Literature Review of Nanotechnology in the Enhanced Oil Recovery.

Mohammed A Samba*, Yiqiang Li*, Zheyu liu* and Ibrahim A. Amar**.

* Petroleum Engineering Institute, China University of Petroleum-Beijing CUP, China.

** Department of Chemistry, Faculty of Science, Sebha University, Sebha, Libya.

* Corresponding Author: Mohammed_samba@yahoo.com

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ABSTRACT

In recent studies, there has been an increasing focus on Nanoparticles Enhanced Oil Recovery (NPs EOR). NPs EOR is a method that was initially developed to improve microscopic and macroscopic displacement efficiency. In some recent applications, NPs have assisted the conventional EOR methods such as a polymer, surfactant, and Co_2 flooding, with the purpose of increasing the oil recovery. In this literature, the abilities to use NPs in EOR are investigated. The function of different types of NPs, different types of Dispersing agents, availability of nanomaterials in the lab, the effect of NPs to change the properties, future challenges and concerns about the NPs, are reviewed. However, the stability of NPs suspensions is still the biggest barrier to use the NPs in EOR. Upcoming studies are necessary to focus on the outcome of the appropriate techniques of NPs to improve their stability under the worst conditions of reservoirs and investigate new types of NPs.

Keywords: Enhanced Oil Recovery; Nanoparticles Application; Nanoparticles Effect; Nanoparticles Concern; Appendix.

INTRODUCTION

EOR indicates any reservoir method that is used to change the properties inside the reservoir. This change could be between the displacing and displaced fluid or between the displaced fluid and rock inside the reservoir in order to increase the recovery factor (RF), and this change might reduce the interfacial tension, oil viscosity, increase oil swelling, and; also, wettability alteration. As is well known, the EOR period is a very important production period because more than 30 % of the oil in place can be recovered in this period (Green and Willhite 1998). EOR has a lot of methods and every method has its own considerations for use. One of those methods is Chemical EOR. Chemical EOR can be classified into Polymer, Surfactant, Alkaline, and NPs EOR. The NPs are defined as small particulates less than one hundred nanometers and are considered as small sized, ultrafine particles (airborne particles). The application of NPs in EOR studies is increasing due to the ability of some types of NPs to change the reservoir properties or change the displaced and displacing fluid properties.

However, recent studies have shown that NPs can solve many problems in EOR studies due to the advantages of NPs. The main advantages of NPs are their large surface area (Kothari et al. 2010), change the wettability (Ju, Fan, and Ma 2006; Ju and Fan 2009; Ogolo, Olafuyi, and Onyekonwu 2012), reduced oil viscosity (Onyekonwu and Ogolo 2010; M.A. Samba et al. 2019), increased viscosity of the injecting fluid, small quantity required to perform a task (Kothari et al. 2010), reduction of the interfacial tension agent (Ogolo, Olafuyi, and Onyekonwu 2012), introduce additional action when mixed with the conventional methods (Kim et al. 2008), and some types of NPs can be reused (Mohammed A Samba et al., n.d.).

The NPs also have some disadvantages. The main common disadvantage of NPs is the blockage phenomena during the injection. Where, the NPs will lead to block the pores and reduce the RF due to reducing permeability and porosity. This blockage may occur due to the high concentration of NPs (Negin et al., 2016), high salinity of the displacing NPs and reservoir fluids (McElfresh et al., 2012), reservoir temperature (Derjaguin & Churaev, 1974) and single charge of NPs as well. Thus, many challenges are at stake to avoid the blockage (deposition) phenomena while the injection.

Most of NP's studies are tested in the laboratory, so the lab mechanisms are identified and understood. Generally, the NPs is relatively new and it is in the early time to apply it to the field; Hence, the application to apply it as an EOR method is not fully understood. Scientists have been trying to provide a mechanism for applying this technique in the field scale. Based on the lab's optimistic results, in the near future many studies will include how to provide scaling criteria between a lab scale and a field scale. Table 1 shows different types of NPs with their essential EOR applications.

Table 1 Different types of NPs with their essential EOR applications.

Type of NPs material	EOR application
Aluminum Oxide (Al_2O_3), Nickel Oxide (Ni_2O_3), Copper (II) Oxide, CuO, C_2H_5OH and MgO NPs (Polymer Coated), Iron Oxide, (Fe_2O_3/Fe_3O_4).	Mobility ratio.
Tin Oxide (SnO_2), Silicon Dioxide (SiO_2), Hydrophobic Silicon oxide (SiO2), Hydrophilic Polysilicon, Polymer Coated NPs, Spherical Fumed Silica NPs, Alumina Coated Silica NPs Neutrally Wet Polysilicon	Wettability alteration
Silicon Dioxide (SiO_2), Polyacrylamide Microgel, Lipophilic Polysilicon, Ferrofluid NPs, (Polymer Coated)	IFT reduction
NPs (Polymer), Colloidal Dispersion Gels (NanoSized), NPs (Polymer Coated).	Micro and macro efficiency
Aluminum Oxide (Al_2O_3), Silicon Dioxide (SiO_2), Nano clay Polysilicon, Titanium Dioxide (TiO_2) MWCNT - SiO_2	Rheological flow behavior
ZnO Carbon NPs ZrO_2 Carbon Nanotubes Fluids (Ferrotype), magnetic NPs, organic NPs, and inorganic NPs.	Further investigation should be done

Types of Nanoparticles

NPs can be divided into four categories; metal oxide NPs such as (Copper oxide (CuO), Aluminum Oxide (Al_2O_3), Nickel Oxide (Ni_2O_3), Copper Oxide (CuO), Titanium Oxide (TiO), Iron oxide (Fe_2O_3/Fe_3O_4), Magnesium oxide (MgO), Tin oxide (SnO_2), Zirconium Oxide (ZrO_2) and Zinc Oxide (ZnO)), magnetic NPs such as (Ferro Nano-fluids, Cobalt ferrite NPs and $NiFe_2O_4$-chitosan), Organic NPs such as (Carbon NP and Carbon nanotubes) and inorganic NPs such as Hydrophobic silicon oxide (SiO_2) NPs, Silica containing NPs, Spherical fumed silica NPs, Alumina coated silica NPs, Inorganic silica core/polymer-shell nano composite, Silicon oxide treated with silane NPs, Polysilicon NPs, Hydrophobic and lipophilic polysilicon NPs, Naturally wet polysilicon, Nano-structured zeolite, Nano sensors Nano-Sized Colloidal Dispersion Gels, Polymer coated NPs and Polyacrylamide Micro-gel Nano-spheres.

Based on the reviewed papers, the most used category in EOR is the metal oxide NPs. The different types of metal oxide NPs have tested as an IFT depressant, catalyst at the high temperature, reduce the oil viscosity, prevent condensation reactions, and oil swell as well (Clark & Hyne, 1990; Fan et al., 2004; Hashemi et al., 2013; J., 1990; Nares et al., 2007; Song et al., 2009; Wei et al., 2007) . While, the potential of the other categories such as magnetic, organic, and inorganic NPs have only recently come to the notice of EOR researchers (Negin, Ali, and Xie 2016; Nares et al. 2007; Ogolo, Olafuyi, and Onyekonwu 2012; Belcher et al. 2010; Habibi et al. 2012; Wu et al. 2017; Onyekonwu and Ogolo 2010; Lian and Zheng 2015).

Most but not all of the previous types of NPs have been used to test their ability to enhance oil recovery, some types of NPs have been reported to be able to enhance oil recovery such as Al_2O_3, Ni_2O_3, Fe_2O_3, etc. At the same time, some NPs have failed to enhance the oil recovery due to the reduction in permeability, such as MgO and ZnO (Ogolo, Olafuyi, and Onyekonwu 2012). As well as, some types need further investigation in EOR such as ZrO_2, ZnO, Ferro fluids, Spinal Oxide, Magnetic Cobalt Ferrite, Carbon NPs, Carbon nanotubes. In any case, the effect of each type of NPs mainly depends on the type the dispersing agent, the most important issue for petroleum engineers is to understand that not all the types of NPs can be dispersed in water, so different types of fluids have been used as a dispersing agent for NPs.

The Dispersing Agents

The dispersing agent in the formation is an effective factor in improving the RF. Where, dispersing agent can assist the NPs material to soluble or suspend in the solution. The solubility or suspending the NPs material in the solution can ensure long distance transmissibility for NPs material. While, the fail of dispersing agent to soluble or suspend the NPs material can cause precipitation of the NPs material in the solution or it can cause blockage in the pore space during the injection. Thus, the dispersing agent can provide positive or negative results for oil recovery (Ogolo, Olafuyi, and Onyekonwu 2012). Different types of dispersing agent have been tested with NPs in EOR process include brine, distilled water, ethanol, diesel, surfactant, and polymer. During the EOR process prefer to use polar fluids (brine and distilled water) due to the economic side. Typically, the other organic fluids such as ethanol and diesel or chemical solutions (surfactant or polymer), are costly regardless the ability to introduce extra RF and ability to suspend the NPs material in the solution. In any case, some types of NPs such as hydrophobic silicon oxide NPs cannot be dispersed in polar fluids. While, it can only be dispersed in organic fluids. The main issues of different types of NPs cannot be dispersed in different types of fluid due to the charge in the NPs materials in addition to other factors. For example, why the sodium chloride can be easily dispersed inside the polar fluid? It is known that sodium has a positive charge and chloride has a negative charge. When the sodium chloride mixed with the water, the hydrogen in the water molecules starts to attract the negative charge of chloride and surround them, while the hydrogen in the water molecule starts to attract the positive charge of sodium and surround them. The operation continues until all of the crystals break. Meanwhile, during the NPs, most of the types of NPs have only one charge where it is not easy to dissolve or disperse them in the water. Thus, some commercial companies have started to sell saline-treated NPs, which have been treated to have positive and negative charges which make it easy to dissolve or disperse inside the polar fluids. The most common method to modify the surface charges is called Janus particles, where in this method the NPs will be modified by negative and positive charges on opposite sides (Walther and Müller 2008).

Availability of Nanoparticles

To conduct any NPs project, there are two ways to provide the NPs material: by preparing it by following specific procedures and specific methods or obtaining it commercially. The majority of the petroleum engineering studies have reported that the NPs material has been obtained commercially.

The purity of nanomaterial is considered as the main problem with the material that has been provided commercially, because some companies provide some types of nanomaterials with some additivities. These additives enable the NPs to be dispersed in the polar fluids. Some companies introduced materials such as surfactant or polymer to allow the material to be dispersed in the polar fluids. In this situation, the effect of the additional material will equip a part to recover the oil without taking it into account.

The proper way for researchers to explore the real effect of NPs material is to prepare or supervise its preparation, to make sure that there are no additives added to the pure material. In addition, if there are any additives in the nanomaterials, the researcher will be familiar with the effect of the additives. Some researchers have reported that they prepared the NPs and applied them to the EOR process to investigate the real effect of the nanomaterials without any additives (M.A. Samba et al. 2019). Anyway, there are various methods to prepare the nanomaterials and every method has its advantages, such as some methods can give a higher surface area compared with other methods in the case of preparing the same material. The most common methods used to prepare the NPs materials are: Mechanical ball milling, Sputtering, Laser Ablation, Chemical Vapor Deposition (CVD), Mechanochemical method, Etching techniques, Gas Condensation, Chemical Precipitation, Sol-Gel Techniques, Vacuum Deposition and Vaporization, Hydrothermal, Microwave synthesis, Electrochemical method, and Biological method, Theromolysis of metal complexes, Chemical Vapor Condensation (CVC), Electrodeposition and Sonochemical method (Ayuk, Ugwu, and Aronimo 2017).

The preparation of NPs materials (powder) should be carried out using some measurements to characterize different physical properties (shape, surface area, etc.) and chemical properties (connection between the molecules, synthetic control of size and shape, etc.) and make sure that the material that has prepared is a nanomaterial. The most common tests are: Thermal analysis (TG and DTA) which is used to study the thermal behavior, X-ray Diffraction (XRD) which is used to study the particle diameter and shape, X-ray Fluorescence (XRF) which is used to determine the actual percentage, IR Spectroscopy which is used to study the functional groups, and Scanning-electron microscope (SEM) which is used to investigate the particle morphology and diameter. However, the XRD is the most important test to make sure that the material that has been prepared is a nanomaterial. While, the zeta potential is very important for the solution, in order to check whether the solution is stable or not.

THE EFFECT OF THE NANOPARTICLES ON EOR.

The Effect of the Nanoparticles on the Oil Viscosity

Oil viscosity is a significant factor when the EOR method selection is at stake and the mobility ratio required governing the macroscopic sweep efficiency. One of the critical success parameters to increase the oil recovery is to lower oil viscosity. Oil-viscosity can be decreased through the NPs, where the Al_2O_3 and CuO NPs have the ability to reduce oil-viscosity (M.A. Samba et al. 2019; Ogolo, Olafuyi, and Onyekonwu 2012; Shah 2009). Those types of NPs are able to split the oil droplet into small droplets (M.A. Samba et al. 2019). Thus, the high molecules of the oil droplet will be lower and the molecules will be less strongly connected than before when it was in the form of a big droplet. Additionally, the drops which strongly connect the molecules have high friction between the oil droplet and the wall of rocks. Al_2O_3 and CuO can easily change the connected molecules when mixed with oil droplets from a strong connection to a weak connection between the molecules, as shown in figure 1.

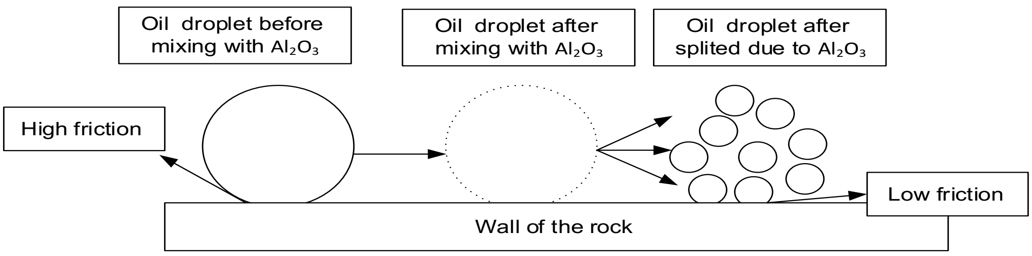

Figure 1 Al_2O_3 mechanism to reduce oil viscosity.

The Effect of the Nanoparticles concentration on EOR

Many studies have reported the effect of different concentrations with regard to improving many properties, such as IFT and oil viscosity. Thus, the oil recovery will be improved. Some

researchers have tested different NPs types (Ni_2O_3, Al_2O_3, TiO, and SiO_2) concentrations. The results have shown that the best RF was using a mixture of Al_2O_3 and SiO_2 with concentration of 0.05% (Alomair, Matar, and Alsaeed 2014). This study indicated that the optimal concentration of NPs should be determined to have maximum oil recovery, not always the higher concentration gives higher RF.

The Effect of the Nanoparticles on the Relative Permeability

Generally**,** Oil droplets in the small pores will be displaced due to wettability changes and nanoparticle adsorption. Thus, the relative permeability of the oil phase (Kro) increases and decreases the resistance to oil flow, while at the same time, the relative permeability of the water phase (Krw) decreases significantly. Thus, the slip flow of nanoparticle dispersion will be equipped apart and has the potential to reduce the injected pressure or enhance flow rate, which can improve the performance of water flooding (Yu et al. 2015).

Nanoparticles Assisted Surfactants

The major challenge facing recent researchers is how to let the NPs propagate a long distance deep into the reservoir with minimal retention. Some researchers have recommended solutions such as coating the NPs material with a specific chemical material such as polymer, surfactant, or their combination to the surface of the nanoparticles material to ensure long-term stability (Kim et al. 2008). In addition, adding the surfactant to the dispersant agent can lead the NPs to propagate a long distance deep into the reservoir with minimal retention (Tola, Sasaki, and Sugai 2017; Wu et al. 2017). At the same time, NPs are able to support and add many advantages to the surfactant. Surfactants should remain chemically stable, with no precipitation for the whole duration of the injection (Puerto et al. 2012). Minimizing or preventing the adsorption of surfactant on the surface of the rock is another challenge in order to keep the process economic (Jabbar et al. 2017). In the last few years, several studies have aimed to reduce the surfactant adsorption by introducing different additives. For instance, the addition of NPs can help to reduce the diffusion and adsorption of the surfactant. This is due to their small size compared to micellar structures and dissolved species which help them to be transported through pores with low retention on the pore walls (Wu et al. 2017).

ZnO, SiO_2 have been reported as being able to reduce the IFT when mixed with the surfactant (Karimi et al. 2012). Figure 2 shows the ability of NPs to reduce the IFT when used with a surfactant (STAREX). The ratio 1:4 for STRX-NS has shown the best performance in terms of the IFT and indicates the saturation adsorption of STRX-NS on the oil water interface (Mashat, Gizzatov, and Abdel-Fattah 2018). In addition, NWPN and HLPN have also been proven to support the ethanol from being weak surfactant to good surfactant. The injection of HLPN and NWPN with ethanol cause a large reduction in IFT between the formation water and oil (Ogolo, Olafuyi, and Onyekonwu 2012).

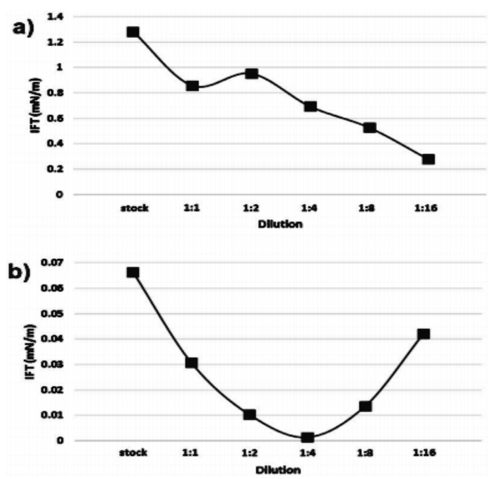

Figure 2 IFT of crude oil with different dilutions of (a) STRX and (b) STRX-NS 19 (Mashat, Gizzatov, and Abdel-Fattah 2018)

Nanoparticles Additive in a WAG process

The Nanoparticles-water alternating gas process has great potential for improving WAG injection, especially at the existence of natural fractures. NPs stayed around injection wells and high permeable zones which increased the recovery factor by more than 11% compared with water alternating gas injection WAG (Yu et al. 2015).

Improving of Macroscopic Displacement by Using Nanoparticles

The macroscopic displacement efficiency is also very important, where the macroscopic displacement efficiency is based on mobility ratio (M) which is also dependent on the viscosity of the displaced fluid and displacing fluid. Polymers are one of the most known agents that have been applied to increase the viscosity of displacing fluids and increase the macroscopic displacement efficiency (Kothari et al. 2010). During the polymer flooding, the existing silica in the polymer solutions can be a successful method for enhancing oil recovery because, besides increasing the macroscopic and microscopic sweep efficiency, NPs that are present in polymer solution can change the surface wettability. In addition, some NPs have proven their ability to increase the displacing viscosity without polymer. Some of those types of NPs are Nickel oxide and Iron oxide NPs in distilled water (Ogolo, Olafuyi, and Onyekonwu 2012).

Nanoparticles Effect on the Pore Throat

A rule of thumb related to the interactions between solid particle size and pore throat diameter (suspended solids or accumulation solids), has been presented by (van Oort, Van Velzen, and Leerlooijer 1993). This rule can be called the "1/3: 1/7 rule". If the particle size is larger than "1/3" of the pore diameter, this will cause external filter cake or plugging behavior. If the solid particle size is between 1/3 and 1/7 of the pore throat diameter, the solid particles will pass the formation but become trapped, and an internal filter cake may be formed. This can also be viewed as partially plugging behavior. If the particle size is smaller than 1/7 of the pore diameter, then the particles will flow easily through the formation, as shown in figure 3. The adsorption of NPs (ZnO and MgO) on surface of the rock and small pore throats blocking may cause a reduction in the porosity and permeability (Ogolo, Olafuyi, and Onyekonwu 2012). Additionally, the blocking of the pore throat may occur due to the accumulation of the NPs to cross the pore at the same time, which is often called Bridge Theory (log-jamming).

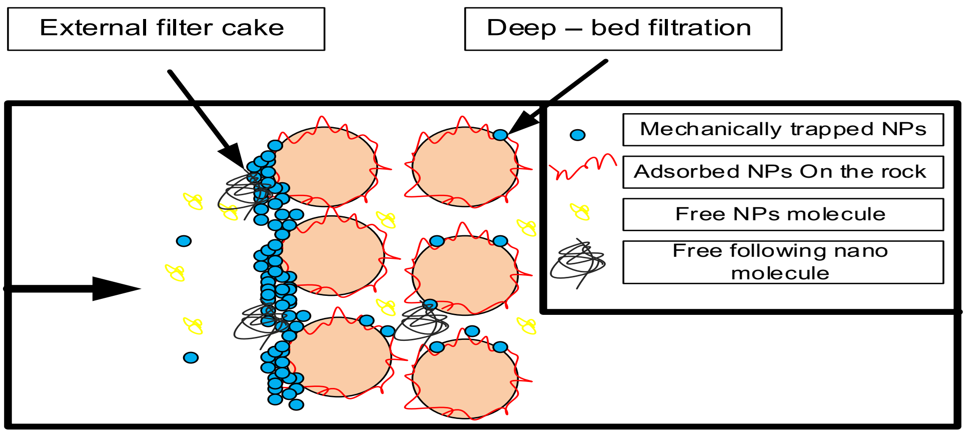

Figure 3 Deep bed formation and external cake formation for NPs around the wellbore.

Effect of Particle Size

The effect of particle size on the recovery factor has been reported in different researches. Silica NPs have been tested with different sizes (140, 120, 100, 87 nm). The injection process was accomplished by every size and compared with the base case (water flooding) which recorded 67% RF. This study noticed that a smaller size has a higher RF which can be enhanced by assisted polymer (Salem Ragab and Hannora 2015).

CONCERNS AND FUTURE CHALLENGES

1. Environmental footprint is a key challenge to be minimized. Where, the NPs are still unclear as its effect on pollution, humans, and environmental sustainability.
2. The reservoir heterogeneity might affect the overall performance of NPs in pores especially at harsh conditions.
3. More efforts should be investigating the different structures, instead of spherical NPs.
4. The cost-effective NPs are one of the main challenges in field application.
5. The adsorption of NPs on different rocks at different conditions is stills poorly understood.
6. More efforts should be investigating the interaction between the NPs and rock surface / oil.
7. More research effort should be investigating the long-term stability for NPs.
8. More efforts should be investigating the effect of NPs charges on the cementing material.

CONCLUSION

An extensive review of the NPs EOR process has been undertaken. The majority of these collections reported a significant increase in RF, generally about 1 to 39 %. The literature shows that the NPs can assist the conventional EOR methods. Therefore, NPS have been considered as assistance agents to form the emulsion, alter the wettability, etc.

Metal oxide NPs is the most widely used and has huge attraction in EOR for sandstone and carbonate reservoirs. While, there are many different types of NPs such as magnetic, organic, and inorganic NP have only recently come to the notice of EOR researchers and need further investigation in the EOR world.

Many parameters should be taken into account during the NPs applications such as size, temperature, stability, Etc. The recovery factor increases with decreasing NPs size and the injection flow rate and increasing temperature.

It is important to develop a sound understanding of the phase behavior of Nano fluids, NPs material preparation, wetting mechanism, and NPs transportation, to avoid retention. The main problem connected with the application of the NPs process seems to be permeability damage, poorly understood of mechanisms and stability over the long-term.

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Appendix .

Nano type	**imple**	**urface area (m2/g)**	**ano size (nm)**	**Dispersing agent**	**Rock type**	**Actions**	**Reference**
Aluminum Oxide	L_2O_3	0	0	Brine	N m	Reduce the viscosity, increase the RF to 5 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Aluminum Oxide	L_2O_3	0	0	Distilled water	N m	Reduce the viscosity, increase the RF to 12.5%.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Aluminum Oxide	L_2O_3	0	0	Ethanol	N m	Reduce the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Magnesium Oxide	gO	0	0	Distilled water	N m	Slightly increase the oil recovery to 1.7 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Magnesium Oxide	gO	0	0	Brine	N m	Reduce the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Magnesium Oxide	gO	0	0	Ethanol	N m	Reduce the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Iron Oxide	e_2O_3	0-60	0-40	Distilled water	N m	Increase the oil recovery to 9.2.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Iron Oxide	e_2O_3	0-60	0-40	Brine	N m	No effect on the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Iron Oxide	e_2O_3	0-60	0-40	Ethanol	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Nickel Oxide	i_2O_3		00	Distilled water	N m	Slightly increase the oil recovery to 2 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)

Nickel Oxide	i_2O_3		00	Brine	N m	Slightly increase the oil recovery to 1.7 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Nickel Oxide	i_2O_3		00	Ethanol	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zinc Oxide	nO	0	0-30	Distille d water	N m	Increase the oil recovery to 3.3 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zinc Oxide	nO	0	0-30	Brine	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zinc Oxide	nO	0	0-30	Ethanol	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zirconium Oxide	rO_2	5	0-30	Distille d water	N m	Increase the oil recovery to 4.2 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zirconium Oxide	rO_2	5	0-30	Brine	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zirconium Oxide	rO_2	5	0-30	Ethanol	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Tin Oxide	nO	0-30	0-70	Distille d water	N m	Increase the oil recovery to 3.3 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Tin Oxide	nO	0-30	0-70	Brine	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Tin Oxide	nO	0-30	0-70	Ethanol	N m	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Silane Treated Silicon Oxide	iO_2	400	0-30	Distille d water	N m	Slightly increase the oil recovery to 0.8 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)

Silane Treated Silicon Oxide	iO_2	400	0-30	Brine	N m	Increase the oil recovery to 4.2 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Silane Treated Silicon Oxide	iO_2	400	0-30	Ethanol	N m	Increase the oil recovery to 5 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Hybrophbic Silicon Oxide	iO_2	00-140	0-20	Ethanol	N m	Slightly increase the oil recovery to 1.7%.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Neutrally Silicon Oxide	WNS	400	0-30	Brine	S andstone	Increase the oil recovery to 38.75%	(Onyekonwu and Ogolo 2010)
Naturally wet silicon Oxide	WNS	400	0-30	Brine	S andstone	Increase the oil recovery to 29.23%	(Onyekonwu and Ogolo 2010)
Lphobic and Hydlic PN	HPN	00-600	0-60	Brine	S andstone	Slightly increase the oil recovery to 0.75 %.	(Onyekonwu and Ogolo 2010)
Lipophobic & hydrophilic PN	HPN	00-600	0-60	Brine	S andstone	Slightly increase the oil recovery to 1.92 %.	(Onyekonwu and Ogolo 2010)
Hydrophobic & lipophilic PN	LPN	00-140	0-20	Brine	S andstone	Increase the oil recovery to 36.67 %	(Onyekonwu and Ogolo 2010)
Hydrophobic & lipophilic PN	LPN	00-140	0-20	Brine	S andstone	Increase the oil recovery to 29.01%	(Onyekonwu and Ogolo 2010)
Zinc Oxide	nO	5-50	0-30	Anioni c surfactant	S andstone	Alter the wettability to more water wet.	(Tola, Sasaki, and Sugai 2017)
Zirconium oxide NPs	rO_2	m	4	Anonio nic surfactant	C arbonate	Alter the wettability to more water wet.	(Karimi et al. 2012)
Nonferrous metal		2	0-150	Anioni c surfactant	S andstone	Increase in the oil recovery by 35%,	(Suleimanov et al.2011)

Copper oxide	uO	m	50	CO_2-PDMS	Sandstone	Raised the oil recovery from 58% to 71% .	(Shah 2009)
Illinois-Institute -Technology	IT	m	9	Brine	Sandstone	Increase the oil recovery to 32%	(Zhang et al.2014)
Silica nanofluid	iO_2	m	0	Brine	Sandstone	Increase the oil recovery to 53%	(Zhang et al.2014)
Magnesium oxide	g O	m	m		Sandstone	stable solution has noticed which can provide low formation damage	(Assef et al. 2016)
Mixture of Nps	iO_2, l_2O_3, nd Cu			Distilled water	/	Al_2O_3 and TiO_2 have enhanced the critical heat flux compared with Cu which was very close to water without NPs.	(Cieśliński et al 2014)
Titanium oxide	iO_2			/	Carbonate	Alter the wettability was noticed.where the RF of heavy oil was 11%.	(Ehtesabi et al 2015)
Magnesium oxide	gO			/	Sand pack	MgO NPs increase the RF and avoid fines migration; hence, avoid decrease the size of pore throat.	(Huang, et al 2015)
Hydrophobic & lipophilic PN				/	Sandstone	The adsorb of Nps on the walls of the rock has been noticed. Thus, the porosity reduction may occur but still alter the wettability.	(Li, et al 2015)
Silicon Oxide	iO 2	45	0.0	CAPHS and SiO_2-GLYMO	Sandstone	The results shown the ability of SOi_2 to assist the surfactant in the harsh condition. The gain was 3.12 to 5.39 % .	(Zhong et al., 2020)

Zinc oxide	nO		5	Polyethylene glycol .	Sandstone	ZnO nanofluid was successfully recovered 26.2% of OOIp.	(Latiff et al., 2011)
Mixture of Nps	i,Al_{23} Si O		1-20	HCl, NaOH	Sandstone	APTES modified the negative surface charge of NP by grafting its positive amino ions on the surface, and it reduced the IFT.	(Ngouangna et al., 2020)
Mixture of Nps	l_2,Cu, Ti, Si O	0 to 60	0	CO_2 foams	Sandstone	The amounts of oil recoveries achieved were 17.4%, 12.3%, 6.5%, and 5.1% by SiO2, Al2O3, TiO2, and CuO NPs respectively.	(Bayat et al., 2016)
Mixture of Nps	io_2, faz co iron			Sodium dodecyl sulfate	Clay, Sandstone	The effect of NPs on RF in sp is helpful for successful design of nano sp during flooding processes	(Cheraghian, 2017)
Mixture of Nps	i,Al_2, Fe, Ni, n O	0 to 400	0- 70	Polymer	Sandstone, carbonate	improved solubility and stability, greater stabilization of foams and emulsions, and more facile transport through porous media.	(ShamsiJazeyi et al., 2014)
Mixture of Nps	**l_2**, Ti, Si O			Water	limestone	The results shown a reduction of oil viscosity and IFT and swept them toward the producer.	(Esfandyari Bayat et al., 2014)
Silicon Oxide	iO2	40	0–70	Water	/	The result suggests that a concentration of 4 g/L could alter the wettability from a strongly oil-wet to a strongly water- wet.	(Roustaei & Bagherzadeh, 2015)

Silicon Oxide	iO2	00	4	Surfactant and formation water	Sandpack	The results shown that the SDS foam stability is increased when SiO_2 Nps added tp the solution. The SiO2/SDS foam shows better temp tolerance than the SDS foam	(Sun et al., 2014)
Silicon Oxide	iO2	00	to 40	Synthetic brine NaCl3	Sandstone	The results shown that the Rf will increase with decrease the NPs size. also, the contact angle of solution also decreased as NPs size decreased.	(Hendraningrat et al., 2013)
Coal fly ash		00		Bulk foam	Sandstone	In this study the nano-ash has stabilized the nitrogen foam in presence of crude oil at harsh condition.	(Eftekhari et al., 2015)
Mixture of Nps	L_2, Si, Cu oxide		0 to 40	CO_2 Foam	/	The results shown that the EOR resistance and stability can be achieved by using relatively low concentration of NPs. Among all types of NPs used aluminum oxide NPs showed the highest CO2 foam properties performance.	(Manan et al., 2015)
Silicon Oxide	iO_2	0		Salt-water	Carbonate rocks	The SiO_2 showed excellent anti- temperature and anti- salinity property. The RF has improved to 16%, comparing with about 8% .	(Zhao et al., 2018)
Gum and nickel	iCl_2 H_2O	00- 00	0	Polymer	Sandstone	The results showed that RF was 5.98% with xanthan- nickel Np mixture compared to 4.48 and 4.58% of RF during the separate flooding of xanthan and Np.	(Rellegadla et al., 2018)
Aluminium oxide	l_2O_3	00-230	0	polyacrylmide	Sandstone	Oil displacement test in sandstone cores at typical reservoir temperature and salinity showed that AL_2O_3 , PNF had 11.3% incremental oil recovery over conventional HPAM.	(Gbadamosi et al., 2019)