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Minireview of Formation Damage Control through Nanotechnology Utilization at Fieldwork Conditions

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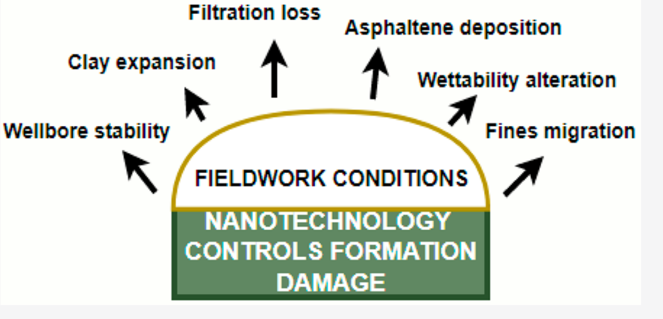
ABSTRACT: Nanomaterials have been used in the oil and gas industry to improve thermal stability, rheology properties, and reactivity through fluid dispersion into the formation. Nanomaterials in producing wells can control formation damage near the wellbore regions. Foreign fluid invasion to the reservoir rock during drilling, fracturing, completion, enhanced oil recovery, and workover causes an interaction with the rock formation and fluids. This results in formation damage such as clay swelling and deflocculation, solid particle invasion, and asphaltene precipitation, all of which reduce production and lead to significant economic losses. In this review, we present the application of nanomaterials to oilfields as a way of optimizing production with minimal formation damage near the wellbore regions. Also, this review presents how the laboratory experiments from nanomaterials were upscaled to oilfields. The different types of nanomaterials used to control formation damage across producing fields around the world were investigated. This study has shown that nanomaterials are more effective than traditional materials to be used in oilfields for controlling formation damage during various stages of oil and gas development and it recommends that the effect of the relationship between nanoparticle size and type should be explored for effective application. However, because formation damage is caused for a variety of reasons, this work points out that many types of nanomaterials need to be combined to achieve multipurpose mitigation. Furthermore, more research concerning the dispersion of nanoparticles in cement slurry and fracturing fluid should be undertaken.



1. INTRODUCTION

Formation damage is an undesirable phenomenon in the oil and gas industry that can have an impact on the overall performance of the field during drilling, completion, stimulation, EOR, and workover operations.[1−3] These operations allow foreign fluid to infiltrate the formation, resulting in an interaction between the foreign fluid and the formation fluid or the foreign fluid and the formation rock, which can cause formation damage, lowering well productivity and inflicting significant economic losses.[4,5] To minimize and manage the degree of formation damage in various types of reservoirs, several researchers have conducted experiments and studies regarding formation damage mitigations.[6−9] For many years, formation damage has been regarded as a challenge in the oil and gas industry and has become a focal point of research.[3,4] This formation damage is linked to the action of clay minerals such as swelling and deflocculation, solid particle invasion, fine migration and generation, and sand and asphaltene deposition, all of which can cause formation damage, resulting in changes in porosity and permeability, as well as a considerable reduction in oil production.[10,11]

To attain complete production potential in oil fields with minimal formation damage, the operation fluids and their properties must be improved. Without improvement of fluids, especially operation fluids (drilling, completion, EOR, and stimulation fluid), and their properties, the production potential for extracting the greatest value of oil and gas from the well may never be obtained. In recent years, some researchers have focused on the use of high-performance materials to control formation damage near the wellbore region. Nanoparticles are one such high-performance material that has gained acceptance in oil field research worldwide.[12−19] Nanoparticles are the simplest kind of structure with nanometer-scale dimensions, which can be defined as a cluster of particles fused and

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combined, forming a radius in nanometer ranges or less than 100 nm.[20−22] At these nanoscale ranges, unique properties can be acquired that set them apart from traditional materials. Such unique properties are large area per volume ratio, high reactivity, dispersibility, and thermal and chemical stability.[23] The large area per volume ratio and small size (nanometer range) are compared to the bulk materials. Nanoparticles can be carbon nanoparticles, nanofibers, magnetic nanoparticles, nanofilms, or nanocomposites as determined by their physicochemical properties, as well as nanoscale size ranges.[24,25] In addition, nanoparticles can be solid particles or nanofluids with a stable suspension, as demonstrated by Fakoya and Shah,[34] in which the nature of the nanoparticles provides unique properties or specific features compared with those of micro- and macro-materials.

High reactivity of nanoparticles can be achieved due to the presence of functional groups at the particle's surface which more easily interact and react with other compounds, formation rocks, or reservoir fluids. Nanoparticles have recently demonstrated high potential for application in oil fields for improving drilling, completion, stimulation, workover, and EOR performance due to their reactivity and interactivity with the formation fluids and rocks.[10,20,26−30]

Furthermore, current findings of different researchers have shown that adding nanoparticles to operation fluids can reduce formation damage while enabling oil to flow toward the producing well.[31−36] Traditional materials[37−39] in EOR, drilling, stimulation, and completion operations are effective, but they face numerous challenges such as filtration loss, high cost of processing, limited ability to sweep oil from the rock formation, mobility ratio challenges, fine migrations, and deposition of asphaltene and they are easily affected by HP/HT formations.[40] Currently, nanotechnology research and development in the petroleum industry is been extremely active and has demonstrated promising results. Many authors have suggested nanomaterials as the best control for formation damage in the oil and gas industry.[17,41−43] In addition, nanomaterials can be applied effectively in drilling operations,[44−47] well completion,[48,49] cementing,[50,51] perforation,[52,53] enhanced oil recovery,[54−58] hydraulic fracturing,[59−61] and clay expansion[62−64] to control formation damage. However, the majority of research on nanotechnology in the oil and gas industry has focused more on laboratory studies than field studies,[65,66] as we explain in section 2. There is a paucity of literature on the use of nanotechnology in oilfields that demonstrates its utility and efficiency in controlling formation damage during oilfield development.

Franco et al.[67] recently demonstrated the application of nanotechnology in the oil and gas sector. They applied nanotechnology in EOR, water shutoff, dewatering, and improvement of production in heavy oil, and their results were based on the oil production rate. Ngata et al.,[5] on the other hand, studied the deployment of nanotechnology in the oil and gas industry to control formation damage. Their research showed that nanotechnology can be applied during drilling, completion, EOR, and stimulation. However, their study was mostly focused on laboratory experimental work with little fieldwork to demonstrate the efficiency of nanotechnology in controlling formation damage. Although we are aware that nanotechnology can increase oil production, there is a scarcity of research to illustrate how it might be utilized to prevent formation damage at the field scale.

Therefore, the main aim of this work is to provide a comprehensive review of nanoparticle applications in oil and gas fields to control formation damage based on extrapolating the laboratory results to field scale. To achieve this aim, we present this work in two parts. The first part (section 2) is on field applications undertaken in various producing fields worldwide to ascertain the true influence of nanoparticles on formation damage control during oil and gas field development. The second part (section 3) highlights areas for future research on nanoparticles in the oil and gas industry based on the findings of this study.

2. FIELD AND TRIAL APPLICATIONS OF NANOTECHNOLOGY FOR FORMATION DAMAGE CONTROL

Many investigations on nanotechnology have been conducted in laboratories.[17,47,63,68−76] Thus, it is necessary to assess the effectiveness of nanotechnology in oil and gas fields and its effect in preventing formation damage. This would help to serve as a point of convergence between the academic and industrial sectors by extending laboratory findings to a broader range of applications under field conditions. The following case studies show how nanoparticles have been employed to reduce formation damage and boost oil production in different parts of the world.

2.1. China Offshore Field, KL21-1-B1 Well. The well KL21-1-B1 is found at Bohai Bay in China. The field trial work for nanoparticles was done in June 2019 to improve productivity and lessen the risk of formation damage from poor water injection as in December 2015 200 m^3/d of water was injected into the formation to recover oil. After a comprehensive study, it was found that the KL21-1-B1 well had suffered from the following problems:[77]

1. The reservoir was associated with thin interlayers in the vicinity of the wellbore zone, and it contained poor reserve properties that are ineffective for water injection.
2. The formation contained clay minerals that caused formation damage by hydration expansion, which restricted fluid flow to the producing well.
3. Pollution from the completion fluid was caused by fluid leakage of 80 m^3.
4. Formation of scales from water injection inhibited normal fluid flow into the producing well.

To overcome the poor performance of water injection in the field, it was decided that the application of biological nano-polysilicon could be better than traditional materials (water). The experimental results from biological nano-polysilicon demonstrated increased stability of fluid, while permeability also increased by 30.4% of the initial value from the core sample obtained from the rock formation.[77] It was concluded that biological nano-polysilicon has potential for use in field tests, and the KL21-1-B1 well was selected for its test application. The stimulation technique was performed using biological nano-polysilicon injection to improve the performance of the well by overcoming the reservoir challenges encountered with the previous water flooding method. The results from this field test showed that after treatment of the well, injectivity was increased from 90 m^3/d to 150 m^3/d with decrease of injection pressure from 18.7 to 5.5 MPa. This means that biological nano-polysilicon as nanoparticles was effective and satisfactory in the KL21-1-B1 well to overcome formation damage, providing the desired results.[77]

However, in China, research involving nano-polysilicon materials has been extended to different oil fields such as

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Shengli, Daqing, Zhongyuan, Karamay, Xinjiang, Zhongyuan, and Jiangsu oilfields (Table 1). The application of nano-polysilicon materials showed remarkable success, especially for its retention properties[78] to improve the injection capacity, resulting in increased permeability and production. Nano-polysilicon has been used in EOR techniques in different countries such as Siberia and Udmurki fields and showed improvement in injectivity, as well as reduction in injection pressure.[79] Table 1, summarizes the fieldwork studies using nanoparticles in China's oil and gas fields. It highlights the action of nanomaterials in controlling formation damage that restricts the natural flow of oil to the producing well.

2.2. Colombian Oil Fields. Nanotechnology in Colombia has been used on a wide scale to reduce formation damage[87] and improve oil recovery[88] to enhance oil production and meet the country's energy requirements. Colombia possesses 2.3 billion barrels of proven oil reserves from which 13% of oil production has declined in the last year according to the report from the National Hydrocarbons Agency (NHA).[13] The application of nanotechnology in Colombia resulted in a significant increase in oil production and reduction of the risk of formation damage. The fieldwork was conducted in Cupiagua, TN, Castilla, and Chichimene fields,[14,89,90] and summary of field application of nanoparticles is provided in Table 2.

2.2.1. Cupiagua Sur Field. The Cupiagua Sur Field in Colombia is located northeast of Bogota and contains crude oil with a 38 API gravity and formation properties of 21 mD permeability, and 6.5% porosity.[78] The main challenges of formation damage in this field were asphaltene, fines, and mineral deposits around the wellbore regions, as well as fluid blockage from completion operations, resulting in a significant decrease in permeability.[91] To overcome the challenges of formation damage at the Cupiagua Sur field, wells CPSXL4 and CPSXL5 were recommended for the trial work applying the stimulation technique with nanoalumina as nanoparticles. The structure of nanoalumina coated with nanosilica can be observed in Figure 1. The surface is very reactive and interactive to inhibit further formation damage[21,92] such as clay swelling and deflocculation near the wellbore region.

2.2.1.1. The CPSXL4 Well. To control formation damage around the wellbore zone, 220 bbl of nanofluid with nano-alumina and a mixture of 411 bbl as displacing fluid were injected into the targeted penetration radius of 7.2 ft to the reservoir. Nanoalumina is very reactive and has a good tendency for the sorption of asphaltene. To determine the effect of nanoalumina, they examined another well, well CPSXL5.[94]

2.2.1.2. The CPSXL5 Well. This well together with CPSXL4 well underwent treatment with nanoalumina as nanoparticles. To prevent further formation damage, 180 bbl of nanofluid with nanoalumina and the mixture of displacing fluid (DAX) were injected into the targeted penetration radius of 9.2 ft to the reservoir. Nanoalumina is very reactive, has a good tendency for sorption of the asphaltene, and inhibits its further formation. The process of stimulation was divided into four stages: stage 1, base-case stage; stage 2, postpickling stage; stage 3, post-acid–organic, chemical stimulation stage; and stage 4, postinhibition stimulation stage. Some conclusions can be drawn from the data from these two wells (CPSXL4 and CPSXL5), which are presented in Figure 2.

Figure 2A shows that the API gravity in the CPSXL4 well increased from 40 to 41.5 after the stimulation process was completed. Figure 2B depicts the oil production rate in the CPSXL4 well, which was increased from 1704 to 2984 BOPD

Table 1. Application of Nanoparticles in EOR Techniques in China Oilfields to Control Formation Damage and Increase the Production Rate of Oil

oil field areas	nanomaterials	application and results	ref
Xinglongtai and Liaohe oilfield	MD film[a]	applied to EOR to prevent formation damage; production and recovery rate increased to 7092 t and 1.68%, respectively	Ke and Wei[80]
Changqing, Ansai, and Jiangsu oilfield	MD film and modified nanosilica	applied to EOR to increase reactivity and stabilize the process; daily production of oil was observed to increase from 0.78 to 1.31 t, while the efficiency in oil displacement was observed to increase from 10% to 27.9%	Oseh et al.,[81] Donghong,[82] Xiong et al.[83]
Shengli and Zhongyuan oilfield	surface-modified SiO_2 nanoparticle	nanoparticles increased the water injection to 100 m^3/d^4.	Ke and Wei,[80] Haiying et al.[84]
Wendong, Zhongyuan oilfield	surface-modified SiO_2 nanoparticle	surface-modified SiO_2 nanoparticles were effectively applied to the EOR methods and the oil recovery was increased by 49%	Ke and Wei[80]
Wangji and Henan oilfield	polymerized nanosilica SiO_2	injected to the damaged wells; as a result, the injection pressure increased from 6 to 8.9 MPa, while the oil production increased too	Yuan et al.[85] and Cai et al.[86]

[a]Molecular deposition film.

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Table 2. Summary of Field Application of Nanoparticles to Control Formation Damage in Colombia Oilfields[14,67,94,99]

oilfield areas	nanomaterials used	application and results	refs
Cupiagua oil field			
CPSXL4 well	220 bbl of nanoalumina (Al_2O_3)	applied to formation damage caused by asphaltene, fines, and mineral deposits around the wellbore regions; incremental oil production of 1200 bls and 376 bls in both wells; API performance increased from 40 to 41.5 and the skin reduction were achieved.	Martinez[91] and Zabala Romero et al.[94]
CPSXL5 well	180 bbl of nanoalumina (Al_2O_3)		
TN oil field and another field trial in Colombia	148 bbl of silica-based nanofluid	applied to the formation damage caused by fine migration, asphaltene deposits, and scale formation; formation damage was removed, and production rate increased to 48 and 60 BOPD for more than 18 months	Zabala et al.[95]
Castilla oil field			
CN154 well	200 bbl of oil-based nanofluid (Al_2O_3)	sediments and water that blocked the normal flow of the well declined by approximately 11% and oil production rate increased by 270 BOPD and 280 BOPD in CN154 and CN174	Zabala et al.[98]
CN174 well	150 bbl of oil-based nanofluid (Al_2O_3)		
Chichimene oil field			
CHSW26 well	86 bbl of oil-based nanofluid (Al_2O_3)	improved skin factor from magnitude of 23 to 6.2 for CHSW26 and 47 to 19 for CH39; oil production rate increased by 310 BOPD and 87 BOPD in CHSW26 and CH39 well	Zabala et al.[98]
CH39 well	107 bbl of oil-based nanofluid (Al_2O_3)		

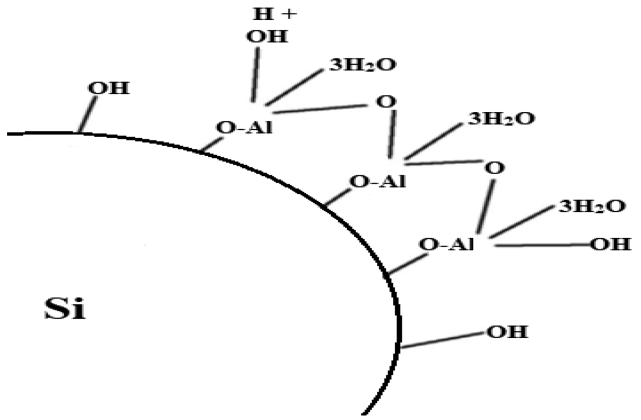

Figure 1. Nanoalumina (alumina surface coated with nanosilica, which is reactive to the clay minerals). Reproduced with permission from ref 93. Copyright 2019 Elsevier.

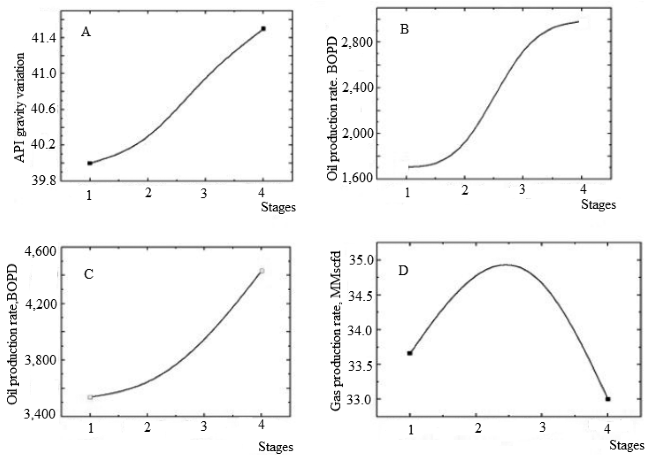

Figure 2. CPSXL4 (A, B) and CPSXL5 (C, D) well results. Reproduced with permission from ref 95. Copyright 2017 Elsevier.

following the stimulation operation. For the CPSXL5 well, oil production rate increased from 3538 BOPD to 4433 BOPD after the stimulation operation, as shown in Figure 2C. Figure 2D, on the other hand, shows that the CPSXL5 well gas production rate increased when nanoalumina was applied and then declined afterward from 33.66 MMscfd to the maximum of 35.0 MMscfd before declining to 33.0 MMscfd, indicating that nanoalumina successfully allowed gas flow during its application. In general, the use of nanoparticles to stimulate formations was successful in reducing formation damage and increasing oil production rates.

2.2.2. Castilla and Chichimene fields. These fields are located in Colombia[96] and contain heavy oil[97] in which oil-based nanofluid (OBN) was used to control formation damage by controlling wettability and oil viscosity.[98] The Castilla field suffered from severe formation damage such as asphaltene deposit (30%), mineral scales (14%), and damage from the drilling and completion process (56%). However, the Chichimene field suffered from formation damage like emulsion damage and skin effect of 29, 31.9, and 37 in magnitude. The following are the descriptions of each oilfield.

2.2.2.1. Castilla Field. In the Castilla field, two wells were used for the field trial works. These were the CN154 and CN174 wells. Oil-based nanofluid (Al_2O_3, 200 bbl and 150 bbl, respectively) was injected in the CN154 and CN174 wells. The nanofluid was injected into the targeted penetration radius

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of approximately 3 ft. The results showed that sediments and water that restricted the normal flow of the well declined by approximately 11% and the oil production rate increased by 270 BOPD and 280 BOPD in CN154 and CN174 respectively.[98]

2.2.2.2. Chichimene Field. In the Chichimene field, two wells were used for the field trials, CHSW26 and CH39 wells. Oil-based nanofluid (Al_2O_3), 86 bbl and 107 bbl, was injected in CHSW26 and CH39 wells, respectively. The nanofluid was injected into the targeted penetration radius of approximately 3 ft. The results showed that the oil production rate increased by 310 BOPD and 87 BOPD in CHSW26 and CH39 wells, respectively. The application of nanofluid at the Castilla field improved the skin factor from 23 magnitudes to 6.2, while the skin factor of the Chichimene field was observed to change from 47 magnitudes to 19 as described in Figure 3A,B respectively.[98]

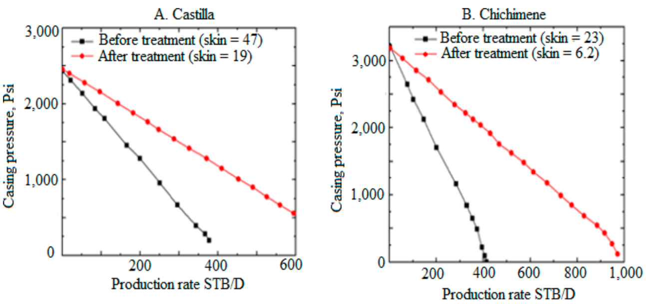

Figure 3. Before and after skin effect at Castilla and Chichimene fields. Reproduced with permission from ref 95. Copyright 2017 Elsevier.

2.2.3. TN Field and Three Other Wells. The TN field is found in Magdalena Valley, Colombia. Its crude oil contains an average of 36 API gravity. The formation damage associated with this field is organic and inorganic scale. Nanofluid was applied in chemical stimulation from June 2014 to October 2015. This stimulation included five wells. The result showed that nanofluid inhibited scale formation, removed any formation damage related to the organic scale, and increased the production rate to 60 BOPD for more than 18 months in all five wells. The trend of oil production, which is above the baseline, can be observed from Figure 4. The trials were extended to other wells for the purpose of cleaning the wells during drilling and piping, controlling organic and fines migration that could damage the well, and restricting the flow of formation fluid to the producing well. Silica nanofluid was applied, and 148 bbl was injected into the formation. The incremental oil production was observed to

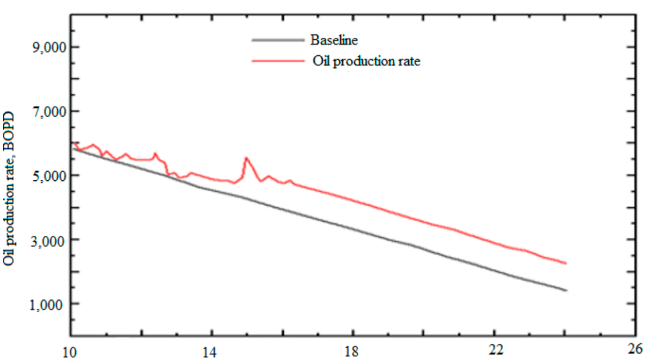

Figure 4. Effect of nanofluid stimulation at TN oilfield. Reproduced with permission from ref 95. Copyright 2017 Elsevier.

increase from 48 BOPD to 134 BOPD after the application of nanosilica fluid. This signifies that the nanosilica fluid managed to inhibit the formation damage to the well and can be applied to the other well suffering from the same problems to control the formation damage.

2.3. The Gulf of Mexico. In the Gulf of Mexico, a field study of nanoparticles was conducted in a deep water well with a reservoir temperature of 160 °F, a water depth of about 2500 ft, and pay zone ranges between 15769 and 15860 ft, and the well was stimulated with nanoparticle-coated proppant.[100] The problem in this well is fines migration, which plugged the porous media near the wellbore region, causing formation damage. The formation damage has caused production to decline from 7500 to 2200 BOPD and 6000 to 2000 MCF of gas. The fracking process to the damaged well consisted of 97000 lb 20/40 mesh proppants treated with nanoparticles. These treated proppants together with nanoparticles were injected at loading of 1 lb per 1000 lb of proppant to the damaged wells. The well resumed its normal flow at the end of the treatment process, and nanoparticles mitigated the formation damage by absorbing fines and preventing their accumulation and plugging of the near-wellbore region.[101]

The results, shown in Table 3, demonstrate that after six months of proppant treatment with nanoparticles, the well

Table 3. Nanoparticle-Coated Proppant Performance in the Gulf of Mexica Damaged Well[101]

	oil, BOPD	gas, MCF
at the beginning before treatment	2200	2000
3 months after treatment	3200	2700
6 months after treatment	2800	2700

recovered its normal productivity with 2800 BOPD and 2700 MCF of gas without fines migration or formation damage. This indicates that the nanoparticle-coated proppant was effective for control of formation damage caused by plugging of fines in the near-wellbore zone.[101]

2.4. Reconcavo Basin in Brazil, 1-UR-2-BA well. The 1-UR-2-BA well is found in the Reconcavo basin in Brazil.[102] The well is drilled in shale and unconsolidated formation. This formation is associated with wellbore instability and sticking of the drilling pipes due to mineral reactions.[103] A nanofluid was applied to the well 1-UR-2-BA to attain effective wellbore stability and formation damage control. During drilling, the nanofluid was applied to the interval of 515 to 1600 m, which seems to be very reactive.[101] The results showed that the nanofluid was applied successfully and prevented wellbore failure, provided good lubricity and easy transportation of cuttings, and prevented formation damage in a reactive shale zone from clay swelling potential, Figure 5. In addition, the nanofluid reduced the filtration loss, which could react with the formation fluid or formation rock and might cause formation damage. When nanofluid reacts with clay minerals or shale, it can adsorb them and prevent either swelling or deflocculating to the porous channel systems, which may be plugged restricting normal flow. Figure 6 describes the retention process when nanoparticles are applied to the porous system of the formation rocks.[79,104]

2.5. Chaves County, New Mexico. Formation damage associated with the deposition of paraffin around the wellbore region can cause substantial economic losses to the well.[105−107] In Chaves County, New Mexico, United States, a well was

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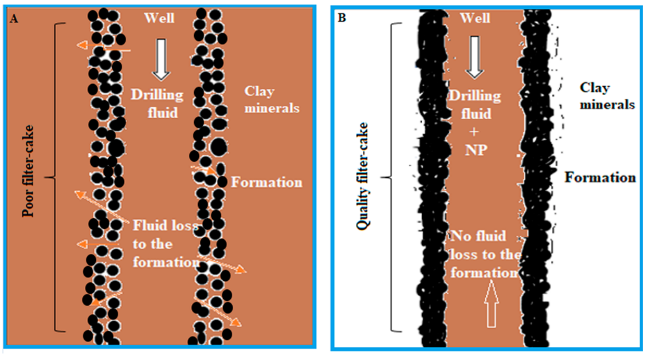

Figure 5. Effect of nanoparticles during drilling.

suffering from paraffin deposit, and it was decided to treat it with nanofluid. The treatment job was initiated with a total fluid of 2000 L, and 60% of the fluid contained 17% (v/v) nanofluid solution, while the other 40% of the fluid contained a paraffin solvent. The treatment was performed with an oiler, which is hot, and the well was shut in at least for 8 h for the reaction of nanofluid with the targeted zone.[108]

The results showed that when treatment was completed production resumed after a large volume of paraffin flowed out, meaning that the nanofluid was effective in removing the paraffin deposit and polymer filter cake, which restricted the normal flow of reservoir fluid and caused formation damage. The production rose from 6 to 12 BOPD. Thus, the treatment was successful with the use of the nanofluid solution.

2.6. Scurry County, Texas. In Scurry County, Texas, United States, a trial with nanofluid was conducted to treat a paraffin deposit around the wellbore region. Paraffin can plug and restrict the normal flow of oil to the producing well and cause formation damage.[109−111] Before treatment of the well with nanofluid, the damaged well was producing approximately 14 m^3/day together with a water cut of 50%. It was decided to treat the well by using nanofluid to inhibit the deposition of paraffin near the wellbore region. The treatment was initiated with total fluid of 2812 L. A volume of 563 L was used as the amount of nanofluid without paraffin solvent. The well was shut in at least for 8 h to wait for the reaction of nanofluid with the targeted zone to reduce the extent of damage.[108]

The results showed that the treatment was successful and the production resumed after large volumes of paraffin flowed back, meaning that the nanofluid removed the paraffin deposit and any associated polymer filter cake, which can result in the formation damage. In addition, the production was observed to rise from 14 m^3/day to 22 m^3/day (Table 4).

Table 4. Effect of Nanofluid in Treating Paraffin Deposits[108]

	oil production rate (m^3/day)
at the beginning before treatment	14
after treatment with 563 L nanofluid	22

2.7. Field X, Iran. Iran has been using nanomaterials for oil and gas research in recent years.[67,112−114] Nanotechnology was applied in one of the unknown Iranian oilfields in the country's south. The formation contains shale rocks, which are linked to different challenges such as fluid loss, lack of chemical stability, borehole collapse, well kicking, and sticking of the pipes. Well X with 6-1/4″ as a drilling hole was selected for the field test, and the targeted depth was set from 4820 to 5180 m. This is an unstable depth of the formation, which has an average thickness of 350 m. Previous drilling operations before the introduction of nanomaterials were not successful due to a variety of formation challenges caused by shale sensitivity, including wellbore instability, drilling pipe sticking, hole deviation, excessive torque, and drag, all of which increased drilling operation time and cost. To reduce these challenges caused by shale sensitivity,[115] nanomaterials were used during drilling. Table 5 shows the compositions of the drilling fluids that were employed.

Table 5. Water-Based Mud with Additives Including Nanofluids[116]

amount of additive	types of materials
0.3−0.5 wt %	soda ash (Na_2CO_3)
0.1 wt %	caustic soda (NaOH)
7 wt %	potassium chloride (KCl)
10 vol %	nanomaterial solution (fMWCNTs and fNPG)
5−7 wt %	sodium bentonite

Drilling with this nanomaterial-based drilling fluid improved the operation by offering strong rheological qualities, thermal stability, and control of shale mineral sensitivity near the wellbore. Nanomaterial-based drilling fluids reduced formation damage by minimizing fluid loss to the formation and generating high-quality mud cake,[44] which prevented the reactivity of filtrate with shale minerals and prevented severe formation damage and borehole instability. All of the aforementioned drilling problems were eliminated, and the operating performance of the nanomaterial-based drilling fluid, fMWCNTs and fNPG (Figure 7),[116] improved over the preceding traditional drilling fluid.

In addition, many nanomaterials are used around the world in fieldwork conditions to control formation damage. Table 6

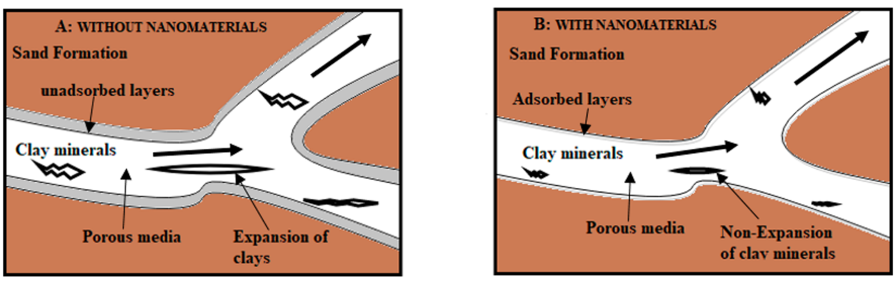

Figure 6. Action of nanoparticles to control clay expansion in the porous system: (A) narrow porous channel system due to formation damage; (B) wide porous channel systems mitigated by nanoparticles through the retention process. Reproduced with permission from ref 104. Copyright 2018 Elsevier.

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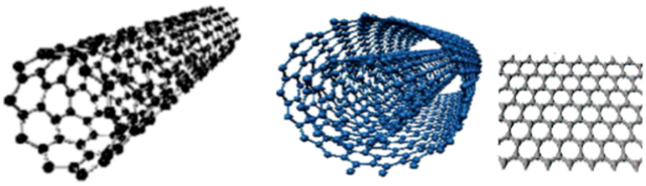

Figure 7. Functionalized multiwall carbon nanotubes (fMWCNTs)[117] and nanoporous graphene.[117] Reproduced with permission from ref 118. Copyright 2020 Elsevier.

shows some of the types of nanomaterials used and their results worldwide.

3. FUTURE RESEARCH IN NANOTECHNOLOGY APPLICATION FOR FORMATION DAMAGE CONTROL

Based on the findings of this review, the following issues should be addressed for future research:

1. The optimal nanoparticle or nanofluid composition should be determined according to the type and morphology of nanomaterials. Nanoparticles were utilized to improve the rheological and thermal properties of drilling mud during drilling, but there is no clear explanation of how nanoparticle size (nanoscale ranges) affect their efficiency. This study recommends more research should be conducted to determine the relationship between nanoparticles and morphology to make nanotechnology more beneficial.[5]
2. The majority of previous laboratory and field research has focused on the impact of nanoparticles such as silicon dioxide (SiO_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), copper oxide (CuO), graphene (G), iron oxide (Fe_2O_3), and carbon nanotubes (CNTs) on formation damage control by application of one type of nanoparticle. However, a formation can contain multiple formation damage types such as solid invasion, fines migration, etc.[125,126] Research should be conducted on the use of multiple types of nanomaterials to provide multipurpose mitigation of intricate formations with multiple types of formation damage.
3. Further research should be done to better understand the uniform dispersion tendency in cement slurry[36] and fracturing fluid given that nanoparticles have large surface areas.
4. The oil and gas industry must focus more on conducting appropriate nanotechnology research under field and trial conditions to control formation damage, as there are not sufficient case studies conducted in the field for more practical experience.[5]
5. If the procedures and steps are not followed correctly during the oil and gas development process, nanoparticles can agglomerate and block pore throats hence reducing the permeability and porosity, Figure 8. For example, nanoparticles must travel a long distance to the reservoir formation during EOR or stimulation without maximum retention, which can reduce normal permeability. To minimize permeability and porosity reduction, oil and gas operators should consult all evidence-based recommendations in applying nanoparticles.
6. Determining nanomaterial concentration, size, flow rate, and pore throat diameter is critical because it prevents nanoparticles from jamming (Figure 8) in the pore throat, reducing permeability or failing to disperse nanomaterials to the target area or fracturing fluid, resulting in high injection pressures.[127]
7. The study suggests that further research should be conducted into finding more cost-effective ways to produce nanoparticles, as oilfields need vast quantities of nanomaterials, which are expensive to obtain.

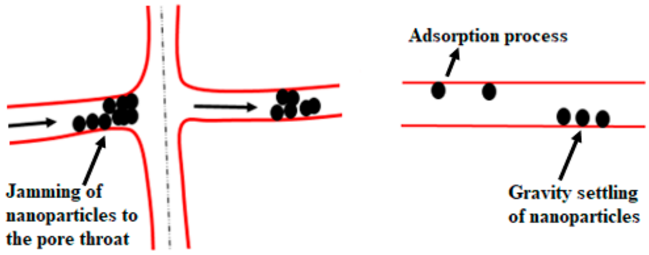

Figure 8. Description of retention process of nanomaterials in the porous media.

4. SUMMARY AND CONCLUSIONS

Nanotechnology has demonstrated remarkable success in controlling formation damage in all oilfields by reducing asphaltene, scales, fines migration, clay minerals, and other precipitates. The results from laboratory experiments suggest that nanotechnology can be applied in field conditions. However, understanding and experimenting with nanotechnol-

Table 6. Summary of Application of Nanomaterials to Control Formation Damage in Fields around the World[67]

field	types of nanofluids or nanoparticles	achievements	refs
Alberta, Canada, six field tests	calcium-based NPs (CNPs) at a concentration of 0.5 wt %	reduction of mud loss of 22−34%, which could result in formation damage	Borisov et al.[119]
Chaheji oilfield in China	nano-micron microspheres with polymer gel composition	pore throat plugging was prevented in the porous system; it was possible to control the expansion of clay minerals and oil to 4003 tons	Tiangyang et al.[120]
Khabaz Oil Field in Northern Iraq	1.2 g/L nanosilica (SiO_2) and 1.2 g/L iron dioxide (Fe_2O_3) nanoparticles	Fe_2O_3 nanoparticles reduce fluid loss by up to 37.9%, while SiO_2 nanoparticles reduce fluid loss by up to 48.3%	Shibeeb et al.[121]
Myanmar onshore site	boron-based nanomaterial (PQCB)	reduction of torque of 36.36% was achieved and 41% of the permeability was regained; 40% fluid loss was achieved	Krishnan et al.[122]
Algyo Field, Hungary	1 g/L liquid nanosilica	water cut reduction from 95−98% to 40%	Lakatos et al.[123]
Chevron's fields in Texas and Oklahoma areas, central United States	coating materials of nanolaminated alloy	prevented downhole corrosion and erosion as well as wear of downhole equipment; reduced cost of operations and improved safety and longevity of production	Paz et al.[124]

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ogy is critical for greater success in oilfields. The effectiveness of formation damage control, particularly in Colombia, prompted more nanotechnology applications in other wells, including the TN field. All wells that used nanotechnology showed a positive trend and increased success in preventing formation damage. The use of nanotechnology in drilling operations stabilizes boreholes by reducing filtration loss, which can react with formation fluid or rock, weakening the mechanical strength of the near-wellbore region and creating wellbore instability. This was demonstrated at the 1-UR-2-BA well in Brazil's Reconcavo Basin and an unknown field in Iran. Nanotechnology has been employed for EOR in Chinese oilfields to repair damage to wells caused by water injection such as scaling and clay mineral response that caused formation damage by hydration expansion, which restricted fluid flow to the producing wells, and environmental pollution caused by completion fluid. This research opens a promising future for the oil and gas industry in terms of improving or enhancing formation damage control using nanotechnology.

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NOMENCLATURE

API = American Petroleum Institute
EOR = enhanced oil recovery
HP/HT = high pressure/high temperature
bbl = barrel
IFT = interfacial tension
DVR = degree of viscosity reduction
DAX = diesel–alcohol–xylene
BOPD = barrels of oil production per day (removing organic deposits)
STB/D = standard barrel per day
MCF = thousand cubic feet
MMscfd = million standard cubic feet per day
fMWCNT = functionalized multiwall carbon nanotube

BPD = barrels per day
fNPG = functionalized nanoporous graphene
CNT = carbon nanotube

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