et al., in 2015 on the application of drilling fluids along with nanoparticles and lost circulation materials (LCM) [315]. According to their research, this combination results in a thinner filter cake creation and dramatically lowers fluid loss. This behavior can be explained by the nanoparticles' capacity to close the tiny spaces that exist between the micron-sized particles, as seen in Fig. 7. The researchers' experiment, which used calcium nanoparticles at a concentration of 0.5 wt percent, produced an impressive 22–34 % decrease in overall fluid loss. Recently, Hajipour et al., 2023 examined the effects of polyacrylamide, iron oxide, and hydrophilic silicon oxide nanoparticles on the rheological and filtration characteristics of water-based drilling mud. At a concentration of 1 wt percent, they discovered that silicon oxide nanoparticles enhanced the drilling mud's rheology by up to 15 %. However, because of the interaction between clay plates and silica nanoparticles, the gelatinous characteristics of the drilling mud reduced with decreasing concentrations of nanoparticles. Furthermore, when the polymer and nanoparticles were added to the drilling mud, the nanoparticles obstructed the mud cake pores, which further reduced the filtration rate. As a result, the mud filtrate was significantly reduced, going from 128 cc to 14 cc [316].

4.6. *Application of nanoparticles in oil well exploration*

Petroleum geologists are capable of conducting exploration, a process that involves utilizing various techniques to locate hydrogen resources beneath the earth's surface. The depletion of oil resources over time has rendered them less accessible, thereby necessitating the implementation of more advanced procedures to enhance field characterization performance and ultimately increase the amount of oil recovered. A comprehensive understanding of the intended reservoir's characteristics can aid in maximizing oil and gas extraction. Despite the utilization of current sophisticated methods for oil recovery, such as thermal approaches, gas injection, water flooding, and chemical flooding, a significant amount of oil and gas may remain unrecovered [318,319]. Furthermore, apart from their ineffectiveness, these conventional methods of oil recovery are also commercially disadvantageous [298,319]. Conventional electrical sensors are often unsuitable for sustained use in challenging settings, as the operations conducted in deep wells occur within an extremely harsh environment [320]. The current techniques employed for reservoir characterization are inadequate, as they only provide superficial penetration and limited information. To overcome these technological challenges and effectively explore unconventional oil and gas sources, it is imperative to employ unconventional methods and exceptional materials. Furthermore, these methods and materials must comply with environmental regulations and address safety concerns. To ensure precise evaluation of temperature, pressure, oil, and gas flow rates, and to withstand harsh environments, researchers are endeavoring to develop a novel generation of sensors [321–324]. Furthermore, they possess the capability to penetrate the wells to a significant depth and meticulously examine the interplay between the rocks and hydrogen deposits, unimpeded by electromagnetic fields. The attainment of optimal reservoir performance necessitates the utilization of advanced computational and imaging techniques [322]. Various synthesis techniques can be utilized in the field of nanotechnology to produce highly effective nanomaterials, which can facilitate the development of unique sensors and imaging contrast agents [323,324]. In comparison to their macroscopic counterparts, nanomaterials exhibit notable variations in their optical, magnetic, and electrical properties. Furthermore, at low-volume fractions, they can form percolated geometric and electrical structures. The integration of nanoparticles and smart fluids can yield an exceptionally efficient sensor capable of operating effectively in demanding environments, while delivering accurate measurements of temperature, pressure, oil flow rate, and stress in deep wells [325]. The utilization of nanomaterials in tandem with advanced computational techniques and magnetic probes presents a promising avenue for the application of these materials as imaging markers [326–329]. The implementation of chemical techniques to induce segregation of nanomaterial into distinct fluid domains has been shown to enhance reservoir characterization and pore sizing. In this context, the small pore size, extensive surface area, and high mobility of nanoparticles are deemed critical factors [301,330]. Scientists are currently engaged in the development of nanosensors capable of performing reservoir characterization, identifying various fluid types, and monitoring fluid flow [324]. Not only that but also are currently engaged in the development of nanosensors capable of penetrating deep wells. Furthermore, the utilization of hyperpolarized silicon nanoparticles for the purposes of oil prospecting and imaging is being explored [311,331–333]. The utilization of a nanotomography (nano-CT) apparatus holds significant potential in furnishing valuable insights into the distribution of pore sizes, as well as facilitating the acquisition of high-resolution images of shale and gas sand [334]. The objective of nanotechnology in this domain is to create a nanorobot that possesses the ability to comprehensively map and assess the functional parameters of a reservoir.

4.7. *Application of nanoparticles in metering and storage*

The fundamental constituents of the oil and gas sector comprise of metering and storage apparatus. The quantification of the quantity of oil and gas generated is accomplished through the utilization of meters, while the retention of the oil and gas in storage until it can be transported to a refinery or processing facility is referred to as storage [335–337]. In the realm of metering and storage systems, a plethora of options exist, each with its own set of advantages and disadvantages [337]. Which includes *Positive displacement meters, Coriolis meters,* and *ultrasonic meters* to mention. *Positive displacement meters*, which measure the volume of oil or gas that is displaced by a spinning piston or impeller, are among the most widely used metering methods [338,339]. Coriolis meters are utilized to quantify the alteration in frequency of a vibrating tube when a flow of gas or oil traverses it [340,341]. Ultrasonic meters are utilized to quantify the duration required for acoustic waves to traverse an oil or gas flow [342,343].

The present storage technologies that are being employed include underground storage tanks, above-ground storage tanks, and pipelines [344]. Above-ground storage tanks are commonly utilized for the storage of substantial quantities of oil and gas. These tanks are typically constructed from either steel or concrete materials [300]. Underground storage caverns, typically constructed from salt or limestone, serve as a significant repository for oil and gas. Conversely, pipelines are utilized for long-distance transportation of these resources. The selection of metering and storage technology is contingent upon several factors, including the quantity of oil and gas to be measured or stored, the desired level of precision, and the environmental impact. The reliable and secure functioning of oil and gas operations is contingent upon the appropriate selection and implementation of metering and storage technology [345]. Oil and gas companies have the potential to mitigate waste and ensure the timely availability of their produced resources by employing precise measurement techniques to determine the volume of oil and gas generated, and storing them in a secure and safe manner. Given the criticality of these resources, companies are investing significantly in research endeavors to develop innovative nanoparticle technologies that can enhance their operational efficiency [320]. The utilization of nanoparticles in the fields of metering and storage has generated considerable interest, particularly in the development of innovative sensors. The production of sensors with heightened sensitivity and precision, surpassing those of traditional sensors, can be achieved through the incorporation of nanoparticles [286]. The enhanced molecular interaction capabilities of nanoparticles can be attributed to their significantly larger surface area. This unique characteristic renders nanoparticles suitable for the development of highly sensitive sensors capable of detecting even the slightest alterations in the composition of gas or oil. The acquired data can be utilized to monitor the quality of gas or oil and identify any potential issues. Furthermore, nanoparticles can be employed in the creation of sensors designed to detect leaks in storage tanks or pipelines, thereby preventing spills and safeguarding the environment. The application of nanotechnology knowledge is instrumental in achieving these objectives.

5. Challenges pertaining nanoparticles

Nanoparticles possess the potential to revolutionize various aspects of the oil and gas industry, ranging from drilling and completion to enhanced oil recovery (EOR) and flow assurance. However, the widespread adoption of nanoparticles in the oil and gas field is impeded by several challenges that require attention. These challenges include cost, durability, compatibility, safety, and regulation [346]. The production and use of nanoparticles can be expensive, thereby limiting their commercial adoption in the oil and gas industry [185–187]. Furthermore, nanoparticles are susceptible to degradation in the harsh downhole environment, which can limit their effectiveness and longevity [346]. Achieving compatibility between nanoparticles and other fluids and materials used in the oil and gas industry can be challenging, particularly for nanoparticles designed for specific applications. Additionally, nanoparticles can pose a safety hazard if not handled properly, as they can be easily inhaled or ingested [347,348]. The use of nanoparticles in the oil and gas industry is a relatively new technology, and there are few regulations governing their use, leading to uncertainty and delays in commercialization [348]. In addition to these general challenges, specific challenges are associated with different nanoparticle applications in the oil and gas field. For instance, using nanoparticles for EOR requires them to travel deep into the reservoir and remain stable in the harsh downhole environment [349–351]. Researchers are working to address these challenges by developing new methods for synthesizing nanoparticles with controlled size, shape, composition, and surface properties [347]. They are also devising new ways to deliver nanoparticles to their target destination and reduce their toxicity.

5.1. *Future perspective*

Nanoparticles possess the potential to revolutionize the oil and gas industry. Their distinctive properties enable them to enhance the efficiency and sustainability of all facets of the industry, ranging from exploration and drilling to production and refining. By reducing the interfacial tension between oil and water, nanoparticles facilitate the flow of oil through reservoirs. Additionally, they can modify the wettability of reservoir rocks, rendering them more oil-wet and less water-wet, thereby further improving oil flow. Furthermore, nanoparticles can effectively seal unwanted pores and fractures, redirecting fluids to previously untapped areas of the reservoir. Moreover, they enhance the performance of drilling fluids and other chemicals employed in oil and gas operations. The potential applications of nanoparticles in the industry are vast and promising. As nanotechnology continues to advance, we can anticipate witnessing even more innovative and groundbreaking uses of nanoparticles in the oil and gas sector.

5.2. *Economic feasibility*

According to the financial review of the third quarter of 2023 by the US Energy Information Administration, the average daily price of Brent crude oil in 3Q23 was 12 % lower compared to 3Q22, with an average of $86 per barrel. On the other hand, the Henry Hub daily average price experienced a significant decrease of 67 % during the same period, averaging at $2.66 per million British thermal units. Fig. 8 in their report illustrates the fluctuations in oil prices, which can be attributed to various factors such as production rates, conflicts, and the availability of crude oil. To address this issue, it is crucial to implement an economically feasible solution that enhances productivity while minimizing costs. This approach would not only help stabilize the fluctuating prices but also reduce overall expenses.

The proposed solution in this particular case involves the utilization of nanoparticles, which possess distinctive properties that have the potential to bring about significant changes in various industries, including the oil and gas sector. We can make use of nanoparticles to assess the financial feasibility of proposed oil and gas projects or investments [352,353]. By harnessing the capabilities of nanoparticles, decision makers can evaluate crucial factors such as reservoir characterization, enhanced oil recovery techniques, and

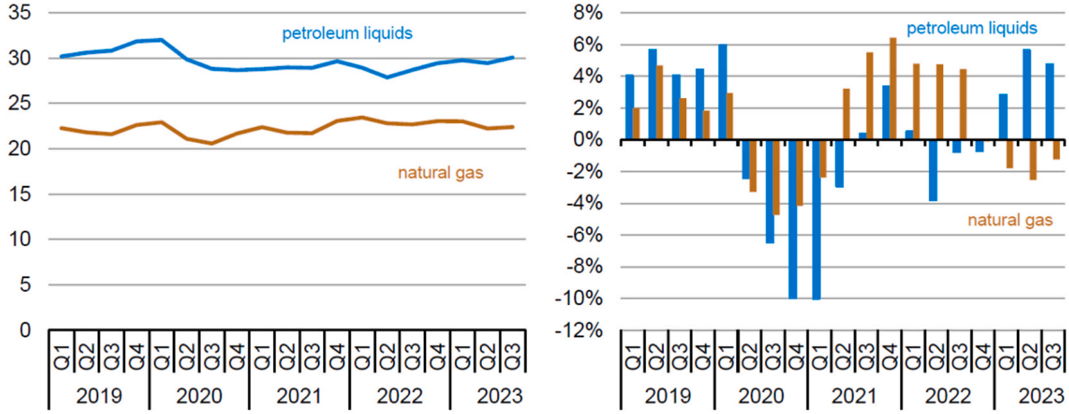

Fig. 8. Petroleum liquid and natural gas Production 2019–2023 (a) Million Barrels of oil equivalent per day, (b) Year-over - year percentage change. (Data source: U.S. Energy Information Administration).

environmental impact, thereby facilitating well-informed decisions regarding the viability and profitability of the project [354]. Nanoparticles provide valuable insights into reservoir properties, which are vital for estimating recoverable reserves and predicting production rates [355,356]. Through the application of nanoparticles, information about porosity, permeability, fluid saturation, and geological heterogeneity can be obtained [357,358]. Injecting nanoparticles into the reservoir enables the tracking of fluid flow paths and identification of preferential channels within the rock formation [359–361]. Also, nanoparticles improve the sweep efficiency and reduce the interfacial tension between oil and water thereby enhancing oil recovery [362,363]. Nanoparticles can serve as effective mobility control agents during water flooding operations. By carefully adjusting the size, concentration, and surface chemistry of nanoparticles, optimization of their ability to displace oil from the pore spaces within the reservoir can be done [364]. Consequently, this leads to higher rates of oil recovery and increased profitability for EOR projects. That aside, In the present era of heightened environmental awareness, it is imperative for decision makers to take into account the ecological ramifications of oil and gas projects. Nanoparticles present themselves as invaluable tools for evaluating and mitigating the environmental risks associated with these ventures [365]. These minuscule particles can be utilized to identify and monitor potential leaks or the migration of contaminants in underground reservoirs. The introduction of nanoparticles specifically designed for this purpose into the subsurface, enables operators to track their movement and identify potential pathways for contamination [366]. With this knowledge, proactive measures can be taken to prevent environmental harm and ensure regulatory compliance. Thus, the use of nanoparticles offers a comprehensive understanding of the reservoir's dynamics, enabling informed choices regarding the project's feasibility and profitability.

6. Summary

Finally, a thorough study of the current constraints and general issues has been performed, resulting in a concise yet critical review. The survey results highlight nanoparticles' enormous potential in tackling numerous difficulties faced by the oil and gas industry. Although there are some existing gaps, they are readily crossed given the tremendous progress being achieved, which is partly due to revolutionary advances in nanotechnology. It is critical to maintain a balanced viewpoint by understanding both the early excitement about nanomaterial research and the necessity to explore competing technologies and their limitations. This review article is a good place to start for anyone who want to pursue this path. Oil and gas fuels, being significant contributors to the world's primary energy demands, are expected to maintain their role in this regard for at least a few more decades. Thus, the never-ending quest for enhanced efficiency and enhanced productive oil and gas fields is currently a topic of interest. Nanotechnology, a multidisciplinary branch aimed at fine-tuning objects in the nanoscopic range, opens new horizons to achieve this. The review article therefore discusses the various paths by which the promise of nanomaterials can be realized in the current, changing landscape of the oil and gas field. The pathways discussed are many but not limited to water treatment, enhanced oil recovery, drilling fluid, well stimulation, disinfection, removal of heavy metals discharged from oil and gas production, desalination process, wettability alteration, interfacial tension reduction, and adsorption realizing in-line, advanced sensors; addressing the problem of oil spills; and tailoring the nanoparticles from oilfield waste-streams.

7. Conclusion

The utilization of nanoparticles in the oil and gas industry remains a relatively underexplored area of inquiry. However, mounting evidence suggests that nanoparticles may significantly enhance the efficiency of oil and gas wells. Nanoparticles have the potential to revolutionize the oil industry due to their wide range of applications. They can be utilized in various aspects of the industry, such as drilling fluids, completion fluids, workover fluids, environmentally friendly stimulation fluids, profile modification fluids, heavy oil thinners, oily wastewater treatment materials, and interfacial property changing materials. Specifically, nanoparticles have the potential to augment oil recovery rates, mitigate the viscosity of heavy crude oils, and regulate fluid movement in reservoirs. One of the key advantages of nanoparticles is their ability to efficiently absorb heat, making them suitable for thermal oil recovery methods. Their unique properties make them highly attractive for use in the oil industry. The small size of nanoparticles allows for their efficient use in maintaining borehole stability, improving cement quality, remediating damaged reservoirs, purifying wastewater, and enhancing oil and gas recovery efficiency. Studies have shown that nanoparticles can recover 10 % − 15 % of the initial oil in place during tertiary oil recovery, and with the proper selection of nanoparticles based on the surface charges of the rocks, an additional 20 % − 30 % of the initial oil in place can be recovered. Therefore, the application of nanoparticles in the oil and gas industry has the potential to bring about a revolutionary change in oil production and development.

Despite the numerous potential benefits of incorporating nanoparticles into the oil and gas sector, concerns regarding their safety and environmental impact persist. To comprehensively understand the behavior and fate of nanoparticles within oil and gas reservoirs, as well as their long-term effects on the environment and human health, further research is necessary. That is to say, while the use of nanoparticles in the oil and gas industry holds promise, it is imperative to proceed with caution and conduct additional research to fully comprehend both their potential benefits and risks. With this in mind, we have prepared this review article to provide precise and supportive materials for future research on the applications of nanoparticles in the oil and gas field.

CRediT authorship contribution statement

Marwa Emmanuel: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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