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APPLICATIONS, NANOTOXICITY, ENVIRONMENTAL ASPECTS AND FUTURE CHALLENGES OF NANOTECHNOLOGY IN THE OIL AND GAS INDUSTRY: A REVIEW

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ABSTRACT
In the present review, applications of nanotechnology are employed to amplify the tendencies of growing traditional and cut-off resources of gas and to improve the process of drilling and production of oil and gas by designing it more accessible to separate oil and gas inside the reservoir. The impact of nanotechnology in many areas is more effective, cheaper, and more environment-friendly than what is presently accessible. A summary of various types of nanomaterials used together with a deep investigation of their compliance in advancing the objective factors is widely described. This paper reviews nanotechnology applications in the various parts of the oil patch such as exploration, production, EOR, wettability alteration, refinery processes, and drilling operations including drilling tools, drilling fluids, and cement. The impacts of numerous nanoparticles in drilling fluids and enhanced oil recovery has been explored. This paper gives a notified analysis of the improvements of nanotechnology in exploration as well as production. Moreover, the toxic effects of various nanoparticles and their environmental aspects have been observed and studied. The oil and gas industry can be made greener by nanotechnology. Finally, an outlook on the recent challenges and a few predictions for future applications is also underlined.
Keywords: Nanotechnology, Oil & Gas industry, Nanofluids, Wettability, EOR, Drilling.
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INTRODUCTION

Nanotechnology is an extensive area of research for investigating and advancing the properties of materials at the nanoscale. Nanotechnology has been fruitfully applied in various parts of life, causing better and more effective product manufacture and application. In several areas of society, the effects of nanotechnology have been felt recognizably due to better efficiency and superior products obtained at low cost. Currently, nanotechnology is utilized in many industries, for example, smart materials, surface treatment, medicine, chemical, construction, environment, and food processing.[1-5] Researchers[6,7] stated that though nanotechnology is not much more utilized in the petroleum industry in recent years, nanotechnology has made magnificent progress in its application in oil and gas fields.[8-12] It is suggested by the world energy reports that the crude oil demand is growing worldwide.[13-17] It is hard to discover fresh oil reservoirs as about 30% to 60% of oil leftovers are entrapped within reservoirs. Accordingly, investigators along with oil corporations are trying to separate residual oil in the developed reservoirs by means of new and effective nanotechnology.[18] Although nanotechnologies are more expensive, they can efficiently amplify the production of oil and reduce the total cost of drilling. Due to the use of nanotechnology, the profit of the oil industry is massive. Since nanoparticles can be more efficient in little amounts, therefore, the initial cost of nanoparticles will be higher, but the total cost will be lower. In recent times, silica nanoparticles have been utilized to provide stability in the production of foam of liquid carbon dioxide for the process of carbon dioxide EOR and simplify the development of oil production.[19] Also, iron oxide nano-catalyst is used for in-situ aqua thermolysis procedures to advance the superiority and increase the efficiency of heavy and extra heavy oil.[20] For this purpose, numerous kinds of nano-catalysts were also applied.[21,22] On account of these excessive high-tech and industrial strengths, significant works and inventions were employed to project and characterize nanomaterials, mainly for the oil and gas industries. So, progress along with the

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role of nanotechnology in oil and gas production will be emphasized and interpreted within the present paper. First, the types and functionalization approaches of nanomaterials are discussed concisely. Moreover, the current advancement of nanotechnology as well as its applications in various zones of oil and gas sectors will be summed up. In the end, environmental aspects, nanotoxicity, and upcoming challenges will also be discussed.

Types of Nanomaterials

Nanoparticles

In reality, nanoparticles are not, as simple as we recognize, rather they are made of three layers: the core (principal part of the nanoparticle), the shell layer (chemically, all features are of a different material unlike the core), and the surface layer.[23] Scientists have developed many methods to produce a variety of nanoparticles of various shapes, dimensions, and physical and /or chemical properties. Numerous approaches were applied in the previous years for the synthesis of nanoparticles such as nanoprecipitation[24], solvent evaporation[25], salting out[26], electro hydrodynamic atomization[27], emulsion, and mini-emulsion polymerization[28], and the generation of nanoparticles using the nano-emulsion template[29] and using supercritical fluid technology.[30] The first method applied for synthesizing nanoparticles is solvent evaporation[31] (Fig.-1) and it is mostly used for the synthesis of nanoparticles.[25,31]

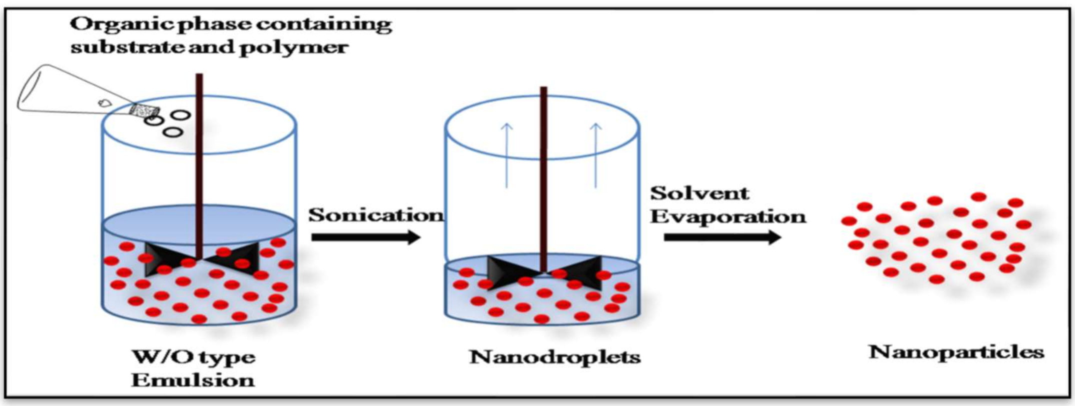

Fig.-1: Preparation of Nanoparticles by Solvent Evaporation Method

Nanocomposites

A Nanocomposite is made of a bulk matrix with one phase of nano size. Because of differences in structure and chemistry, the properties of a nanocomposite differ significantly from those of the component composite materials as well as depend upon dimension, diffusion, accumulation together with constituents of materials.[32-34] Depending on their matrix material, nanocomposites are classified as metal matrix nanocomposite[35], polymer matrix nanocomposite[36,37], and ceramic matrix nanocomposite.[38] Nanocomposites can be used in various ways such as displacing agents to enhance the production of oil in EOR, for example, nanocomposites with polymer-coated and sodium carboxymethylcellulose.[39] Recently, Ali[40] synthesized ZnO/SiO_2/Xanthan nanocomposite (Fig.-2) to reduce the IFT significantly and upgrade the recovery of oil. Due to the extensive applications of nanocomposites, they are known as the 21st-century's materials.

Nano-catalysis

As the particle size of porous materials reduces to nano-dimensions, its applicability as a catalyst is greatly enhanced. The catalytic action of nano-porous materials in diffusion-limited reactions is of better quality. The use of colloidal chemistry methodology for handling the suspensions of nanocrystals causes the formation of microporous two-dimensional and three-dimensional materials for catalysis.[41] Nano-catalysis involves the synthesis of supramolecular materials as well as their characterization at the nanometer level along with their well-disciplined applications[42]. Heterogeneous catalysis progressed by selectivity principles depending completely on nano-catalysis, and methodological catalysis has functioned for ages[42] with the help of minor particles. Nano-porous materials are essential for the petroleum industry.

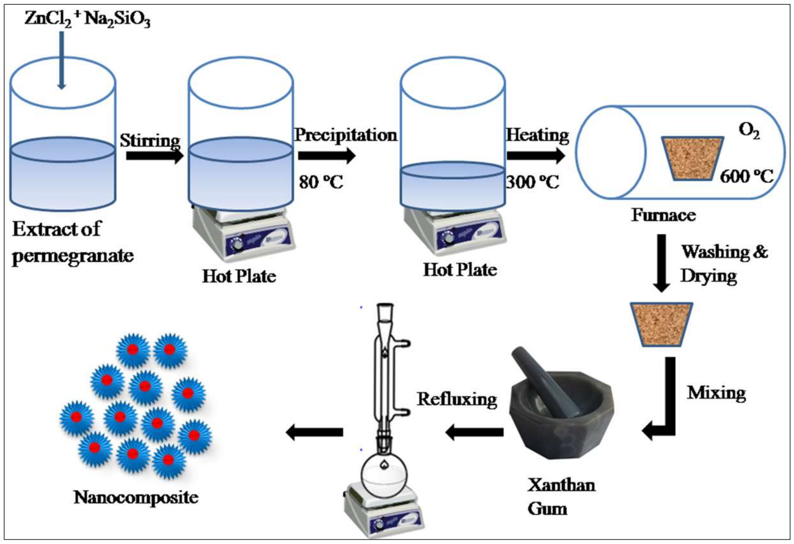

Fig.-2: Synthetic Diagram for ZnO/SiO_2/Xanthan Nanocomposite

Coated Nanoparticles

Nano-coating can provide the requirements in addition to getting improvement of instruments applied in the petroleum industry. The novel type of nanocomposites is composed of two key phases: nanocrystalline and amorphous. Nano-ceramic coating of the surface of the drill bit can critically increase toughness as well as the existence of the bit. Moreover, two- or four-times roughness of the nanocoated bits are at all times increased in comparison to non-nanocoated bits. To achieve this goal, Sengupta and Kumar[43] suggested that the drill bit is generally sprayed with a high-speed plasma of Al_2O_3 and TiO_2 of 20–100 nm. Furthermore, nano-coating is also applied to prevent corrosion in communication pipes. Hence, corrosion may be controlled inside the pipes used in the oil and gas industry.[44]

Nanofluids

Nanofluid is an important component of nanotechnology[45] and it is commonly considered a specific type of colloids[46] and fluid.[47] Two-step techniques are generally used to prepare nanofluids (Fig.-3). In this technique, powdered form nanomaterials are blended with the dispersion fluid with the help of attractive force and ball edge. In recent years, nanofluids are recently used for several different applications in the oil patch, such as completion[48], production[49], and enhanced oil recovery.[50,51] It is noticed that the addition of a little number of nanoparticles in the nanofluids produces comparatively amazing improvement in their properties.[46] As the number of nanoparticles in the nanofluid decreases, the stability of nanofluid is much increased.[52] In the formation of nanofluid, the stability of nanoparticle suspension is an important factor.[51]

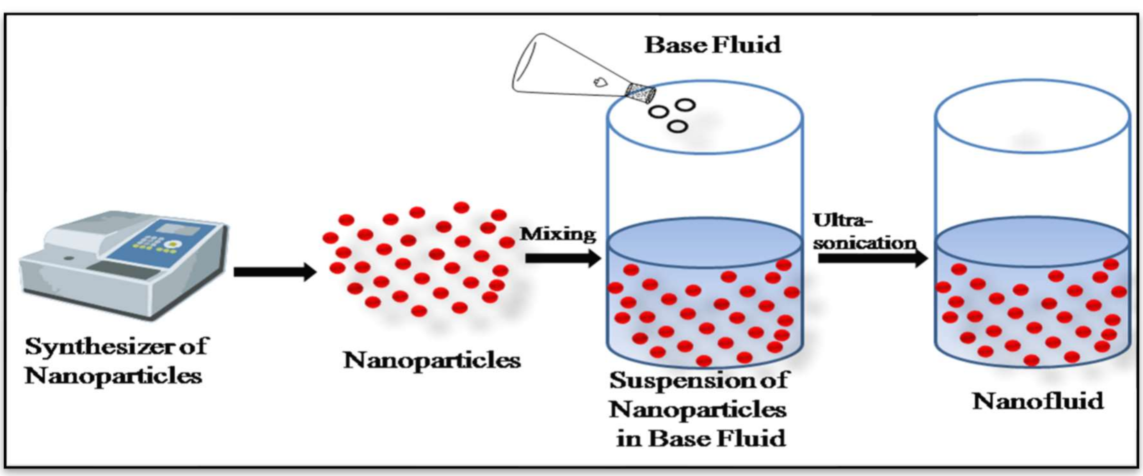

Fig.-3: Two-Step Method for the Preparation of Nanofluid

Applications of nanotechnology in the Oil and Gas Industry

Exploration

In progressing the oil and gas fields, the first action is exploration. Hydrocarbon exploration is extremely hazardous and believed as one of the most important and costly actions.[53,54] Nano dust, a specific type of nanosensor is used in the pore spaces for various purposes capable of providing information during exploration monitoring fluid and recognizing fluid type.[55] Liu H[56] suggested that analysis of the composition of minerals and structure of micropores, determination of organic constituents, and specification in situ categorization of reservoirs can be studied by applying nanotechnology. Nanoelectromechanical system (NEMS) is a device which has been developed to integrate mechanical and electrical functions at the nanoscale which permits it to shift into the micropore of reservoirs. Nano sensing devices made up of advanced nanoparticles are inserted in reservoirs for the characterization of reservoir parameters.[57] Fluorescence nanoparticles have been synthesized for tracing intelligent fluid.[58]

Production

Traditional oil resources are limited in such a way that most of oil corporations are in progress to achieve and generate alternative oil reserves, for example, heavy and extra heavy oil in addition to bitumen hydrocarbons.[53] Alternative oil recovery is regarded as the greatest important task due to the existence of sulfur, oxygen, nitrogen, and metals.[53,59] Researchers suggested that significant heating of reservoirs is needed to recover unconventional reserves.[60] Furthermore, Kong and Ohadi[61] stated that nano-catalysts might also offer an explanation in support of advancing possessions of heavy oil and bitumen. On the other hand, Li[62] studied the role of nano-nickel catalysts and found that they have the ability to reduce the viscosity of heavy oil. An excellent application of nanotechnology is the production of petroleum from shale and tight reservoirs.[53,59] Li[62] defined hydraulic fracturing to improve the production in reservoirs with small porousness. For this purpose, a fracturing fluid is injected to create cracks in the rock formation.[63] The recovery of hydrate in the production phase can be improved by using nanotechnology when the water cage decomposes to liberate the hydrocarbon. This goal is completed using nickel-iron nanoparticles by injecting them into the formation of hydrate.[64]

Enhanced Oil Recovery (EOR)

Enhanced oil recovery[65-67] is one of the most developed and advanced techniques to enhance oil recovery rates and production efficiency. In the process of EOR, hydrocarbons are recovered by injecting the reservoir with substances which are either do not fit generally in the reservoir or do not naturally exist in it.[68,69] Due to greater energy requirements, the global oil reserves are to be consumed professionally and proficiently and recover[65,66,70-72] additional oil. It is observed that approximately 15% to 50% of oil volume in the reservoir can be recovered[65,66] as well as 50 % to 85% of original oil volume remains in the reservoir after primary and secondary recovery methods.[66,71,73] Nanofluids are an innovative technology that is now applied in EOR[74-76] and are able to assist drilling through providing superior wettability alteration and developed drag reduction.[77,78] Oil recovery is improved by altering wettability from oil wet to water wet.[51,79,80] Adsorption of nanoparticles at the fluid -fluid interface causes the decrease of nanofluid oil interfacial tension (IFT) with the increasing concentration of nanoparticles.[81,82] There is a strong effect of nanoparticles on the IFT. The oil recovery can be made better by using nanoparticles of silicon oxide.[83,84]

Wettability alteration

Wettability is an important factor that commands the location and delivery of fluids into the formation.[85] There are various factors, like reservoirs' nature, the concentration of nanoparticles, nature of nanoparticles, and hydrophobicity which affect the wettability alteration. The wettability of a rock can be changed from oil-wet to water-wet by nanoparticles and moreover, the wettability of a water-wet rock can also be strengthened by them.[86] Moradi investigated that the wettability of carbonate rock can be changed by adsorbing nanoparticles of silicon oxide on the surface.[87] Multi-walled carbon nanotube silicon oxide nanofluids have also been studied for wettability alteration of different samples of rock. The change of wettability of reservoir rock from oil-wet to water-wet in the petroleum industry is expressed in terms of wettability alteration.[88] It is deeply studied that the oil recovery rate is greater in water-wet reservoirs and lower in the case of oil-wet.[88] Benjumea[89] designed nanofluids of different concentrations ranging and studied wettability alteration via the contact angle and imbibition tests. The wettability of sandstone cores was observed to be changed from an oil-wet state to water-wet due to nanofluids. The process of improving the imbibition and restoring the original core wettability can be found with the help of nanoparticles. Researchers also found that the effectiveness of anionic surfactants can be amplified by nanoparticles, as a wettability modifier, in strengths equal to or less than 500 ppm.[89]

Refinery and Processing

Nanoparticles are important catalysts for petroleum processing and energy conversion as well as they are widely used in refining and processing because they can remove toxic gases. Gas steam separation and removal of impurities from the oil have been done by nanomembranes.[90] Nano-catalysts can be used to upgrade the heavy oils and bitumen so that we can avoid the requirement of transportation and control of these things.[91] Refining and processing decrease the environmental influence of oil-and gas-derived fuels by eliminating injurious pollutants and improving their reliability during combustion. Application of zeolite catalyst in converting the heavy crude oils and its important contributions are constantly felt previously. Zeolite catalyst[92] is presently used to produce more than seven million barrels of oil and gas products per annum and zeolite nanocrystals have high surface activity.[93] With nano-zeolite, the conversion of hydrocarbons can be greatly improved. Vuong[93] studied the catalytic action of many zeolite Y nanocrystals and observed that FCC catalysts of minor nanosized zeolite showed greater relative to greater size. The activation of zeolite catalysts follows a process such as: FCC-100 <FCC-40 <FCC-25.

Drilling and Completion

Drilling operation[53] is the most important and serious activity in finding hydrocarbons in rocks. Extraction of petroleum requires cultivating and drilling with the help of a drill attached to a drill thread, on the rock drum at the base.[94] Specified in detail, all rotary rotation work involves three basic systems which operate simultaneously during drilling.[95] Efficient improvements in mining performance play an important role in increasing hydrocarbon production.[53] Khalil[95] studied the various definitions of drilling fluids and found that they are defined as a combination of liquids and additives which remove cuts from the source well. During the excavation and completion, many difficulties can arise and cause negative commercial and ecological influences. These difficulties can be solved by nanotechnology. In numerous areas of the oil and gas industry, nanotechnology can be applied to avoid instability as a wellbore, pipe sticking, oil recovery efficiency, and last circulation.[95]

Drilling Tools

Traditional drill bits and pipes are damaged due to rubbing and causing a heavy decrease in drilling operation and these challenges can be solved by advancing the wear resistance of the tools.[96] For this problem, the solution is the nanocoating of drilling bits for producing outstanding drilling bits with the aim of advancing the abrasion and non-corrosive nature of the drilling tools.[97,98] Additionally, corrosion is one of the greatest dangerous problems for the destruction and decline of metallic structures e.g. drilling tools. Furthermore, prevention of corrosion in the oil and gas industry is of much more attention and emphasis.[99,100]

Drilling Fluids

To solve the numerous problems arising during drilling operations, many different drilling fluids are invented. Water, oil, and gas[95] are the main types of drilling fluids. The large surface area of nanoparticles makes them chemically more active to increase the superiority of drilling base fluid. Therefore, the properties such as thermal and electrical can be made of better quality. The addition of nanoparticles to drilling fluids stimulates the quality of the fluids.[95] There are many roles of drilling fluids in petroleum products such as stabilizing, lubricating, and cooling the drilling bit.[95,101,102] Multiple drilling challenges can be reduced by using nanoparticles in drilling fluids. Water as the base- nanofluids is capable to reduce the destruction, prevent loss of circulation and rise penetration rate[103] relative to the traditional drilling sludges. Nanofluids are also formed using additives of metal oxides in drilling sludge. Also, Sadeghalvaad and Sabbaghi[104] synthesized a nanocomposite of acrylamide and TiO_2 nanoparticles. Sharma[105] studied kinds of drilling fluids of nano silica that are planned to connect the microcracks and handle water invasion.

Cementing

Cementing is one of the most important processes during drilling and completion operations. It is very challenging[106] to achieve long-term zonal isolation. A well, without complete zonal isolation, will never reach its full production potential. Primary cementing[107] is defined in terms of merging the slurry of cement with water and pushing that one within the annulus. Moreover, its key purpose is to provide entire regional isolation so that fluid migration can be avoided. The property of cementing work is exactly related to the commercial durability of an oil and gas generating well.[108] For cementing of oil well, nanomaterials are used to speed up cement hydration[109], enhance mechanical assets of cement sheath[110], stop gas movement and lower the chance of collapse.[111] The different factors, for example, well condition, mechanical assets of the cement sheath and wellbore geometry[112] determine the capability of a cement system to support regional separation for an extensive period. For durable zonal isolation, it is the basic requirement that flexible cement system should have a great tensile strength and low shrinkage. Attention has been devoted by the researchers in the last few years for the nanoscale fibers.[113-116] Carbon nanofibers and nanotubes contain very large strength with the Young moduli in the range of various terapascals and tensile strength of gigapascal range.[117]

Nanotoxicity

A tiny size and high surface area of nanoparticles might make them toxic substances in the petroleum segment, if exposed at the time of their production and application.[118] Due to their tiny size, nanoparticles can simply enter the cell wall and be stored in a cell.[119] In the oil and gas industry, the nanomaterials, which are most investigated, are nano-silica and nano-metallic oxides which have many influences on human beings and the atmosphere.[120] Oxidation of cells by aluminium oxide can avert respiration and therefore, bring about the demise of the creatures revealed.[121] According to Valdiglesias[122] ZnO can yield reactive oxygen which defaces the cell membrane, directing to DNA and cell variation. In addition, titanium oxide can bring about few contacts with the cells which yield depolarization and cytokine secretion.[123,124] Long-term exposure to nano-silica can bring about the demise of the organisms and due to these drawbacks, nanoparticles are limited in applications in the petroleum industry.[125,126]

Environmental Aspects

Environmental pollution, due to the oil and gas industry, is today receiving worldwide attention. During drilling operations, a very toxic and corrosive H_2S gas can pass through permeable formations. It is, therefore, more essential to eliminate H_2S gas from the mud to decrease pollution of the environment, avoid the corrosion of drilling tools and pipelines, and protect workers' health. Sayyadnejad found that H_2S gas can be eliminated entirely from water-base drilling fluid by the nanoparticles of ZnO having 14-25nm sizes and 44 -56 m^2/g specific surface area. This removal by bulk ZnO was observed in time spending and only 2.5% of H_2S could be eliminated.[127] Silica-titania nanocomposites can be used for the elimination of elemental mercury from combustion resources. The elemental mercury oxidizes to less volatile mercury oxide, photo-catalytically by titanium, while silica increases the adsorption.[128] Nanotechnology signifies a new type of technology for the remedy of the environment which can principally assure to criticize the difficult environmental complications. Nano-iron particles can be efficiently used to transport and purify numerous environmental pollutants like PCBs.[129] Nano- particles and nano-filters can be used to remove heavy metals such as mercury from soil and water. The zero-valent nano-iron particles are used for the remedy of polluted soil and groundwater which affords an additional chance for remediation of the environment.[130,131] Nanomembranes are produced for the remediation of wastewater and seawater desalinization.[132-136] Current progress in nanowires of potassium manganese oxide can purify the oil and remove organic contaminants. The nanowires can soak up and at higher temperatures, the oil can be boiled off the nanowires, giving chance for their reprocess.

Future Challenges

In spite of fast progress in numerous functionalization approaches of nanomaterials, applications of nanotechnology even now suffer from many challenges in the oil and gas industry. Success for low-cost and facile synthetic methods is the main challenge in the progress of nanotechnology for the petroleum industry.[137] Although, many investigations have been done on the progress of synthetic methods of nanomaterials yet exact control of shape, size, and multiformity of nanoparticles is now challenging. Additionally, the present synthetic approaches mostly depend on the cost of ineffective apparatus and environment unfriendly raw materials. Among the present technologies, the cost efficiency in the application of several kinds of nanomaterials is comparatively very small, particularly in upstream. Regrettably, a large dosage of nanomaterials in the oilfield test may appreciably enhance the cost of the process and therefore, wide application of nanomaterials will come to be unfavourable in the oilfield industry.[138] Another challenge faced by the oil and gas sector in the reservoirs, is the transport capability of nanoparticles. This capability has been advanced by modifying the surface of nanoparticles, but the best condition can be attained by various methods that need additional exploration.[139] Advancement in the use of nanotechnology for oil and gas industry cannot be realized until the investigation on the important viewpoints is valued. Hence, upcoming study should not concentrate merely to advance the production of hydrocarbon but should concentrate on the essential parts of its chemistry and engineering. Thus, it averts the leakage of oil into environment and protects the environment by this method.[137,140] Polyvinyl alcohol-cellulose nanofiber, Al_2O_3-poly vinylidene difluoride nanocomposites and chitosan-silica nanocomposites are effectively used for contaminated water management.[138] Nanomaterials have an impression on the environment and the study of their possessions for the future is important. Thus, bottomless investigations of the physical and chemical characteristics of these particles will be greatly significant for an effective identification of their functioning.[138]

CONCLUSION

A comprehensive review of the applications, nanotoxicity, environmental aspects, and future challenges of nanotechnology in the oil and gas industry has been submitted in the manuscript. In the latest years, nanotechnology has produced numerous applications in various parts of the petroleum industry. Numerous nanomaterials such as nanoparticles, nano-catalysis, nanocomposites, coated- nanoparticles, and nanofluids are useful in exploration, drilling, production, enhanced oil recovery, refining, and wettability alteration. It has been studied that the challenges of nanotechnology, now require much general research. As a result of the existence of countless challenges in the current topic, this manuscript offers a study on nanotechnology and its application in various segments of the oil and gas industry.

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REFERENCES

1. A. Saravanan, S. Jeevanantham, R. Jayasree, R.V. Hemavathy, P.S. Kumar and P.R. Yaashikaa, *Nanomaterials,* 701(2021), http://dx.doi.org/10.1016/B978-0-12-822401-4.00011-8
2. J. Sheeja, K. Sampath and R.Manivel, *Rasayan Journal of Chemistry*, **12(1),** 262(2019), http://dx.doi.org/10.31788/RJC.2019.1215002
3. Divya, A. Prithiba and R. Rajalakshmi, *Rasayan Journal of Chemistry,* **12(1)**, 214(2019), http://dx.doi.org/10.31788/RJC.2019.1215039
4. A. D. Dhimdhime, R. S. Talegaonkar, A.K. Wanjari, A. R. Somwanshi and R. D. Ghodile, *Rasayan Journal of Chemistry,* **15(1)**, 504(2022), http://dx.doi.org/10.31788/RJC.2022.1516818
5. L.Y.Y. Lu, B.J.Y. Lin, J.S. Liu and C.Y. Yu, *Journal Business Ethics,* **109(4)**, 583(2012), https://doi.org/10.1007/s10551-012-1432-1
6. B. Peng, J. Tang, J. Luo, P. Wang, B. Ding and K.C. Tam, *Canadian Journal of Chemical Engineering,* **96(1)**, 91(2017)
7. G.S. Negi, S. Anirbid and P. Sivakumar, *Petroleum Research,* **6(3)**, 224(2021), https://doi.org/10.1016/j.ptlrs.2021.03.001
8. J. Shingala, V. Shah, K. Dudhat and M. Shah, *Journal of Petroleum Exploration and Production Technology*,**10**, 3993(2020), http://dx.doi.org/10.1007/s13202-020-00914-4
9. J.A. Ali, K. Kolo, A.K. Manshad, K.D. Stephen and A. Keshavarz, *Applied Nanoscience,* **9**, 397(2018), https://doi.org/10.1007/s13204-018-0923-5

10. Y.M. Hassan, B.H. Guan, H.M. Zaid, M.F. Hamza, M. Adil, A.A. Adam and K. Hastuti, *Crystals,* **11**, 106(2021), https://doi.org/10.3390/cryst11020106
11. A.D. Macheca and B. Uwiragiye, *Chemical Engineering Transactions,* **81**, 1081(2020), http://dx.doi.org/10.3303/CET2081181
12. P.J. Boul and P.M. Ajayan, *Energy Technology,* **8(1)**,1901216(2020), https://doi.org/10.1002/ente.201901216
13. A.D. Macheca and B. Uwiragiye, *Chemical Engineering Transactions,* **81**, 1075(2020), http://dx.doi.org/10.3303/CET2081180
14. D. Landa-Marban, F.A. Radu and J.M. Nordbotten, *Transport Porous Media,* **120(2)**, 395(2017), http://dx.doi.org/10.1007/s11242-017-0929-6
15. M. Talukdar, S.K. Behera, K. Bhattacharya and P. Deb, *Applied Surface Science,* **473**, 275(2018), https://doi.org/10.1016/j.carbon.2022.02.060
16. J.A. Ali, K. Kolo, A.K. Manshad and K.D. Stephen, *Energy Fuels,* **33(2)**, 927(2019), https://doi.org/10.1021/acs.energyfuels.8b03847
17. J.A. Ali, K. Kolo, A.K. Manshad and K.D. Stephen, *Journal of Molecular Liquids,* **284**, 735(2019).
18. J.A. Ali, K. Kolo, S.M. Sajadi, A. Khaksar Manshad and K.D. Stephen, *Micro & Nano Letter,* **14(6)**, 638(2019), https://doi.org/10.1049/mnl.2018.5617
19. A.U. Rognmo, S. Heldal and M.A. Ferno, *Fuel,* **216**, 621(2018), https://doi.org/10.1016/j.fuel.2017.11.144
20. M. Khalil, R.L. Lee and N. Liu, *Fuel,* **145**, 214(2015), https://doi.org/10.1016/j.fuel.2014.12.047
21. L. Wei, Z. Jian-Hua and Q. Jian-Hua, *Journal of Fuel Chemistry and Technology,* **35**, 176*(*2007), https://doi.org/10.1016/S1872-5813(07)60016-4
22. Y. Chen, Y. Wang, J. Lu and C. Wu, *Fuel,* **88(8)**, 1426(2009), https://doi.org/10.1016/j.fuel.2009.03.011
23. I. Khan, K. Saeed and I. Khan, *Arabian Journal of Chemistry,* **12**, 908(2017).
24. A.K. Yadav, A. Agarwal, G. Rai, P. Mishra, S. Jain, A.K. Mishra, H. Agrawal, G.P. Agrawal, *Drug Delivery,* **17(8)**, 561(2010), https://doi.org/10.3109/10717544.2010.500635
25. S. Desgouilles, C. Vauthier, D. Bazile, J. Vacus, J.L. Grossiord, M. Veillard and P. Couvreur, *Langmuir,* **19(22)**, 9504(2003), https://doi.org/10.1021/la034999q
26. S. Galindo-Rodriguez, E. Allemann, H. Fessi and E. Doelker, *Pharmaceutical. Research,* **21(8)**, 1428(2004), https://doi.org/10.1023/B:PHAM.0000036917.75634.be
27. J. Gomez-Estaca, M.P. Balaguer, R. Gavara and P. Hernandez-Munoz, *Food Hydrocolloids,* **28(1)**, 82(2012), https://doi.org/10.1016/j.foodhyd.2011.11.013
28. K. Landfester, *Angewandte Chemie International Edition,* **48(25)**, 4488(2009), https://doi.org/10.1002/anie.200900723
29. N. Anton, J.P. Benoit and P. Saulnier, *Journal of Controlled Release,* **128(3)**, 185(2008), https://doi.org/10.1016/j.jconrel.2008.02.007
30. K. Byrappa, S. Ohara and T. Adschiri, *Advanced Drug Delivery Reviews,* **60(3)**, 299(2008), https://doi.org/10.1016/j.addr.2007.09.001
31. H. Murakami, M. Kobayashi, H. Takeuchi and Y. Kawashima, *International Journal of Pharmaceutics,* **187**, 143(2008).
32. S. Kango, S. Kalia, A. Celli, J. Njuguna, Y. Habibi and R. Kumar, *Polymer Sciencence,* **38(8)**, 1232(2013), https://doi.org/10.1016/j.progpolymsci.2013.02.003
33. M.S. Sajadi, K. Kolo, M. Pirouei, S.A. Mahmud, J.A. Ali and S. Hamad, *RSC Advances,* **8(62)**, 35557(2018), https://doi.org/10.1039/c8ra06028b
34. J.A. Ali, K. Kolo, S.M. Sajadi, A. Khaksar Manshad and K.D. Stephen, *Micro & Nano Letter,* **14(6)**, 638(2019), https://doi.org/10.1049/mnl.2018.5617
35. S.C. Tjong and G.S. Wang, *Materials Science Engineering A,* **386(1–2)**, 48(2004), https://doi.org/10.1016/j.msea.2004.07.021
36. G. Jimenez, N. Ogata, H. Kawai and T. Ogihara, *Journal of Applied Polymer Science,* **64(11)**, 2211(1997), https://doi.org/10.1002/(SICI)1097-4628(19970613)64:11<2211::AID-APP17>3.0.CO;2-6

37. P.H.C. Camargo, K.G. Satyanarayana and F. Wypych, *Materials Research,* **12(1)**, 1(2009), https://doi.org/10.1590/S1516-14392009000100002
38. V.V. Pokropivnyi, *Powder Metallurgy and Metal Ceramics,* **41(5)**, 264(2002).
39. F. Carlesso, G. Zin, S.M.D. Souza, M.D. Luccio, A.A.D. Souza and J.V. Oliveira, *Environmental Technology,* **37(8)**, 952(2016), https://doi.org/10.1080/09593330.2015.1094517
40. J.A. Ali, K. Kolo, A.K. Manshad and A.H. Mohammadi, *Egyptian Journal of Petroleum,* **27(4)**, 1371(2018), https://doi.org/10.1016/j.ejpe.2018.09.006
41. V. Valtchev and L. Tosheva, *Chemical Reviews,* **113**, 6734(2013), https://doi.org/10.1021/cr300439k
42. R. Schl€ogl and S.B. Abd Hamid, *Angewandte Chemie International Edition.,* **43**, 1628(2004), https://doi.org/10.1002/anie.200301684
43. S. Sengupta and A. Kumar, In: IPTC 2013: *International Petroleum Technology conferenc*e,2013.
44. K. Tamalmani and H. Husin, *Applied Science*, **10**, 3389(2020), https://doi.org/10.3390/app10103389
45. M.F. Fakoya and S.N. Shah, *Petroleum,* **3**, 391(2017), https://doi.org/10.1016/j.petlm.2017.03.001
46. L. Hendraningrat and J. Zhang, *Applied Nanoscience,* **5(8)**, 1009(2015), http://dx.doi.org/10.1007/s13204-014-0399-x
47. W. Saenkhumwong and A. Suksri, *Engineering and Applied Science Research,* **44(3)**, 148(2017).
48. D. Lopez, R.D. Zabala, J.C. Cardenas, S.H. Lopera, M. Riazi, C.A. Franco and F.B. Cortes, *Journal of Petroleum Science and Engineering,* **194**, 107483*(*2020), https://doi.org/10.1016/j.petrol.2020.107483
49. Y. Hwang, J.K. Lee, J.K. Lee, Y.M. Jeong, S.I. Cheong, Y.C. Ahn and S.H. Kim, *Powder Technology,* **186(2)**, 145(2008), https://doi.org/10.1016/j.powtec.2007.11.020
50. L.N. Nwidee, A. Barifcani, M. Sarmadivaleh and S. Iglauer, *Intech Open Oil Applied. Science,* **8(4)**, 601(2017)
51. S. Al-Anssari, M. Arif, S. Wang, A. Barifcani, M. Lebedev and S. Iglauer, *Fuel,* **211**, 405(2018), https://doi.org/ 10.1016/j.fuel. 2017.08.111
52. B. Du, J. Li, F. Wang, W. Yao and S. Yao, *Journal of Nanomaterials,* **2015**, 1(2015).
53. M. Khalil, B.M. Jan, C.W. Tong and M.A. Berawi, *Applied Energy,* **191**, 287(2017), https://doi.org/10.1016/j.apenergy.2017.01.074
54. M.N. Agista, K. Guo and Z. Yu, *Applied Science,* **8(6)**, 871(2018), https://doi.org/10.3390/app8060871
55. K. Guo and Z. Yu, *Applied Science,* **8(6)**, 871(2018), https://doi.org/10.3390/app8060871
56. H. Liu, X. Jin and B. Ding, *Petroleum Exploration and development,* **43(6)**, 1014(2016), https://doi.org/10.1016/S1876-3804(16)30129-X
57. Z. Weidong, Y. Wenkui and T. Kezhong, *Petroleum Drilling Techniques,* **37(3)**, 118(2009).
58. N. Agenet, P. Perriat, T. Brichart and N. Crowther, Proceedings of the SPE International Oilfield Nanotechnology Conference and Exhibition, 2012, pp. 278–290.
59. S.J.D. Sofla, L.A. James and Zhang, *Fuel,* **16**, 559(2018), https://doi.org/10.1016/j.fuel.2017.11.091
60. Y.H Shokrlu and T. Babadagli, *Journal of Petroleum Science and Engineering,* **119**, 210(2014), https://doi.org/10.1016/j.petrol.2014.05.012
61. X. Kong and M.M. Ohadi, In: SPE-138241-MS, Abu Dhabi International Petroleum Exhibition and Conference. Society of Petroleum Engineers, 2010.
62. L. Li, G.A. Al-Muntasheri and F. Liang, In: SPE-181283-MS, Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 2016.
63. R. Barati, S.J. Johnson, S. McCool, D.W. Green, G.P. Willhite and J.T. Liang, *Journal of Applied Polymer Science,* **126(2)**, 587(2012), https://doi.org/10.1002/app.36845
64. R. Rangel I, R.L. Thompson, R.G. Pereira and F.L.B. de Abreu, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, **34(3)**, 285(2012), https://doi.org/10.1590/S1678-58782012000300009
65. S. Rychlicki, J. Stopa and P. Wojnarowski, *Acta Montanistica Slovaca,* **11(1)**, 140(2006).
66. D. Landa-Marban, F.A. Radu and J.M. Nordbotten, *Transport Porous Media,* **120(2)**, 395(2017), http://dx.doi.org/10.1007/s11242-017-0929-6
67. E. Kamaei, A.K. Manshad, S.R. Shadizadeh, J.A. Ali and A. Keshavarz, *Materialia,* **8**, 100440(2019), https://doi.org/10.1016/j.mtla.2019.100440

68. X. Sun, X. Li, X. Tan, W. Zheng, G. Zhu, J. Cai and Y. Zhang, *Journal of Petroleum Science and Engineering*, **196**, 107784(2021), https://doi.org/10.1016/j.petrol.2020.107784
69. A. Agi, R. Junin, J. Gbonhinbor and M. Onyekonwu, *Journal of Petroleum Exploration and Production Technology*, **8(4)** 1349(2018), http://dx.doi.org/10.1007/s13202-018-0434-7
70. K.A. Terron-Mejía, R. Lopez-Rendon and A.G. Goicochea, *Scientific Reports*, **7(1)**, 1(2017).
71. T. Underwood, V. Erastova, P. Cubillas and H.C. Greenwell, *Journal of Physical Chemistry C,* **119(13)**, 7282(2015), https://doi.org/10.1021/acs.jpcc.5b00555
72. J. Ali and K. Stephen, *Journal of Chemical and Petroleum Engineering,* **52(1)**, 69(2018), http://dx.doi.org/10.22059/JCHPE.2018.252190.1220
73. A.O. Gbadamosi, J. Kiwalabye, R. Junin and A. Augustine, *Journal of Petroleum and Exploration and Production Technology,* **8(4)**, 1373(2018), http://dx.doi.org/10.1007/s13202-018-0451-6
74. O.J. Emeka, O. Ifeanyi, A. Chikwe, A. Nwachukwu, O. Ndubuisi, O. Ifeanyi and O.A. Chidiebere, *Engineering and Applied Sciences,* **6(2)**, 41(2021).
75. A.S. Mohammed Vipulanandan, *Egyptian Journal of Petrolium,* **27(4)**, 1265(2018), https://doi.org/10.1016/j.ejpe.2018.07.001
76. R. Abhishek, A.A. Hamouda and A. Ayoub, *Applied Sci*ences, **8(7)**, 1093(2018), https://doi.org/10.3390/app8071093
77. M.K. Chaaudhury, *Nature,* **423(10)**, 131(2003).
78. M.N. Agista, K. Guo and Z. Yu, *Applied Sciences,* **8(6)**, 871(2018), https://doi.org/10.3390/app8060871
79. R. Moghaddam Nazari, A. Bahramian, Z. Fakhroueian, A. Karimi and S. Arya, *Energy Fuels,* **29**, 2111(2015), https://doi.org/10.1021/ef5024719
80. G. Zargar, T. Arabpour, A. haksar Manshad, J.A. Ali, S. Mohammad Sajadi, A. Keshavarz and A.H. Mohammadi, *Fuel,* **263**, 116599(2020), https://doi.org/10.1016/j.fuel.2019.116599
81. T. Pak, N.L. Archilha and R. Al-Imari, *Clean Technologies and Environmental Policy,* **20(2)**, 427(2018), http://dx.doi.org/10.1007/s10098-018-1487-5
82. S. Li and O. Torsaeter, *Proceedings of the Society of Petroleum Engineers Middle East Unconventional Resources Conference and Exhibition,* pp.311–323(2015).
83. M. Zargartalebi, N. Barati and R. Kharrat, *Journal of Petroleum Science and Engineering*, **119**, 36(2014), https://doi.org/10.1016/j.petrol.2014.04.010
84. M.S. Kamal, A.A. Adewunmi, A.S. Sultan, M.F. Al-Hamad and U. Mehmood, *Journal of Nanomaterial,* 2473175(2017), https://doi.org/10.1155/2017/2473175
85. E.C. Donaldson, R.D. Thomas and P.B. Lorenz, *Society of Petroleum Engineers Journal,* **9(1)**, 13(2013), https://doi.org/10.2118/2338-PA
86. P. Esmaeilzadeh, N. Hosseinpour, A. Bahramian, Z. Fakhroueian and S. Arya, *Fluid Phase Equilibria,* **361**, 289(2014), https://doi.org/10.1016/j.fluid.2013.11.014
87. B. Moradi, P. Pourafshary, F. Jalali, M. Mohammadi and M.A. Emadi, *Journal of Natural Gas Science and Engineering,* **27**, 64(2015), https://doi.org/10.1016/j.jngse.2015.07.009
88. M. Mohammed and T. Babadagli, *Advances in Colloid and Interface Science,* **220**, 54(2015), https://doi.org/10.1016/j.cis.2015.02.006
89. J. Giraldo, P. Benjumea, S. Lopera, F.B. Cortés and M.A. Ruiz, *Energy Fuels,* **27(7)**, 3659(2013), https://doi.org/10.1021/ef4002956
90. H. Hasheminasab, Y. Gholipour, M. Kharrazi and D. Streimikiene, *Environmental Science* and Pollution Research, **28(12)**, 15305(2021), http://dx.doi.org/10.1007/s11356-020-10789-x
91. J.Y. Ying and T. Sun, *Journal of Electroceramics,* **1(3)**, 219(1997), http://dx.doi.org/10.1023/a:1009931726749
92. S. Suganuma and N. Katada, *Fuel Processing Technology.,* **208**, 106518(2020), https://doi.org/10.1016/j.fuproc.2020.106518
93. G-T. Vuong, V-T Hoang, D-T Nguyen and T-O Do, *Appl Catal A Gen,* **382**, 231(2010), https://doi.org/10.1016/j.apcata.2010.04.049
94. Z. Vryzas and V.C. Kelessidis, *Energies,* **10(4)**, 540(2017), https://doi.org/10.3390/en10040540

95. M.S. Al-Yasiri and W.T. Al-Sallami, *American Journal* of *Nano Research* and *Applications*, **3(3)**, 41(2015).
96. N. Gaurina-Medimurec, B. Pasic, P. Mijic and I. Medved, *Applied Sciences,* **11(2)**, 767(2021), https://doi.org/10.3390/app11020767
97. S. Ponmani, J.K.M. William, R. Samuel, R. Nagarajan and J.S. Sangwai, *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* **443**, 37(2014), https://doi.org/10.1016/j.colsurfa.2013.10.048
98. N. Nabhani and M. Emami, *Nano,* **201**, 23(2012).
99. M.F. Fakoya and S.N. Shah, *Petroleum,* **3(4)**, 391(2017), https://doi.org/10.1016/j.petlm.2017.03.001
100. J.A. Ali, K. Kolo, S.M. Sajadi, K.H. Hamad, R. Salman, M. Wanli, M.H. Hamda, B. Raihana and S.H. Hama, *IET Nanobiotechnology,* **13(7)**, 748(2019),https:// doi.org/10.1049/iet-nbt.2018.5205
101. K. Karakosta, A.C. Mitropouls and G.Z. Kyzas, *Journal of Molecular Structure*, **1227**, 129702(2021), https://doi.org/10.1016/j.molstruc.2020.129702
102. Y. Zheng, A. Amiri and A.A. Polycarpou, *Applied Surface Science,* **527**, 146822(2020), https://doi.org/10.1016/j.apsusc.2020.146822
103. E. Kasiralvalad, *Int. J. Nano Dimens. International Journal of Nano Dimension* ,**5(5)**, 463(2014).
104. M. Sadeghalvaad and S. Sabbaghi, *Powder Technology,* **272**, 113(2015), https://doi.org/10.1016/j.powtec.2014.11.032
105. T. Sharma, S. Iglauer and J.S. Sangwai, *Industrial & Engineering Chemistry Research,* **55(48)**, 12387(2016), https://doi.org/10.1021/acs.iecr.6b03299
106. T. Nochaiya and A. Chaipanich, *Applied Surface Science,* **257(6)**, 1941(2011), https://doi.org/10.1016/j.apsusc.2010.09.030
107. N. Jafariesfad, M.R. Geiker, Y. Gong, P. Skalle, Z. Zhang and J. He, *Journal of Petroleum Science and. Engineering.,* **156**, 662(2017), https://doi.org/10.1016/j.petrol.2017.06.047
108. E.B. Nelson and D. Guillot, Well Cementing. Paris, Schlumberger, p773 (2006)
109. X. Pang, P.J. Boul and W.C. Jimenez, *SPE Drilling and Completion,* **29(1)**, 98(2014), https://doi.org/10.2118/168037-PA
110. Y.A.P. Mercado, J.C.C. Ramirez, A.C.H. Acevedo and S.I.M. Méndez, Patent CA2643866(2013).
111. C.W. Roddy, C. Jiten, C. Roger, C.P. Rahul, T. Abhijit, D. Abhimanyu and L.G. Christopher, Patent US7784542B2(2010).
112. M.J. Thiercelin, B. Dargaud, J.F. Baret, W.J. and Rodriquez, *SPE Drilling and Completion*, **13 (4)**, 266(1998), https://doi.org/10.2118/52890-PA
113. M.S. Konsta-Gdoutos, Z. S. Metaxa and S.P. Shah, *Cement and Concrete Composites,* **32(2)**, 110(2010), https://doi.org/10.1016/j.cemconcomp.2009.10.007
114. L. Li, X. Yuan, J. Sun, X. Xu, S. Li, and L. Wang, *Proceedings of the International Petroleum Technology Conference,* **1**, 85(2013)
115. T. Nochaiya and A. Chaipanich, *Applied Surface Science,* **257(6)**, 1941(2011), https://doi.org/10.1016/j.apsusc.2010.09.030
116. B.M. Tyson, R.K. Abu Al-Rub, A. Yazdanbakhsh, Z. Grasley, *Journal of Materials in Civil Engineering,* **23(7)**, 1028(2011), http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000266
117. F. Sanchez and K. Sobolev, *Construction and Building Materials,* **24(11)**, 2060(2010), https://doi.org/10.1016/j.conbuildmat.2010.03.014
118. A. Bera and H. Belhaj, *Journal of Natural Gas Science and Engineering,* **34**, 1284(2016), https://doi.org/10.1016/j.jngse.2016.08.023
119. J.A. Arnot and F.A.P. Gobas, *Environmental Reviews,* **14,** 257(2006), https://doi.org/10.1139/a06-005
120. A. Sarkar, D. Sarkar and K. Poddar, Nanotoxicity: Sources and Effects on Environment. In: Microbial Nano Bionics. Springer, Cham pp. 169–179 (2019)
121. A.F. Prakash, G.J. Dushendra Babu and M. Lavanya, *International Journal of Nanotechnology and Application,* **5 (2),** 99(2019), https://doi.org/10.2174/1389200221666200103091753
122. V. Valdiglesias, C. Costa and G. Kilic, *Environment International,* **55C**, 92(2013), https://doi.org/10.1016/j.envint.2013.02.013

123. N. Wiesmann and W. Tremel, *J. Brieger, Journal of Materials Chemistry* B**, 8(23)**, 4973(2020), http://dx.doi.org/10.1039/D0TB00739K
124. M. Ghosh, A. Chakraborty and A. Mukherjee, *Journal of Applied Toxicol0gy.,* **33 (10)**, 1097(2013), https://doi.org/10.1002/jat.2863
125. J. McCarthy, I. Inkielewicz-Stępniak and J.J. Corbalan, *Chemical Research in Toxicology,* **25 (10),** 2227(2012), https://doi.org/10.1021/tx3002884
126. S. Murugadoss, D. Lison and L. Godderis, *Archives of Toxicology,* **91,** 2967(2017), http://dx.doi.org/ 10.1007/s00204-017-1993-y
127. M.A. Sayyadnejad, H.R. Ghaffarian and M. Saeidi, *International Journal of Environmental Science and Technology,* **5 (4)**, 565(2008), http://dx.doi.org/10.1007/bf03326054
128. W. Tungittiplakorn, C. Claude and W.L. Leonardo, *Environmental Science and Technology*, **39(5)**, 1354(2005), http://dx.doi.org/10.1021/es049031a
129. W. Zhang, *Journal of Nanoparticle Research,* **5,** 3(2003).
130. Z. Shi, D. Fan, R.L. Johnson, P.G. Tratnyek, J.T. Nurmi, Y. Wu and K.H. Williams, *Journal of Contaminant Hydrology,* **181,** 17(2015), https://doi.org/10.1016/j.jconhyd.2015.03.004
131. D. O'Carrol, B. Sleep, M. Krol, H. Boparai and C. Kocur, *Advances in Water Resources,* **51,** 104(2013), https://doi.org/10.1016/j.advwatres.2012.02.005
132. L. Bashambu, R. Singh and J. Verma, Metal /metal oxide nanocomposite membranes for Water Purification. *Materials Today,* **44(1),** 538(2021).
133. S. Honarparwar, X. Zhang, T. Chen, A. Alborzi, K. Afroj and D. Reible, *Membranes,* **11(4),** 246 (2021), https://doi.org/10.3390/membranes11040246
134. N. Barati, M.M. Husein and A. Azaiez, *Journal of Membrane Science,* **617,** 118641(2021), https://doi.org/10.1016/j.memsci.2020.118641
135. M.T. Amin, A.A. Alazba and U. Manzoor, *Advances in Materials Science and Engineering,* **825910**, 1(2014).
136. I. Gehrke, A. Geiser and A. Somborn-Schulz, *Nanotechnology, Science and Applications,* **8,** 1(2015), http://dx.doi.org/10.2147/NSA.S43773
137. J. Abdo and M. Haneef, *Journal of Energy Resources Technology,* **134(1),** 014501(2012), https://doi.org/10.1115/1.4005244
138. N. Chegenizadeh, A. Saeedi and X. Quan, *Petroleum*, **2**, 324(2016), https://doi.org/10.1016/j.petlm.2016.10.002
139. M.F. Fakoya and S.N. Shah, *Petroleum,* **3**, 391(2017), https://doi.org/10.1016/j.petlm.2017.03.001
140. M.S. Zaman, M.R. Islam and S. Mokhatab, *Journal of Petroleum Science and Technology,* **30,** 1053(2012), https://doi.org/10.1080/10916461003752553

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