Literature Review of Nanotechnology in the Enhanced Oil Recovery.

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ABSTRACT

In recent studies, there has been an increasing focus on Nanoparticles Enhanced Oil Recovery (NPEOR). NPEOR is a method that was initially developed to improve microscopic and macroscopic displacement efficiency. In some recent applications NP have been 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 NP in EOR are investigated. The function of different types of NP, different types of Dispersing agents, availability of nanomaterials in the lab, the effect of nanoparticles to change the properties, future challenges and concerns about the NP, are reviewed. However, the stability of suspensions of NP is still the most barrier to use NP in EOR. Upcoming studies are necessary to focus on the outcome of the appropriate techniques of NP to improve their stability under the worst conditions of reservoirs and investigate new types of nanoparticles.

Keywords: Enhanced Oil Recovery, NP applications, NP Effects, NP Concerns.

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 NPEOR. The NP are defined as small particulates less than one hundred nanometers and are considered as small sized, ultrafine particles (airborne particles). The application of NP 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 NP can solve many problems in EOR studies due to the advantages of NP. The main advantages of NP 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 NP 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 in 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 involved are identified and understood. Generally, the NPs is relatively new and is in the early time to applied it in the field; Hence, the application to apply it to EOR is not fully understood. Scientists have been trying to provide a mechanism for applying this technique in field scale. Based on the lab 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 shown 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 NP, organic NP, and inorganic NP.	Further investigation should be done

Types of Nanoparticles

NP can be divided into four categories; metal oxide NP 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 NP such as (Ferro Nano-fluids, Cobalt ferrite NP and $NiFe_2O_4$-chitosan), Organic NP such as (Carbon NP and Carbon nanotubes) and inorganic NP such as Hydrophobic silicon oxide (SiO_2) NP, Silica containing NPs, Spherical fumed silica NP, Alumina coated silica NP, Inorganic silica core/polymer-shell nano composite, Silicon oxide treated with silane NP, Polysilicon NP, Hydrophobic and lipophilic polysilicon NP, Naturally wet polysilicon, Nano-structured zeolite, Nano sensors Nano-Sized Colloidal Dispersion Gels, Polymer coated NP and Polyacrylamide Micro-gel Nano-spheres.

Based on the reviewed papers, the most category has been used in EOR is the metal oxide NP. The different types of metal oxide Np 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 NP 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 NP have been used to test their ability to enhance oil recovery, some of those NP 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 of NP have failed to enhance the oil recovery due to the low permeability problem, 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 NP, Carbon nanotubes. In any case, the effect of each type of NP based on the different dispersing agent, the most important issue for petroleum engineers is to understand that not all the types of NP can be dispersed in water, so different types of fluids have been used as a dispersing agent for NP.

The Dispersing Agents

The dispersing agent in the formation is an effective factor in improving the RF. Where, dispersing agent can assist the Np material to soluble or suspend in the solution. The solubility or suspending the NP material in the solution can ensure long distance transmissibility for NP material. While, the fail of dispersing agent to soluble or suspend the NP material can cause participation of the NP 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 used with NP 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 cannot be dispersed in polar fluids such as hydrophobic silicon oxide NP. While, it can only be dispersed in organic fluids. The main issues of the different types of NP cannot be dispersed in different types of fluid due to the charge in the NP materials in addition to other factors; for example, why can sodium chloride be easily dispersed inside the polar fluid? It is known that sodium has a positive charge and chloride has a negative charge. When we put the sodium chloride in 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 NP, most of the types of NP 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 NP which have been treated to have positive and negative charges that will 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 NP will be modifies by negative and positive charges on opposite sides (Walther and Müller 2008).

Availability of Nanoparticles

To conduct any NP project, there are two ways to provide the NP material: by preparing it by following specific procedures and specific methods or by obtaining it commercially. Most of the petroleum engineering studies have reported that they obtained the NP 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 add 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 the engineers taking this into account.

The proper way to explore the effect of NP material is for the researchers to prepare or supervise its preparation, to make sure that no additives are 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 NP materials (powder) should be carried out using the 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), used to study the thermal behavior, X-ray Diffraction (XRD), used to study the particle diameter and shape, X-ray Fluorescence (XRF), used to determine the actual percentage, IR Spectroscopy, used to study the functional groups, and Scanning-electron microscope (SEM), 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, for the solution, the zeta potential is very important 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 choosing the EOR method and the mobility ratio governing the macroscopic sweep efficiency. One of the critical success parameters to increase the oil recovery is that lower oil viscosity. Oil-viscosity can be decreased through the NP, 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 NP 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 in the form of a big droplet. Additionally, the drops that 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.

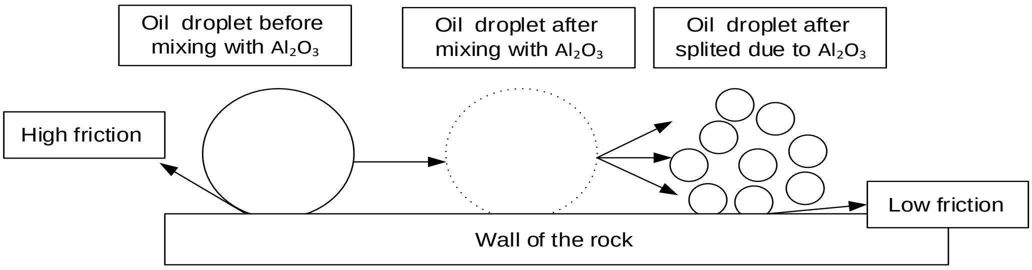

Figure 1 Al_2O_3 mechanism to reduce oil viscosity.

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 NP types Ni_2O_3, Al_2O_3, TiO, and SiO_2 different concentrations. The results shown that the best RF was using a mixture of Al_2O_3 and SiO_2 with concentration of 0.05% wt hybrid NP (Alomair, Matar, and Alsaeed 2014). This study indicated that the optimal concentration of NP 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 have 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 NP propagate a long distance deep into the reservoir with minimal retention. Some researches has recommended solutions such as coating the NP 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 additional, adding the surfactant to the dispersant agent can lead the NP 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, NP are able to support and add many advantages to the surfactant EOR method. 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 the addition of different additives. For instance, the addition of nanoparticles 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 nanoparticles to reduce the IFT when used with a surfactant (STAREX). The ratio 1:4 for STRX-NS has 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 injected of HLPN and NWPN with ethanol cause a large reduction in IFT between the formation water and oil (Ogolo, Olafuyi, and Onyekonwu 2012).

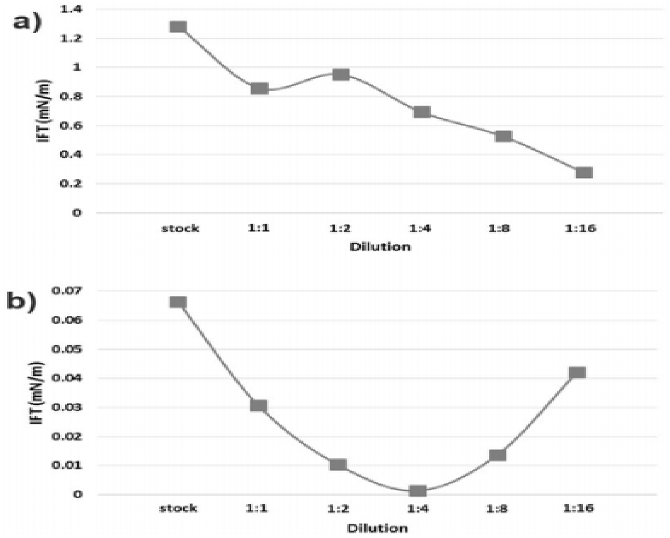

Figure 2 IFT of crude oil with different dilutions of (a) STRX and (b) STRX-NS 19 (Mashat, Gizzatov, and Abdel-Fattah 2018)

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. Nanoparticles are able to stay around injection wells and high permeable zones. The NP are able to increase 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 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 exist silica in the polymer solutions can be a success method for enhancing oil recovery because, besides increasing the macroscopic and microscopic sweep efficiency, NP 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 NP 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), 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 partly 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 NP (ZnO and MgO) on surface of the rock and small pore throats blocking may cause to a reducing 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 NP to cross the pore at the same time, which is often called Bridge Theory (log-jamming).

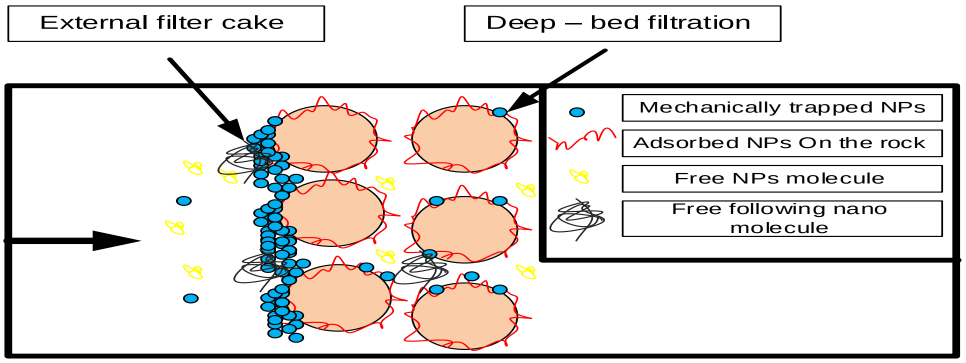

Figure 3 Deep bed formation and external cake formation for NPs around the wellbore.

Effect of Particle Size

The effect of particle size on the recovery factor has been reported in different researches. Silica NPs has 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. It was 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 NPs are still unclear as is their effect on pollution, humans, and environmental sustainability.
2. The reservoir heterogeneity might affect the overall performance of NP in pores especially at harsh conditions.
3. More efforts should be investigating the different structures, instead of spherical NP.
4. The cost-effective nanoparticles are one of the main challenges in field application.
5. The adsorption of NP on different rocks at different conditions stills poorly understood.
6. More efforts should be investigating the interaction between the NP and rock surface / oil.
7. More research effort should be investigating the long-term stability for NP.
8. More efforts should be investigating the effect of NP 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 increasing in RF, generally about 1 to 39 %. The literature shows that the NPs can assist the conventional EOR methods. Therefore, NPS have 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 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 NP transportation, to avoid retention. The main problem connected with the application of a NP process seems to be permeability damage, poorly understood of mechanism and stability over the long-term.

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Appendix .

Nano type	**Simple**	**Surface area (m2/g)**	**Nano size (nm)**	**Dispersing agent**	**Rock type**	**Actions**	**Reference**
Aluminum Oxide	AL_2O_3	60	40	Brine	Nm	Reduce the viscosity, increase the RF to 5 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Aluminum Oxide	AL_2O_3	60	40	Distilled water	Nm	Reduce the viscosity, increase the RF to 12.5%.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Aluminum Oxide	AL_2O_3	60	40	Ethanol	Nm	Reduce the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Magnesium Oxide	MgO	50	20	Distilled water	Nm	Slightly increase the oil recovery to 1.7 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Magnesium Oxide	MgO	50	20	Brine	Nm	Reduce the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Magnesium Oxide	MgO	50	20	Ethanol	Nm	Reduce the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Iron Oxide	Fe_2O_3	40-60	20-40	Distilled water	Nm	Increase the oil recovery to 9.2.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Iron Oxide	Fe_2O_3	40-60	20-40	Brine	Nm	No effect on the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Iron Oxide	Fe_2O_3	40-60	20-40	Ethanol	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Nickel Oxide	Ni_2O_3	6	100	Distilled water	Nm	Slightly increase the oil recovery to 2 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Nickel Oxide	Ni_2O_3	6	100	Brine	Nm	Slightly increase the oil recovery to 1.7 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Nickel Oxide	Ni_2O_3	6	100	Ethanol	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zinc Oxide	ZnO	90	10-30	Distilled water	Nm	Increase the oil recovery to 3.3 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zinc Oxide	ZnO	90	10-30	Brine	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zinc Oxide	ZnO	90	10-30	Ethanol	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zirconium Oxide	ZrO_2	35	20-30	Distilled water	Nm	Increase the oil recovery to 4.2 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zirconium Oxide	ZrO_2	35	20-30	Brine	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Zirconium Oxide	ZrO_2	35	20-30	Ethanol	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Tin Oxide	SnO	10-30	50-70	Distilled water	Nm	Increase the oil recovery to 3.3 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Tin Oxide	SnO	10-30	50-70	Brine	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Tin Oxide	SnO	10-30	50-70	Ethanol	Nm	Reduction in the oil recovery.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Silane Treated Silicon Oxide	SiO_2	>400	10-30	Distilled water	Nm	Slightly increase the oil recovery to 0.8 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Silane Treated Silicon Oxide	SiO_2	>400	10-30	Brine	Nm	Increase the oil recovery to 4.2 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Silane Treated Silicon Oxide	SiO_2	>400	10-30	Ethanol	Nm	Increase the oil recovery to 5 %.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Hybrophbic Silicon Oxide	SiO_2	100-140	10-20	Ethanol	Nm	Slightly increase the oil recovery to 1.7%.	(Ogolo, Olafuyi, and Onyekonwu 2012)
Neutrally Silicon Oxide	NWNS	>400	10-30	Brine	Sandstone	Increase the oil recovery to 38.75%	(Onyekonwu and Ogolo 2010)
Naturally wet silicon Oxide	NWNS	>400	10-30	Brine	Sandstone	Increase the oil recovery to 29.23%	(Onyekonwu and Ogolo 2010)
Lphobic and Hydlic PN	LHPN	400-600	20-60	Brine	Sandstone	Slightly increase the oil recovery to 0.75 %.	(Onyekonwu and Ogolo 2010)
Lipophobic & hydrophilic PN	LHPN	400-600	20-60	Brine	Sandstone	Slightly increase the oil recovery to 1.92 %.	(Onyekonwu and Ogolo 2010)
Hydrophobic & lipophilic PN	HLPN	100-140	10-20	Brine	Sandstone	Increase the oil recovery to 36.67 %	(Onyekonwu and Ogolo 2010)
Hydrophobic & lipophilic PN	HLPN	100-140	10-20	Brine	Sandstone	Increase the oil recovery to 29.01%	(Onyekonwu and Ogolo 2010)
Zinc Oxide	ZnO	35-50	20-30	Anionic surfactant	Sandstone	Alter the wettability to more water wet.	(Tola, Sasaki, and Sugai 2017)
Zirconium oxide NPs	ZrO_2	Nm	24	Anonionic surfactant	Carbonate	Alter the wettability to more water wet.	(Karimi et al. 2012)
Nonferrous metal	/	12	70-150	Anionic surfactant	Sandstone	Increase in the oil recovery by 35%,	(Suleimanov et al.2011)
Copper oxide	CuO	Nm	>50	CO_2-PDMS	Sandstone	Raised the oil recovery from 58% to 71% .	(Shah 2009)
Illinois-Institute -Technology	IIT	Nm	19	Brine	Sandstone	Increase the oil recovery to 32%	(Zhang et al.2014)
Silica nanofluid	SiO_2	Nm	20	Brine	Sandstone	Increase the oil recovery to 53%	(Zhang et al.2014)
Magnesium oxide	Mg O	Nm	Nm		Sandstone	stable solution has noticed which can provide low formation damage	(Assef et al. 2016)

Mixture of Nps	TiO_2, Al_2O_3, and 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	TiO_2	/	/	/	Carbonate	Alter the wettability was noticed.where the RF of heavy oil was 11%.	(Ehtesabi et al 2015)
Magnesium oxide	MgO	/	/	/	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	SiO 2	445	10.0	CAPHS and SiO_2-GLYMO	Sandstone	The results shown the ability of SOi_2 to assisit the surfactant in the harsh condition. The gain was 3.12 to 5.39 % .	(Zhong et al., 2020)
Zinc oxide	ZnO	/	45	Polyethylene glycol .	Sandstone	ZnO nanofluid was successfully recovered 26.2% of OOIp.	(Latiff et al., 2011)
Mixture of Nps	Ti,Al_{23} Si O		11-20	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	Al_2,Cu, Ti, Si O	10 to 60	40	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	Sio_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	Si,Al_2, Fe, Ni, Sn O	10 to 400	10- 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	**Al_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	SiO2	140	20–70	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	SiO2	200	14	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	SiO2	300	7 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	/	100	/	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	AL_2, Si, Cu oxide	/	10 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	SiO_2	30	/	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	$NiCl_2$ $6H_2O$	200-800	50	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	Al_2O_3	400-230	20	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)