energy&fuels

pubs.acs.org/EF Review

Review of Developments in Nanotechnology Application for Formation Damage Control

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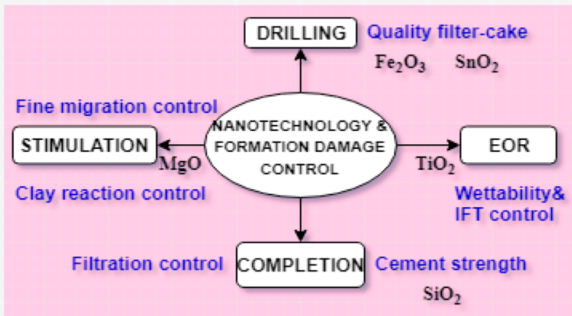
Cite This: https://doi.org/10.1021/acs.energyfuels.1c03223 Read Online



ABSTRACT: Formation damage has the potential to impair and weaken reservoir productivity and injectivity, causing substantial economic losses. Oil and gas wells can be damaged by various mechanisms, such as solid invasion, rock−fluid incompatibilities, fluid−fluid incompatibilities, and phase trapping/blocking, which can reduce natural permeability of oil and gas near the wellbore zone. These can happen during most field operations, including drilling operations, completion, production, stimulation, and enhanced oil recovery (EOR). Numerous studies have been undertaken in recent years on the application of nanotechnology to aid the control of formation damage. This review has found that nanotechnology is more successful than traditional materials in controlling formation damages in different phases of oil and gas development. This is facilitated by their small size and high surface area/volume ratio, which increase reactivity and interactivity to the adjacent materials/surfaces. Furthermore, adding hydrophilic nanoparticles (0.05 wt %) to surfactants during EOR alters their wettability from 15 to 33%. Wettability alteration capabilities of nanoparticles are also exemplified by carbonate rock from oil-wet to water-wet after the concentration of 4 g/L silica nanoparticles is added. In addition, mixing nanoparticles to the drilling fluid reduced 70% of fluid loss. However, the mechanisms of impairment of conductivity in shale/tight formations are not consistent and can differ from one formation to another as a result of a high level of subsurface heterogeneity. Thus, the reactivity and interaction of nanoparticles in these shale/tight formations have not been clearly explained, and a recommendation is made for further investigations. We also recommend more nanotechnology field trials for future research because deductions from current studies are insufficient. This review provides more insights on the applications of nanoparticles in different stages of oil and gas development, increasing our understanding on the measures to control formation damage.

1. INTRODUCTION

In oil and gas industries, it is essential to preserve the permeability of formation, especially at the near-wellbore region,[1,2] because the possibility of formation damage is high during most field operations from the drilling stage to a final assisted recovery operation.[3] Undesirable consequences of formation damage may occur at different stages, like during drilling, production, completion, hydraulic fracturing, and workover operations.[4−7] The formation damage has the potential to impair the productivity and injectivity of the reservoir,[8] especially around the vicinity of the wellbore.[2] Formation damage in the petroleum industry is very challenging to diagnose[10] because it is related to a number of factors.[9] That means that the attempt to inhibit formation damage requires costly methods and is time-consuming, with uncertain successes in many cases.[11]

In recent years, a significant number of studies have been conducted on the use of nanotechnology to assist in controlling formation damage and reducing costs and the time of operation in oil and gas fields.[12−20] Nanotechnology contributes an unprecedented potential for technological advances to control formation damage in different phases of oil and gas development, such as during drilling, completion, production, stimulation, and enhanced oil recovery (EOR). Nanotechnology is technically defined as the study and application of nanoparticles with the simplest form of structures with the dimensions ranging from 1 to 100 nm.[21,22] At this scale, nanoparticles possess distinctive characteristics, which are superior to traditional materials.

Received: September 21, 2021
Revised: December 8, 2021

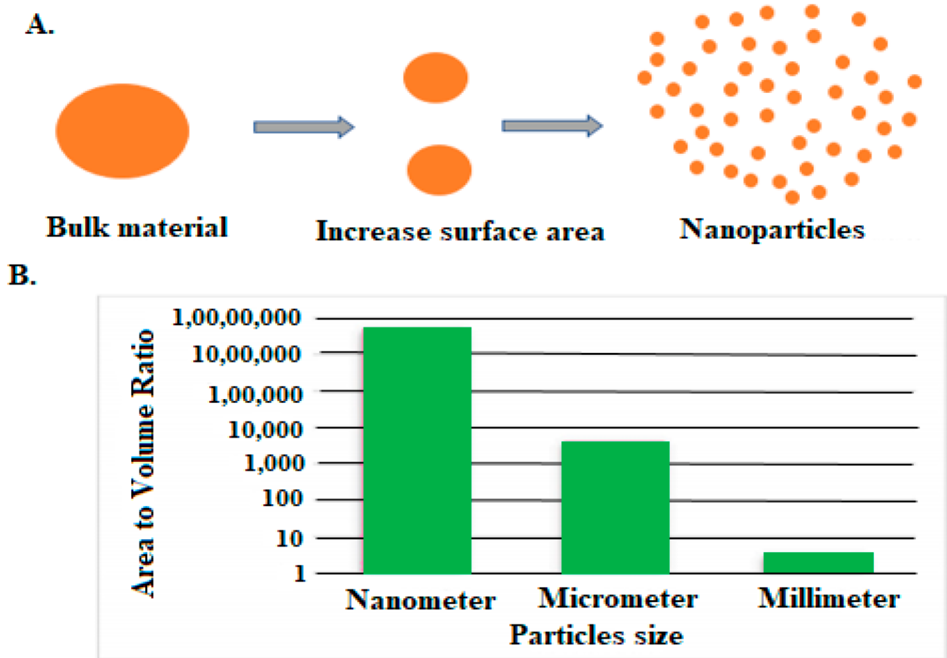


Figure 1. Nanoparticles with an increasing surface area and high surface/volume ratio from panels A and B. This figure was reproduced with permission from ref 1. Copyright 2020 Elsevier.

Having a small size in the nanoscale range[23] and a high surface area/volume ratio[22] can increase the reactivity and interactivity to the adjacent materials/surfaces (Figure 1). Nanoparticles can flow easily and penetrate deeply in porous systems because of their small size. Also, their large surface area/volume ratio increases the contact area and exhibits physical−chemistry conditions by attaching chemical compounds with adjacent surfaces.[23−25]

With these unique physicochemical characteristics, nanoparticles have gained wide attention and have been applied in oil and gas fields. The most used nanomaterials in the petroleum industry include silicon oxide (SiO_2),[27] aluminum oxide (Al_2O_3),[28] magnesium oxide (MgO),[29] iron oxide (Fe_2O_3), nickel oxide (NiO),[30] and titanium dioxide (TiO_2).[31] Nano-based materials are used in drilling,[18,19,32] exploration,[33] completion,[3,34] enhanced recovery,[20] and stimulation techniques.[14] They can control formation damage by minimizing the risk of plugging and solid movement with effective stabilization of the well and are suitable to control fine instability and migration.

López at el. researched Al_2O_3 nanomaterials to remove formation damage caused by asphaltene under static conditions.[2] They concluded that the interaction of the nanoparticle with asphaltene managed to prevent self-association of asphaltene that might precipitate and deposit in the porous system by neutralization of polar forces from the affinity of asphaltene.[3−5] However, a study published by Parsaei et al. has found that iron oxide nanoparticles may eliminate asphaltene deposits in porous media.[6] Huang et al. published a study in 2010 that described applications of the nanoparticle to control fine migration during the hydraulic fracturing process.[7] They concluded that, when the proppant is coated by nanoparticles, the possibility to control fine migration is high because the proppant can have high surface forces that control fine movement. When fines are mixed with nanoparticles, nanomaterials can have the ability to change the potential of surfaces of the fine, which lowers repulsion forces between fines and rock and lowers the production of fines.[8] Sometimes, nanoparticles, like SiO_2, can be used as additives that stabilize the well.[9] When added to surfactants, they can reduce permeability damage more efficiently than regular surfactants.[10]

During EOR processes, formation damage may happen as a result of pore plugging and chemicals trapped in a porous system. This impairs formation permeability, with the processes being resultantly subjected to high injection cost.[11,12] The application of nanoparticles, such as SiO_2 and Al_2O_3, with their ultrasmall size (1−100 nm)[13] can penetrate the porous system without pore blocking, as opposed to typical materials with a larger size of more than 100 nm. This helps to avoid formation damage because the contacting areas with nanoparticles become large as a result of the macroscopic sweep efficiency being increased. During all of this time, the permeability cannot change. Instead, the reactivity can be increased.[14] Many studies of nanotechnology have been conducted in laboratories. However, there is a need to evaluate the efficiency of nanotechnology to control formation damage in real fields.

For instance, Tianping et al.[15] explained the field case study that used nanoparticles to control formation damage in the Gulf of Mexico oil field, with a reservoir temperature of 160 °F, water depth of about 2500 ft, and pay zone ranges between 15 769 and 15 860 ft. The field production declined from 7500 to 2200 barrels of oil per day (BOPD) and from 6000 to 2000 thousand of cubic feet (MCF) of gas. They used 97 000 lb 20/40 mesh proppants, which were treated with nanoparticles in the fracking process to the damaged wells. Per the results, nanoparticles managed to mitigate the formation damage by absorbing fines and preventing their accumulation and plugging to the near-wellbore region. They concluded that after (6 months) proppant treatment with nanoparticles, the well recovered to its normal productivity, with 2800 BOPD, while that of gas is 2700 MCF, without fine migration or formation damage.[15]

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Borisov et al.[16] investigated the drilling process using oil−base drilling fluid with and without nanoparticles. They explained that the drilling fluid with nanoparticles is likely to reduce fluid loss by making thin filter cake compared to a fluid without nanoparticles (Figure 4). They concluded that the drilling fluid with nanoparticles reduced 22−34% fluid loss compared to traditional fluid when 0.5 wt % calcium nanoparticles were introduced.[16]

Zabala et al.[17] developed models for formation damage analysis at Castilla and Chichimene fields using nanofluid to treat the formation damage. The Castilla field suffered from severe formation damage, like asphaltene deposit (30%), mineral scales (14%), and 56% from the drilling and completion process. However, the Chichimene field suffered from formation damage, such as emulsion damage and skin effect of 29, 31.9, and 37. They treated wells by 86 bbl of nanofluid for the Castilla field and 107 bbl for the Chichimene field. They concluded that application of nanofluid at the Castilla field changed the skin effect from 23 to 6.2, while at the Chichimene field, the skin effect changed from 47 to 19, as shown in Figures 2 and 3, respectively.[17]

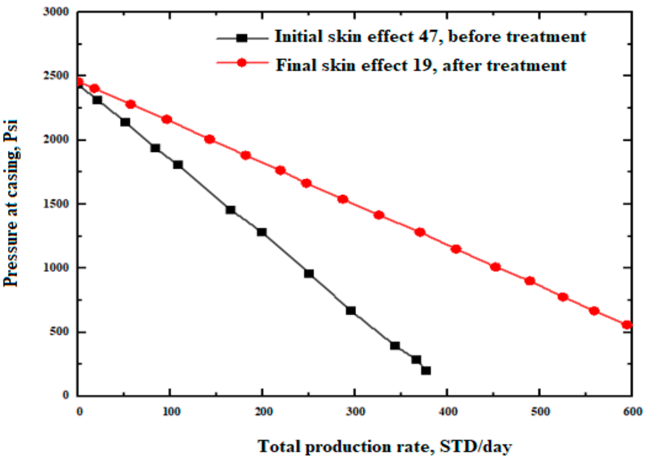

Figure 2. Before and after the skin effect at the Castilla field. This figure was reproduced with permission from ref 18. Copyright 2017 Elsevier.

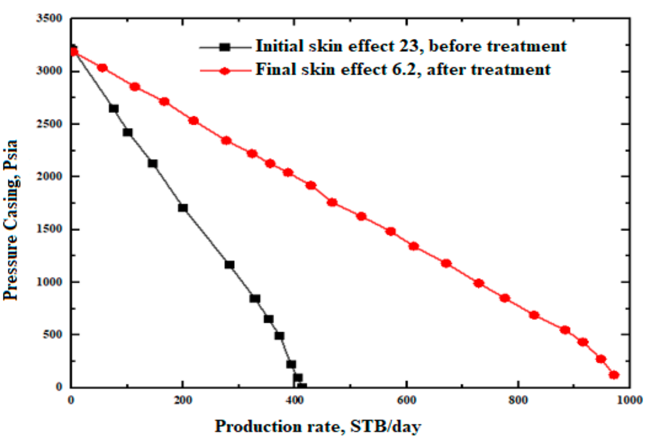

Figure 3. Before and after the skin effect at the Chichimene field. This figure was reproduced with permission from ref 18. Copyright 2017 Elsevier.

Camilo et al.[18] studied the use of nanotechnology in the oil field in Cupiagua, Colombia. The employment of nanoparticles and nanofluid to control formation damage after asphaltene deposition was observed near the wellbore region.[19] The CPSXL4 well was chosen for field testing by injecting 220 BOPD of the nanofluids with alumina nanoparticles into the reservoir formation. The results reveal that the skin effect improved when they conducted nodal analysis to check the skin effect after the operation. The asphaltene deposits near the wellbore region were reduced and allowed fluid to flow to the producing well, which make the production increase to 300 BOPD. However, following the success of the first trial in the CPSXL4 well, the use of nanoparticles in the Colombian fields was expanded to other wells. Nanoparticles were found to be beneficial in controlling formation damage and increasing production.

Furthermore, the application of nanoparticles in China was discussed by Yongxiang et al. Field trials with nanoparticles were undertaken in Jiangsu, Daqing, Henan, and Shengli oil fields. The end outcome has demonstrated the expected advancement.[20,21] At the Shengli oil field, modified silica (SO_2) nanoparticles were injected into the reservoir formation using a volume of 3−20% of the pore volume. By replacement of the hydration membrane, the modified silica (SO_2) nanoparticles have managed to change the wettability of the rock and allowed oil to flow.[20]

This review discusses the overview of nanomaterials that control formation damage in oil and gas reservoirs. It examines the applications of nanotechnology and its damage control during drilling, completion, EOR, and hydraulic fracturing processes in recent years. This work provides a compressive review on the fields and laboratory investigations. Finally, it suggests and recommends the future research for nanotechnology applications.

2. APPLICATION OF NANOTECHNOLOGY FOR FORMATION DAMAGE CONTROL

2.1. Application of Nanotechnology for Formation Damage Control during Drilling. Drilling the wellbore into subsurface formations is the earliest stage in the life of a well in petroleum industries. Usually, it introduces foreign material into the reservoir rocks, such as drilling fluids, to prevent the high influx of formation fluids to the wellbore.[22] While preventing the influx of formation fluids, drilling fluids also form a filter cake, which is a thin layer that temporarily seals the pore to prevent the fluid invasion to the formation. To control the influx of formation fluids to the wellbore, the pressure of the drilling fluid columns is always high, to exceed the pore pressure by at least 200 psi.[22,23] During this time, the fluid loss is extremely high and the filtrate from water-based mud can manage to invade the formation (see Figure 4A). However, the mud filtrate that has managed to invade the formation alters the properties of the formation fluids and, as a result, can plug the near surface pores, causing the formation damage.[24,25] Most of the mechanisms cause formation damage during drilling, like fluid−fluid incompatibility, which forms emulsion and slugs that can block and plug the porous system and decrease the flow capacity of gas and oil.[26,27] Another mechanism is rock−fluid incompatibility, which is a chemical reaction between rocks and fluid, such as clay swelling or clay deflocculation with water. The outcome of the reactions can plug the porous media[28,29] and cause formation damage. Also, the mechanism of solid materials from weighting agents, such as bentonite, together with the fines from drilling cuttings can invade and plug the permeable parts of the formations, causing

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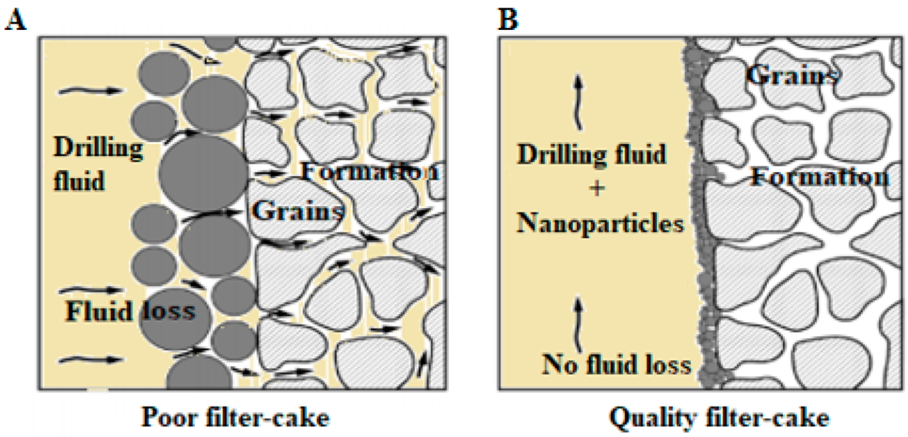

Figure 4. Drilling mud losses while drilling (A) lost circulation materials (LCMs) and (B) application of nanoparticles. This figure was reproduced with permission from ref 32. Copyright 2015 Springer Nature.

Table 1. Function of Iron Oxide Nanofluids in 5% Bentonite Aqueous Suspension at 25 °C and Atmospheric Pressure[47]

sample	nanoparticles + sample	yield stress (Pa)
5 wt % bentonite		1.27
5 wt % bentonite	0.5 wt % iron oxide (30 nm) + 5 wt % bentonite	1.80
5 wt % bentonite	5 wt % iron oxide (30 nm) + 5 wt % bentonite	7.67
5 wt % bentonite	0.5 wt % iron oxide (3 nm) + 5 wt % bentonite	3.33
5 wt % bentonite	5 wt % iron oxide (3 nm) + 5 wt % bentonite	36.89

significant formation damage, leading to low production of oil and gas.[25] The last mechanism is the formation of phase trapping within the porous system, which can block and affect the normal flow of formation fluid to the wellbore during production.[27]

It is essential to control the formation damage during drilling to minimize operation costs or to abandon the well. In this regard, many researchers have recently conducted numerous studies to design proper drilling fluid using nanotechnology, which consists of nanomaterials to control formation damage in hydrocarbon fields.[30−32]

2.1.1. Drilling Fluid and Formation Damage Control. For the stable development of drilling jobs, rheology and filtration control are essential properties to be highly optimized to control fluid invasion or fluid loss because the result of formation damage can easily occur.[33]

During oil and gas drilling, the wellbore instability is challenging, especially in shale formations.[34] This is due to the shale hydration expansion process,[35] in which the filtrate from water-based drilling fluid managed to invade the formation.[36] When water-based drilling fluid is used,[36] the water filtrate can invade shale formation through micropore throats, weak structures, or natural cracks, resulting in fluid−fluid incompatibility; hence, the hydration expansion process of shale can occur, causing cause severe formation damage[35] and weakening the strength and mechanical support of the shale rocks, resulting in wellbore instability during drilling operations.[37]

Currently, drilling with nanomaterials proved to have promising results as a result of their distinctive characteristics, like large surface area and high thermal conductivity.[32,16,4] Many researchers have demonstrated that, with a low concentration of nanomaterials in drilling fluids, the outcome has shown the best performance in fluid rheology behavior and filtration properties.[38−40] However, to avoid wellbore instability, we should improve the properties of rheology and thermal stability of the drilling mud by introducing various nanoparticles to plug the nanopore throat, natural fractures, and micropore structures during drilling. These nanoparticles include titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), silica nanoparticles (SiO_2), carbon nanotubes (CNTs), copper oxide (CuO), and iron oxide (Fe_2O_3), which control filtrate loss to the formation that may cause formation damage and wellbore instability.[41−43]

Figure 4B shows the addition of nanoparticles that forms quality mud cake and wellbore stability during drilling and eliminates many forms of damage around the vicinity of the wellbore.[44] In ultralow-permeable zones, like in shale, nanomaterials prevent water movements between the wellbore and shale formation by plugging the pores.[45] Studies have shown that, when nanomaterials are blended with drilling fluid, their potential to reduce fluid loss is more than 70%.[46]

It has been reported that designing drilling fluid with nano-based material is very crucial to have better rheological properties, which have the tendency to reduce fluid loss in high-permeable reservoir formation.[46] In 2011, the study was conducted by Jung et al. in which bentonite (5 wt %) was mixed with iron oxide (Fe_2O_3) nanoparticles with a nanoscale size of 3 and 30 nm. The sample was tested, and the results have shown that 0.5 wt % iron oxide (30 nm) with 5 wt % bentonite exhibits high reduction of fluid loss control that may cause formation damage, as indicated in Table 1 and Figure 5. The rheological properties were improved by increasing the viscosity, interaction capability, and yield stress.[47] This is because the critical net charge of 0.5% iron oxide (30 nm) with 5% bentonite was obtained, meaning the forces of repulsion and attraction were in such a proportion that clay platelets aligned face to face rather than face to edge. This alignment can reduce the surface area of penetration of the filter cake formation.[47,48]

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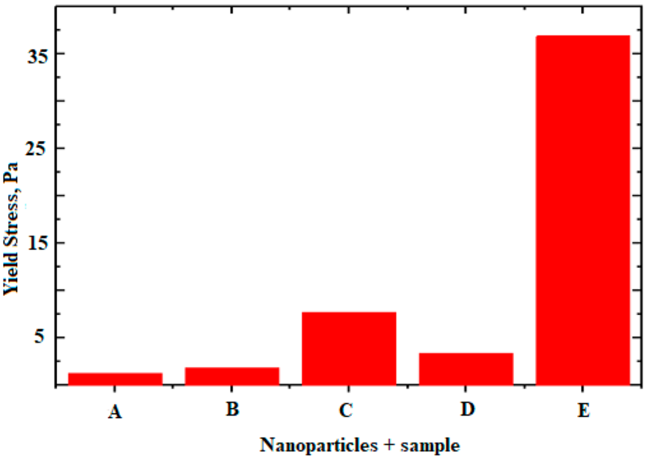

Figure 5. Effect of bentonite fluid with and without incorporated nanoparticles at 25 °C. A represents 5 wt % bentonite without nanoparticles; B represents 0.5 wt % iron oxide (30 nm) + 5 wt % bentonite; C represents 5 wt % iron oxide (30 nm) + 5 wt % bentonite; D represents 0.5 wt % iron oxide (3 nm) + 5 wt % bentonite; and E represents 5 wt % iron oxide (3 nm) + 5 wt % bentonite. B shows better rheological properties than the others, which can have the ability to reduce fluid loss in the formation of a high-permeable reservoir by having a low yield stress.

Tin oxide (SnO_2) was employed as a nanoparticle by Parizad et al.[49] to examine its influence on fluid loss control in water-based drilling fluids. Mixing tin oxide (SnO_2) with water-based drill fluids increased the rheology and filtration capabilities, according to a study by Parizad et al. However, the volume of fluid filtration was reduced by 20% when 2.5 g/L tin oxide (SnO_2) nanoparticles were added in water-based drilling mud. The filtration remained unchanged when tin oxide (SnO_2) nanoparticles were added. Many studies have used nanoparticles to control formation damage by preparing good and standard rheological and filtration qualities, as shown in Table 2.

The experiments have shown that, by incorporating nanoparticles into drilling fluids, considerable improvements in rheology and filtration characteristics can be achieved, which are critical attributes in reducing formation damage, such as fluid loss, wettability change, slugs, and emulsion formation. Several studies involving drilling fluid and nanoparticles and how they serve to reduce formation damages have been conducted with a variety of authors.[57−59]

Johanna et al.[48] conducted an experiment to investigate the effect of silicon dioxide (SiO_2) in the filtration and rheological qualities of water-based mud (bentonite). They used tetraethyl orthosilicate to make SiO_2 nanoparticles and also used silica nanopowder at 10−20 nm, which are at the fumed state. The addition of these nanoparticles to the water-based mud (bentonite) increased the plastic viscosity, yield point, and yield stress by 12, 19, and 100%, respectively. It also improved formation damage by reducing the fluid loss and total filtration volume by 67 and 49%, respectively. Mahmoud et al.[60] did another experiment in 2016 to assess the effect of iron oxide and silica nanoparticles with 0.5 wt % water-based mud (WBM) at 200 °C. According to the findings, silica had the largest yield stress of 130%, whereas iron oxide had little change of 42% yield stress. However, for iron oxide and silica nanoparticles, the plastic viscosity result has grown by 166 and 211%, respectively. These investigations have revealed that choosing a drilling fluid with appropriate nanoparticles is critical for preventing formation damage during drilling. It protects filtration and rheological behaviors, which might prevent the consequences that can degrade the formation and cause harm to the formation.

2.2. Application of Nanotechnology for Formation Damage Control during Well Completion. During completion, activities, such as the casing process, cementing job, gravel packing, perforating and installing of a production tree, completion fluid, or workover fluid, may be applied. During this time, the completion and workover fluids/cement can invade the reservoir formation and cause the solids and mud filtrate to plug into porous systems of formation. In this situation, the effective permeability and pore volume can be decreased and lead to formation damage around the wellbore regions.[45] Yili et al. conducted research on a Western Sichuan tight gas reservoir to examine the formation damage as a result of fluid loss, and they concluded that the average formation damage degree induced by drilling fluid loss is 68.51% and increases to 78.70% when the kill fluid loss is taken into consideration.[28] In this case, the possibility to cause the formation damage by altering the formation fluid property is high. The formation damages associated with well completion fluid can be mentioned as (1) pore channel system blockage during the cement job,[61] (2) interaction between cement additives and reservoir fluids, which lead to scaling, clay reactions, fine migration, and silica dissolution, (3) invasion of fluid solids and filtrate fluid from completion or fine invasion during perforation into the formation,[62,63] and (4) wettability changes when completion fluid additives are applied.

To control formation damage in the completion job, there is a need to study and select the best completion fluids/cement slurry with less formation damage, so that it can protect the reservoir.[64]

The introduction of nanotechnology in the oil and gas fields has paved the way to fight against formation damage during completion activities.[48,65] The completion fluids can contain various nanoparticles to improve their efficiency, especially

Table 2. Application of Nanoparticles in Drilling Fluid To Prevent Formation Damages

nanoparticles (NPs)	function	references
iron oxide (Fe_2O_3)	reduction of fluid loss	47 and 50
silica nanoparticles (20 nm diameter, SiO_2)	prevent water invasion into shale; improve rheology properties	51 and 52
metal oxide, nanomaterials, and nanopolymer	filtrate loss of the water-based drilling fluid control	45 and 53
Al_2O_3 nanoparticles	prevent asphaltene self-association and lead to changes in the wettability of the porous media; improve rheology properties	54 and 55
nanoclay, zinc oxide, and CNT−polymer nanocomposite	improve rheology properties and reduce fluid loss	38−40
cellulose nanofibers (CNFs), titanium oxide, and zinc titanate	rheology and filtration control	55 and 56

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fluid loss and viscosity, which may damage the reservoir formation. It may contain nanosilica, nano iron oxide, ferromagnetic nanoparticles, surface-modified nanoparticles, carbon nanotubes, etc., which are better than conventional completion fluids.[66]

Well cementing is a technique in the oil and gas industry that involves injecting cement into the gas or oil wellbore through the annular space between the casing and the rock formation after the drilling operation is completed (Figure 6).[67,68] Cementing isolates zones by restricting fluid communication across the different zones in the formation of the reservoir. In addition, it provides casing and structural support to withstand the loads/pressure during well production.[45,67,69]

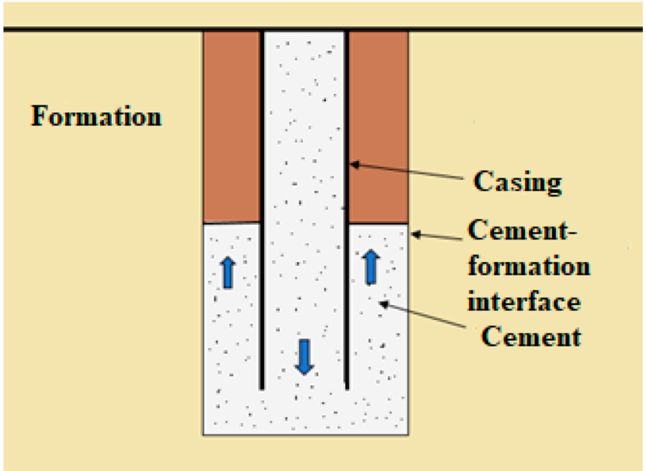

Figure 6. Schematic diagram for primary oil well cementing.

Furthermore, failure to achieve a high-strength cement bond between the casing and the rock formation might lead to further issues and formation damage: blockage of pore channel networks in wellbore regions when cement filtrate manages to invade the formation, interaction between cement additives and reservoir fluids resulting in scaling, clay reactions and silica dissolution, formation of fluid leakage, contamination of fresh water and formation fluids, and fluid loss during injection.[61,70,71] This formation damage leads to a decline in the permeability and productivity of the reservoir, resulted in a high cost of remedy with uncertain success.[72]

To control formation damage during cementing, we need to have a high-strength cement bond between the casing and the rock formation to have a complete hydrocarbon production by modifying cement properties and functionalities. Currently, the use of cement with nanomaterials demonstrated promising results to control formation damage. Nanoparticles enhance zonal isolation and early strength development and provide casing and structural strength for withstanding the loads/pressure during well production.[45,67,69,73−75]

In the oil and gas sector, there are four main phases of well cements, which are C_3A, C_4AF, C_3S, and C_2S.[1,76] These phases contain lime and some alkali sulfate. Each phase has a specific task to complete to deliver high-quality cement. C_3A and C_4AF phases are responsible for rheology and gelation control, while C_3S and C_2S phases control compressive strength of the cement. Consider the reactions below:[76]

$$2C_3S + 6H \rightarrow C{-}S{-}H + 3CH$$

$$2C_2S + 4H \rightarrow C{-}S{-}H + CH$$

During the reaction of C_3S and C_2S with water, C−S−H gel and calcium hydroxide (CH) are formed. Generation of C−S−H gel is very important because it provides strength to cement. When nanosilica is added to the cement, there is an acceleration of the earlier strength of the cement C−S−H gel as a result of reactivity of pozzolanic, which prevents additional reactivity with the formation fluids, which could result in formation damage.[77]

Patil and Deshpande[77] conducted research into the use of nanosilica in cement formulations. They came to the conclusion that nanosilica contributed to early cement strength and fluid loss management. Tables 3 and 4 show results from the Patil and Deshpande experiment.

Table 3. Effect of Nanosilica to Compressive Strength of Cement[77]

silica	compressive strength (psi) before adding nanoparticles	compressive strength (psi) after adding nanoparticles
0	172	690
micrometer-sized silica	160	610
nanosilica	460	2203

Table 4. Effect of Nanosilica to the Fluid Loss Control[77]

nanosilica (gal/sk)	fluid loss additive (% bwoc)	fluid loss (mL/30 min)
0	0	52
0.2	0	34
0	0.5	38
0.2	0.5	22

Table 3 shows the ability of nanosilica to provide the compressive strength to the cement. When nanosilica is employed, compressive strength increases from 460 to 2203 psi, but without it, compressive strength increases from 172 to 690 psi. It proves that nanosilica is beneficial to the cement strength.

Table 4 shows that nanosilica has a significant impact on fluid loss. The result demonstrates that using 0.2 gallon per sack (gal/sk) nanosilica with 0.5% by weight of cement (bwoc) fluid additive reduces fluid loss to 22 mL/30 min. However, Table 4 shows that, when a fluid loss additive of 0.5% bwoc is used without nanosilica, fluid loss might be as high as 38 mL/30 min. When drilling fluid was used without nanosilica and fluid loss additives, fluid losses can be as high as 52 mL/30 min.

On the other hand, many types of nanomaterials have been considered as additives in cement (iron oxide, titania, alumina, etc.).[78] Many researchers have recommended nanosilica materials (SiO_2) as the nanomaterial to be used in cementing jobs. Nanosilica materials have higher performance and are the most cost-effective, promising, and efficient compared to the traditional cement materials.[45,79−85] Chithra et al.[86] conducted an experiment to see how nanosilica affects cement strength. They employed nanosilica with a size of 5−40 nm and 0.5, 1, 1.5, 2, 2.5, and 3% by weight of cement to replace the Portland cement. This study was performed for several days at curing times of 3, 7, 28, 56, and 90 days. The findings revealed that nanosilica accelerated and improved the strength of cement as a result of its pozzolanic qualities, which promoted reactivity

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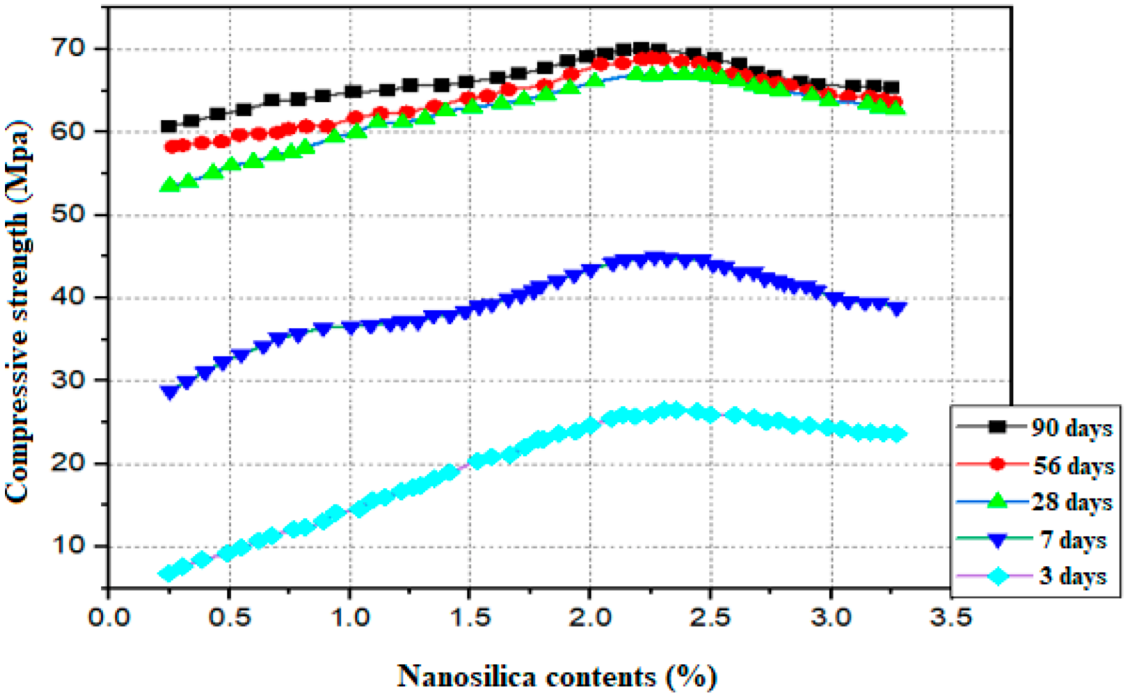

Figure 7. Compressive strength of cement from different curing times with nanosilica. This figure was reproduced with permission from ref 1. Copyright 2020 Elsevier.

and interactivity in the cement. In addition, nanosilica attained the best compressive strength as the curing days rose, according to the findings. Figure 7 shows that 2% nanosilica had the maximum compressive strength of roughly 70 MPa after 90 days. The nanosilica has enhanced cement strength, which is one of the most important aspects for stabilizing cement and preventing formation damage.

Nanosilica proved its performance according to its mechanisms in the cement slurry as a result of its size in the nanoscale range[45] and high surface area/volume ratio,[13] which increase the reactivity and interaction by filling several cement matrix voids, giving cement a dense structure. When rheology and fluid loss improved, the formation damage improved too, in the sense that permeability around the wellbore can be effective and unchanged. Several studies emphasized that adding nanosilica to the cement slurry promotes the strength, stability, rheology, reduction of the cement setting time, and zonal isolation.[1] Nanosilica can control well damage and extend the well life. Determination of the optimum amount of nanosilica is necessary because current field trial work is scarce. For a better understanding, more field trials and studies are recommended.

2.3. Application of Nanotechnology for Formation Damage Control during EOR. EOR is used to recover oil from a reservoir after the energy recoverable by primary and secondary recovery methods has declined.[87] It focuses to recover oil that has remained in a petroleum reservoir after primary and secondary recovery methods has been depleted. It recovers oil through the injection of fluids and energy that are not ordinarily present in the reservoir. The techniques of EOR include chemical flooding, thermal techniques for heavy oil, water flooding (low salinity), and CO_2 flooding. Application of EOR techniques are associated with formation damages to the oil and gas formations.[14,88,89] The formation damage during EOR includes[90] (1) clay expansion (swelling), fine migration, clay swelling deflocculation, and phase trapping/blocking[91,92] and (2) wettability alteration, ion exchange, pH increase, and dissolution of organic components.[93−96]

Formation damage in EOR techniques needs more attention and awareness in many operating companies because production in potential oil resources tends to decline.[97,98] It needs more efficient and less expensive techniques to minimize and control formation damage to avoid increases in operational cost and time.[72] In recent decades, the introduction of nanotechnology in the oil and gas development has demonstrated a useful way to inhibit formation damage during EOR operations. The application of nanomaterials has caught the interest of many researchers in EOR, and its potential increases day after day.[89,99−102] Nanomaterials exhibit distinct solutions when introduced into porous media to improve EOR methods and to avoid formation damage in oil reservoirs.[93] When nanomaterials are mixed with chemical fluids during EOR, improved results can be seen in terms of oil recovery and control formation damage, like reduction of phase trapping, control of fine migration, wettability alteration, reduction of drag, asphaltene precipitation, and emulsion stabilization.[103,104] This is due to their distinct qualities, such as a small size in the nanoscale, good thermal stability, effective adsorption capacity, ease of functionalization, and large surface area/volume ratio.[105,106]

2.3.1. Interfacial Tension (IFT) Reduction. IFT in oil and gas is the tendency that forces act on the fluids having different characteristics, such as filtrate invasion (foreign and formation fluids) to the reservoir formation during the drilling or fracturing process.[107−109] When the IFT becomes high, it can strongly hold water and block the natural flow of oil or gas, causing formation damage. This remark was supported by Gao et al.[110] by explaining that high IFT negatively affects oil production during fracturing fluid processes, thus inducing formation damage. On the other hand, Fengpeng et al.[111] conducted research on the effect of water blocking as a result of the fractures in tight formation when the hydraulic

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fracturing process is applied. They applied numerical simulation to demonstrate their output. They deduced IFT trapping of water in the reservoir matrix and concluded that reducing IFT can reduce formation damage and result in load recovery improvement.

However, IFT is directly related to capillary pressure.[112] Thus, to control formation damage caused by IFT, there is a need to reduce the capillary pressure.[113] When capillary pressure is reduced, its ability to hold and trap liquid is reduced too, and then IFT becomes low, allowing for more oil to flow in the producing well. To achieve interfacial reduction, nanoparticles have been used to improve EOR processes and control formation damage caused by IFT.[93,114−116] Figure 8 shows the nanomaterials that can change the surface of a liquid by adsorbing and separating the surface forces of the liquid. When nanoparticles are added, the IFT becomes reduced.[94]

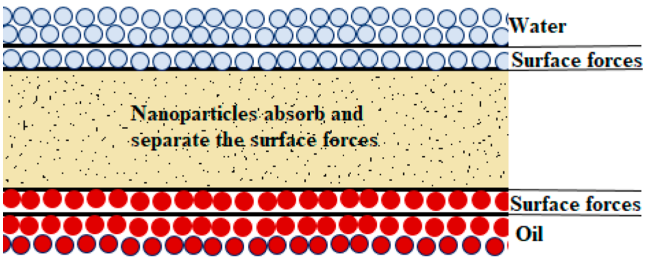

Figure 8. Diagram shows nanoparticle (NP) action in the oil/water interface.

Suleimanov et al.[93] performed an experiment concerning the application of nanofluid in EOR to study the effects of IFT to the reservoir formation. The results have shown that, when nanomaterials were applied, surface tension becomes reduced 70−79% when only the mass of sulphanole solution of 0.004−0.0078% was considered. However, nanoparticles improved the rheology of the fluid, which increased the surfactant solution, changed the surfactant/oil interface, and reduced the IFT.[117] Furthermore, the introduction of a small amount of 0.1 vol % TiO_2 at 15 nm size nanofluid to the formation can show a significant reduction of IFT by raising the temperature, while the surface tension becomes adsorbed.[118] The experiment conducted by Tushar and Jitendra about nanofluid silica (SiO_2) used for IFT reduction in chemical EOR operations used conventional polymer (P) and surfactant polymer (SP) methods to compare to nanoparticle−polymer (NP) and nanoparticle−surfactant−polymer (NSP) fluids, which were added at 1.0 wt %.[119] Figure 9 has shown that NSP fluids achieved the best result to reduce IFT compared to other methods. Another experimental study conducted for TiO_2 shows that the application of TiO_2 nanoparticles to the EOR fluids can adsorb the air−water interface and reduce IFT.[120] Also, non-ferrous metal nanoparticles can stabilize nanofluids and significantly reduce 70−90% IFT.[93]

As explained previously, the formation damage caused by water blocking is common, especially in tight formation in which the filtrate managed to invade the formation and restrict the natural flow of reservoir fluids as a result of IFT. Nanoparticles can have the ability to reduce IFT and lower capillary pressure and irreducible water saturation. Therefore, nanoparticles remove considerable phase trapping that could block fluid flow and cause formation damage of the reservoir.

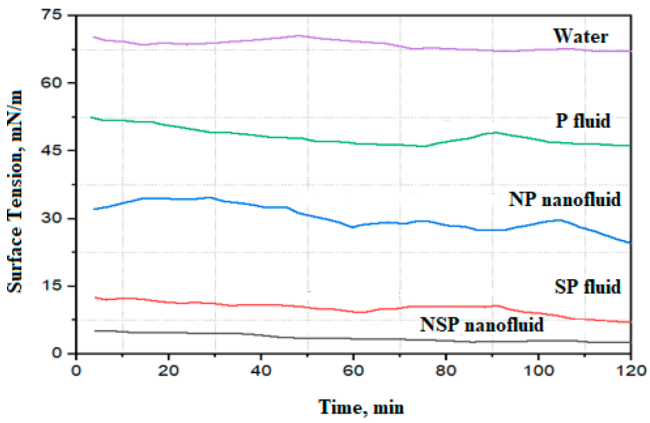

Figure 9. Water surface tension reduction when added polymer fluid (P fluid), surfactant−polymer fluid (SP fluid), nanoparticle−polymer SiO_2 (NP nanofluid), and SiO_2 nanoparticle−surfactant−polymer (NSP nanofluid) at 25 °C and 1.0 wt % SiO_2 concentration for nanofluids. This figure was reproduced with permission from ref 119. Copyright 2017 Elsevier.

2.3.2. Wettability Alteration. Wettability defines the affinity properties of two kinds of fluids in the formation surface when immiscible liquid is available.[121] However, the surface of the rock can be water-wet (A), mixed-wet (B) (intermediate), and oil-wet (C)[122,123] with specific angles, as shown in Figure 10.

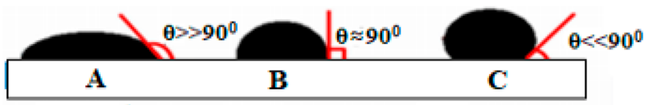

Figure 10. Rock wettability with different angles.

Wettability performs a significant role in fluid displacement efficiency within porous systems during EOR. However, the change of wettability near the wellbore zone from water-wet to oil-wet can affect reservoir properties and the extraction of oil and gas and, consequently, induce formation damage.[124,125] This wettability alteration leads to a pressure drop and decline of oil permeability and restricts oil flow to the producing well.

Therefore, the alteration of wettability from water-wet to oil-wet is unfavorable, especially the near region of the wellbore.[126] To account for wettability, the relative permeability and capillary pressure are the basic parameters mainly dependent upon the wettability.[127] If the reservoir is water-wet, the imbibition is high and the rate of forming a trapping phase is significant.[125] Furthermore, when the reservoir is characterized by low water saturation, capillary pressure increases because the results of the imbibition and holding water can cause the trapping phase; hence, the flow of oil to the wellbore decreased.[128] Thus, there is a need to control wettability properties around the vicinity of a wellbore with improved additives to avoid any form of formation damage resulting from alteration of wettability.

Nanomaterials can be used during EOR techniques to control wettability change within the porous system to ensure sufficient flow of formation fluid to avoid formation damage. Maghzi et al. performed a study on the application of silica nanoparticles in a water-flooding process and deduced that silica nanoparticles managed to alter wettability properties from oil-wet to water-wet.[96]

https://doi.org/10.1021/acs.energyfuels.1c03223
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Silica nanoparticles can be used as additives during EOR to change the wettability.[95,96] However, adding hydrophilic nanoparticles of 0.05 wt % to the surfactants during EOR managed to alter the wettability from 15 to 33%.[129] Furthermore, nanopowder of silica has a high tendency of showing hydrophobicity and lipophilicity; once it is absorbed on the rock surface, it can alter wettability.[93] However, it is also important to note that TiO_2 nanofluids can do the same as silica in altering the wettability properties.[94]

Another instance of wettability alteration as a result of silica nanoparticle usage can be found in the study by Abass and Hadi,[130] with deduction of the same via changing the concentration of silica nanoparticles (0, 1, 2, 3, 4, 5, and 6 g/L) (Table 5). They reported 4 g/L as an appropriate

Table 5. Alteration of Wettability When SiO_2 Nanoparticles with Different Concentrations Are Added to the Chemical Agents on the Surface of the Carbonate Rock[130]

step	concentration of nanosilica (g/L)	effect of alteration of wettability (changes of contact angles)
a	0	θ = 107.785°
b	1	θ = 142.785°
c	2	θ = 98.552°
d	3	θ = 73°
e	4	θ = 56.857°
f	5	θ = 52.275°
g	6	θ = 52.275°

concentration to change the wettability of the surface of the carbonate rock from oil-wet to water-wet properties to achieve the contact angle of less than 90°, which is preferable for a water-wet surface (Figure 11), with the latter required for oil to

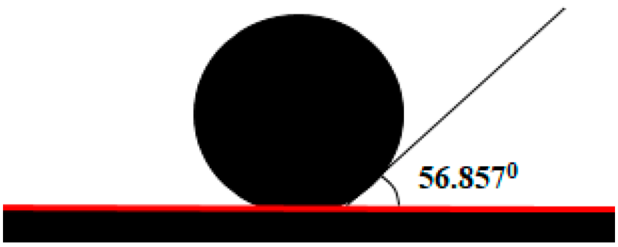

Figure 11. Alteration of wettability in the concentration of 4 g/L nanosilica for step e from Table 5.

flow toward the production well without damaging the near-wellbore zone, as described in the results obtained from their experiment. Tables 6 and 7 show details of the different nanoparticles, which control formation damage during EOR techniques, including the silica nanoparticles. Nanoparticles

Table 7. Formation Damage during the EOR Technique and Some Nanoparticles Used To Control Formation Damage

EOR method	formation damage	nanoparticles used	references
chemical flooding	asphaltene deposit	Al_2O_3	2
	foam/emulsion	SiO_2	
thermal techniques for heavy oil	hydrate	SiO_2	101
	clay swelling and defloculation	polyethylene glycol (PEG)-coated silica	138 and 102
low-salinity water flooding and CO_2 flooding	wettability alteration	hydrophilic, Fe_2O_3 silica, ZrO, and TiO_2	93−96
	molecular/ionic adsorption	SiO_2	8
	fine migration	polyethylene glycol (PEG)-coated silica	102
	phase trapping	MgO, SiO_2, and Al_2O_3 polysilicon nanoparticles	99, 100, and 139

can interact and mix with fluid and rock to improve the reservoir properties, including wettability alteration. When the optimum concentration of nanoparticles increased, the permeability improved and the possibility of formation damage is significant. The wettability alteration is achieved as a result of wettability alteration from an oil-wet property to a water-wet property as a result of the adsorption ability and the reaction of the surface of the rock to the nanoparticles.

Most studies have shown the positive influence of polyethylene glycol (PEG)-coated hydrophilic, Fe_2O_3, Al_2O_3, ZrO, TiO_2, coated silica, MgO, SiO_2, Al_2O_3, and polysilicon nanoparticles in EOR. In general, these nanoparticles, when added to the chemical fluids during EOR with the specific concentrations, can improve oil displacement efficiency by inhibiting formation damage via mechanisms, like phase trapping, fine migration, wettability alteration to achieve water-wet conditions, reduction of drag, asphaltene precipitation, and emulsion stabilization. However, further investigation is required for possible EOR improvements via a combination of different nanoparticle types.

2.3.3. Application of Nanotechnology for Formation Damage Control during Stimulation. Production of oil and gas from tight and shale formation always needs a stimulation technique to create the complex network of artificial hydraulic fractures. A large volume of proppants is pumped into the formation to enhance transportation of shale gas from the formation to the wellbore in commercial quantities.[140−144] Such production requires the complex network of artificial fractures to have sufficient conductivity to sustain the whole period of production.[145] Unfortunately, the techniques for transporting and placing proppants in the formation to hold the fractures exhibit formation damage near the fracture

Table 6. Action of Silica Nanoparticles (SiO_2) with Different Concentrations To Control IFT and Wettability, Minimize Formation Damage, and Improve the Production of Oil during EOR

number	nanoparticles with concentration	media	IFT (mN/m) before and after treatment	contact angle before and after treatment	recovery (%)
1	0.3 wt % SiO_2	propanol	from 38.5 to 1.45[131]	from 134 to 84[131]	
2	0.1 wt % SiO_2	water	from 13.62 to 10.69[132]	from 122 to 24[132]	8.7[96]
3	0.1 wt % SiO_2	ethanol	from 25 to 5[133]	from 135.5 to 66[133]	
4	0.05 wt % SiO_2	brine	from 19.2 to 16.9[134]	from 90 to 26[135]	0−15[136]
5	0 wt % SiO_2	brine	from 21.7 to 4.2[137]	from 87 to 25[135]	12.1[137]
6	0.1 wt % SiO_2	brine	from 21.7 to 4.5[137]	from 83 to 21[135]	16.3[137]
7	0.5 wt % SiO_2	brine	from 21.7 to 5.2[137]	from 82 to 18[135]	24.4[137]

https://doi.org/10.1021/acs.energyfuels.1c03223
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surface that affects fracture packing.[146−148] Many mechanisms impair the fracture conductivity during the process of fracturing.[145,148,149] These include proppant embedment,[150] closure stress effect,[151,152] proppant crushing,[153,154] cyclic stress,[148] fine migration,[155] proppant pack diagenesis,[156,157] and the blockage caused by the gel residue in the proppant pack and gel filter cake at the fracture face.[158,159]

Recent studies have demonstrated that the use of nanoparticles can improve and control formation damage during stimulation[8] compared to conventional methods. Nanoparticles can maintain the efficient and high conductivity of the fractures to extend the period of oil and gas recovery.[160] Having a small size,[45,161,162] nanoproppants show significant properties, like flowing easily and deep penetration into an existing network of fractures, and hold the fracture from closure pressure, allowing oil or gas to flow to the producing well.[160] However, during this time, nanoparticles can increase the reactivity and interactivity, which can connect fines by changing the surface charges of the fine and lowering the existing repulsion force between formation grains and fines.[163,164] In this situation, the production and movement of fines, which might weaken the conductivity of the fractures and cause formation damage, are prevented. This view is supported by Huang et al. that nanoparticles have shown better results when silica PEG nanoparticles impregnated with inorganic brines of KCl and NaCl or PEG-coated nanoparticles hinder swelling properties of montmorillonite that can plug into the pore throat during stimulation and destabilize the flow efficiency of formation fluid to the producing well.[7]

However, Jiang et al. demonstrated that the use of nanoparticles during stimulation can control the formation damage near fracture zones. They explained that, when nanoparticles are associated with viscoelastic surfactants (VES) used during stimulation, they can have the ability to improve rheological properties and filter cake that can prevent the fluid loss to the formation, which might destabilize the mechanical strength of the rock formation and cause formation damage. In addition, having nanoscale properties, nanoparticles can penetrate into the porous system and flowback together with formation fluids without generating formation damage.[13,45] The study conducted at Atoka shale to examine fluid penetration to the formation after the addition of nanoparticles showed that fluid penetration was reduced between 16 and 72%, while that of the Gulf of Mexico was reduced between 17 and 27%.[16] Nanoparticles can be used widely during stimulation and bring positive results in terms of maximizing production and controlling formation damage. Barati et al. explained that nanoparticles during stimulation techniques can be used to clean the formation after the fracturing process, such as polyelectrolyte complex nanoparticles being used as the cleanup materials during the fracturing process.[165,166]

Moreover, nanoparticles can remove formation damage caused by blockage of the gel residue in the proppant pack and gel filter cake at the fracture face,[158,159] resulting from conventional hydraulic fracturing fluids.[167] This is because, as a result of their characteristic small size, good thermal stability, and good rheology characteristics, when nanoparticles are mixed with fracturing fluids, they penetrate into the deep porous system and improve performance compared to when the conventional fluids are used. In this way, formation damage is minimized and improved.[168,169] Therefore, nanoparticles must be considered in stimulation to minimize unnecessary formation damage that is costly to repair.

2.3.4. Nanoparticle Application on the Formation Damage Control Caused by Clay Minerals. Sensitive minerals, such as clays, show the effect on fluid−rock incompatibility mechanisms by ionic exchange with saline water.[170] To control formation damage to the oil and gas formations, the knowledge of the reaction of clay mineral with water/fluid is essential,[171] particularly in shale formation as a result of its richness in clay minerals.[172,173] There are a variety of constituents of clay minerals in reservoir formations, such as kaolinite, chlorite, illite, allophone, smectite, halloysite, vermiculite, mica, and attapulgite−palygorskite−sepiolite.[174] Kaolinite, illite, smectite, and mica are the main constituents in shale formation.[175] The presence of these clay minerals leads to swelling tendency and deflocculation, resulting in a decline in permeability of oil and gas. Swelling of clay minerals can happen when smectite minerals are surrounded by negative charges on their surface,[176] which needs to attract a positive charge to balance or be neutral.[177] As a result of this negative existence in clay platelets,[178] the positive charge of salts [potassium (K), calcium (Ca), and ammonium (NH_3)] will be attracted to clay sides to remain electrically neutral. This can result in the hydration of the interlayer increasing space within the clay minerals. In this regard, salt is attracted to the clay platelets, while water will be substituted in the clay matrix, causing the expansion of clay (Figure 12). The expansion of clay minerals in the pore system creates a considerable reduction in permeability near the fracture zone.[179]

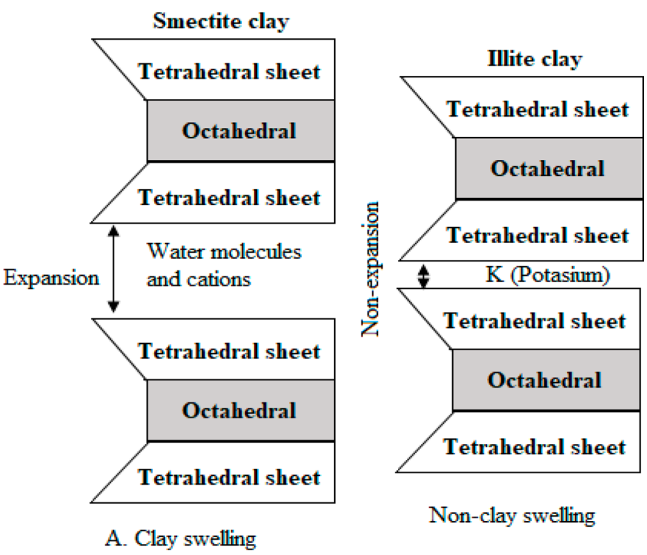

Figure 12. Descriptions of clay structures of non-swelling clay (illite) and swelling clay (smectite). This figure was reproduced with permission from ref 180. Copyright 2019 Elsevier.

Usually, there are several techniques used to control clay swelling to minimize formation damage, such as clay stabilizers, which can neutralize charge differences in clay platelets.[181] Recently, many researchers have been incorporating nanoparticles as clay swelling inhibitors to reduce the effective swelling tendency of clay minerals.[182] Nanoparticles have shown better results when silica PEG nanoparticles impregnated with inorganic brines of KCl and NaCl[183] or PEG-coated nanoparticles hinder swelling properties of montmorillonite that can plug into the pore throat.[102] On other hand, the application of silica nanoparticles particularly to the sand formation can effectively absorb clay minerals and prevent movement and its deposit into porous systems, which may cause formation damage.

To assess the electrostatic potential of nanoparticles to control clay swelling characteristics, Ramin et al.[184,185] used a ζ analyzer device. The change in surface charges to the formation rock surfaces was determined. They found that the ζ potential was positive about 50 mV (Figure 13), indicating

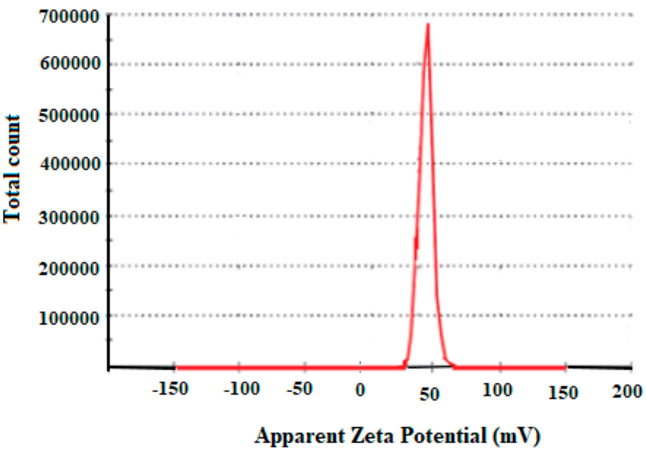

Figure 13. ζ potential (ZP) measurement of nanosilica at 25 °C and pH 7. This figure was reproduced with permission from ref 186. Copyright 2019 Elsevier.

that the nanoparticles used in the experiment were able to absorb negative charges off the surfaces of clay minerals via a neutralizing action, preventing the clay minerals from expanding and moving to the packed column. As a result, a ζ potential of 50 mV is thought to be beneficial in controlling the swelling tendency of clay minerals, which can damage the formation by lowering its permeability.[8] Other studies also deduced that, when the ζ potential of nanoparticles is greater than 30 mV, they are considered suitable nanoparticles for effectively controlling the expansion and swelling of clay minerals.[184]

To control formation damage, altering the surface charges is required, especially to the porous system, using the ζ potential technique.[187] For example, introducing MgO nanoparticles to ζ potential, the surface of the formation rock changes to the positive charge that neutralizes the negative charge from clay platelets and prevents it from swelling. Also, the positive charge can attract the fine particles with a negative charge and prevent fine movement to the porous system.[188] Having a characteristic small size and large surface area/volume ratio and concentration are the factors driving nanoparticle demonstration of promising results in controlling formation damage for clay-rich rocks. However, it is important to note that nanoparticles can absorb all free ions from the clay minerals and control the swelling tendency of the clay mineral, hence preventing formation damage occurrence.

3. FUTURE RESEARCH CHALLENGES AND PERSPECTIVES

This review looked at how nanotechnology can be used to control formation damage in hydrocarbon fields. Despite the fact that a large number of studies have been undertaken on the use of nanotechnology to aid in the control of formation damage in oil and gas fields, its application still confronts different challenges in terms of implementation. The following are the nanotechnology challenges that should be solved in future research:

First, the mechanisms to control formation damage have been discussed in this review but were not well-understood. The mechanisms of impairment of conductivity in shale/tight formations are not consistent and can differ from one formation to another. This owes to a high level of subsurface heterogeneity in terms of mineralogy, microstructure, organic content, temperature, natural fractures, mechanical properties, and other properties. More nanotechnology research and investigations are needed to improve the grasp of reality in these formations on how formation damage can be controlled.

Second, the majority of nanotechnology uses are still in the laboratory or under experiments, despite promising results. There are few field trials to demonstrate the application and outcome of nanoparticles; further field trials are suggested to develop the utilization of nanotechnology.

Third, different nanoparticles have been used in studies, and the results have shown that each nanoparticle exhibited different mechanisms to control formation damage, as shown in Table 3. Future optimization research is required, particularly formulas that specify the number/volume of nanoparticles that should be combined. This will aid in the selection of nanoparticles based on the requirements.

Furthermore, the cost of producing nanoparticles in bulk manufacturing is still being debated to meet the demand in petroleum industries. In comparison to traditional materials, producing high-quality nanoparticles requires a lot of energy and high costs. More research is needed to address this to reduce costs and replace polymer, alkali, and surfactants in the oil and gas industry to control formation damage in large fields.

Additionally, controlling the deliverability of nanoparticles to the desired target zone of the formation requires examining the adsorption and desorption characteristics of nanoparticles, particularly during flow behavior. Further experiments and theories are recommended.

Finally, this review highlighted how different nanoparticles can be used to prevent and limit formation damage; nevertheless, additional research is needed to determine how nanoparticles affect human health. Because nanoparticles are so small on the nanoscale, they are very easy to stay and spread in the air, water, and soil as well as infiltrate our bodies, particularly our skin, eyes, mouth, nose, and ears. There are few emphases in this topic to clarify the environmental and health implications.

4. SUMMARY AND CONCLUSIONS

This paper reviews and provides insight into the applications of nanoparticles to control formation damages in different oilfield operations, including drilling, completion, EOR, and well stimulation techniques. The insights gained from this study are likely to improve our understanding of how to mitigate and eliminate formation damage in oilfields. The following conclusions can be drawn from this review study:

Employing nanoparticles to the oilfields has been shown to establish a good rheology and filtration control that can control formation damage. When modest concentrations of nanoparticles are added to the drilling fluids, the rheology and filtration behaviors are altered and become stable, resulting in high-quality mud cake and wellbore stability (Figure 4B), which can help to eliminate and limit formation damage.

However, combining nanoparticles with drilling fluid has the potential to cut fluid loss by more than 70%. Furthermore, nanoparticles are effective in ultralow-permeability zones, like shale, by hindering water passage between the wellbore and the formation, thus preventing clogging of the pores.

Nanosilica materials (SiO_2) have been proposed by many studies as the most effective nanomaterial to be used in cementing activities as a result of its smaller size and a high surface area/volume ratio that enhances the rheology, fluid loss, and setting time of cement.

During EOR, when nanomaterials are mixed with chemical fluids, they show promising results in minimizing phase trapping, controlling fine migration, wettability alteration, drag reduction, asphaltene precipitation, and emulsion stabilization. However, TiO_2 nanoparticles can adsorb and separate the surface forces of the liquid, resulting in lower IFT and altering wettability.

During hydraulic fracturing, nanoproppants can keep the fracture open from closure pressure for a longer period of time, allowing oil or gas to flow to the producing well. During this time, nanoproppants can affect the surface charges of fines, lowering the current repulsion force between formation grains and fines, reducing the generation and movement of fines, which can limit the permeability of a reservoir. In addition, nanoparticles in clay rocks can balance charge discrepancies in clay platelets by absorbing the clay mineral through molecular interaction. This reduces the action of the clay mineral, such as swelling and deflocculation, which may affect the formation permeability.

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https://doi.org/10.1021/acs.energyfuels.1c03223
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■ ACKNOWLEDGMENTS

The authors acknowledge the support from the China University of Geosciences, Wuhan, China.

■ NOMENCLATURE

API = American Petroleum Institute
LCM = lost circulation material
bwoc = by weight of cement
EOR = enhanced oil recovery
C−S−H = calcium silicate hydrate
C_2−S−H = dicalcium silicate hydrate
WBM = water-based mud
C_3S = tricalcium silicate
C_2S = dicalcium silicate
C_3A = tricalcium aluminate
C_4AF = tetracalcium aluminoferrite
BOPD = barrels of oil per day
MCF = thousand cubic feet
NP = nanoparticle
IFT = interfacial tension

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