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REVIEW

Recent advances in ASP flooding and the implementation of nanoparticles to enhance oil recovery: a short review

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ABSTRACT

Although the world is turning to renewables as a clean alternative source of energy, reliance on oil is expected to continue for more decades. Enhanced oil recovery (EOR) is an efficient way to recover oil after implementing initial methods. Alkali–surfactant–polymer flooding (ASP) has acquired much interest together with nano-fluid that involves using nano metallic oxides in EOR. Nanoparticles have proved their effectiveness in reducing interfacial tension at the interface between the oil and water and have been used with water, polymers, surfactants, alkaline, or a mixture of these components. Incremental oil recovery from applying ASP floods has exceeded 20% OOIP, and this is considered promising performance for unlocking oil reserves for many years to come. Despite that, ASP flooding nowadays faces big challenges presented by fluctuating oil prices, scaling and corrosion of the lifting system, and the formation of relatively strong emulsions that need high-cost treatment after oil production. This review emphasizes ASP flooding and the ASP flooding and the implementation of nanoparticles in extracting more oil using different chemical agents and sheds light on improving the recovery ratio. This study also explains the challenges that face each process and the steps that should be taken in order to overcome these challenges.

KEYWORDS
enhanced oil recovery; alkali–surfactant–polymer flooding; nano-fluid injection; optimum flooding; chemical flooding with nanoparticles

1. Introduction

Crude oil has continued to exist as the primary energy source despite other methods of generating energy from other sources. Due to a reduction in oil

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production in some areas, modern technologies are needed to increase production and balance global demand. Some of these techniques involve adding a surfactant or adding it together with a polymer to the reservoir in a process called surfactant–polymer (SP) flooding. Another combination employs the addition of an organic or inorganic base to the water together with a surfactant or with a surfactant–polymer formulation to produce the so-called alkali–surfactant–polymer (ASP) flooding.

In ASP flooding, the alkaline reacts with naphthenic acids available in crude oil to generate in situ surfactant mixed with the original present surfactant (Khan et al. 2009). A surfactant's presence is important to reduce the interfacial tension (ITF) between the oil and the water liquids (Cheng et al. 2014). The presence of polymer in water solution functions as a modifier that increases the viscosity of water and improves the sweep efficiency, consequently increases the flow rate of oil.

Due to the limitation of applying ASP flooding in a large-scale operation, the urgency to find a new alternative has increased. Nanoparticles (NPs) materials, owing to their large surface area to volume ratio, are widely researched for use in EOR processes (Mokhatab et al. 2006; Cheraghian et al. 2014; Nazari Moghaddam et al. 2015; Cheraghian et al. 2017; Khadem Olhosseini et al. 2020). The latest development in nanotechnology includes adding NPs with polymers and surfactants to form a novel combination that can be used as an injectant. For example, Gbadamosi et al. (2019) studied the use of aluminum oxide (Al_2O_3) nanoparticles as a chemical agent with hydrolyzed polyacrylamide (HPAM) solution. The results of their experimental study indicated that Al_2O_3 was a good agent for EOR operations.

An inorganic nano-silica (SiO_2), metal oxide titanium (TiO_2) NPs and Al_2O_3 NPs were used by many researchers. For instance, Esfandyari Bayat et al. (2014) use them in an intermediate-wet limestone at elevated temperatures between 26 and 60 °C. They found that these NPs lowered the IFT between oil and water phases and, at the same time, modified the sandstone core wettability at nearly the entire examined temperatures. Youssif et al. (2018) investigated the effect of nano-silica with concentrations (0.01, 0.05, 0.1, and 0.5 wt.%) in the flooding stream to improve oil recovery. The optimum concentration of silica nano-fluid corresponding to the maximum oil recovery was 0.1 wt.%. Nano-silica helped in reduced the oil–water IFT and surfactant adsorption on the rock surface.

NPs are essential for a broad range of commercial and research applications due to their physical characteristics and properties. Cheraghian et al. (2020) stated that the demand for NPs for use in EOR is very high. Their study focused on a review of the application of NPs in the flooding process and the effect of NPs on wettability and IFT measurements. In the same regard, it also found the potential of adding nano-titanium dioxide as an agent for improving the efficiency of surfactant flooding in a five-spot glass micromodel. The newly developed nano-surfactant solutions with 1600–2000 ppm sodium dodecyl sulfate were tested. Their experiments showed an improvement for heavy oil recovery using TiO_2 NPs at around 51%. Also, Cheraghian and Tardasti (2012) tested two NPs dissolved in water and injected titanium dioxide and fumed silica into a simulated environment. Through their experiments, it was possible to demonstrate that flows with NPs, especially titanium dioxide, had increased oil recovery. It is concluded that using NPs in water and polymer flooding can benefit the recovery process.

Bera et al. (2020) tested the performance of guar gum with and without silica nanoparticles at different temperature ranges (25–75 °C). Their experiments were conducted using 2000 ppm brine, 4000 ppm guar gum, 0.2 wt.% silica nanoparticles in distilled water as test fluids to recover a waxy crude oil from sandstone cores. Their results showed that guar gum that contains 0.2 wt.% silica nanoparticles was efficient in improving oil recovery by around 44.3% of OOIP. In their efforts to find the benefits of adding nanoparticles and nano-dispersions to enhance oil recovery, Bera and Belhaj (2016) indicated in their article that nanoparticles are effective to recover around 10% as additional oil from sandstone cores. They mentioned that the right choice of nanoparticles also depends on the kind and nature of the inspected oil reservoir.

In order to measure the performance of microemulsion and its level of extraction efficiency on the IFT, Bera et al. (2014) investigated the effect of salinity on an anionic microemulsion through the water solubilization method. The study found that the microemulsion used efficiently reduces the IFT between the crude oil and brine. It is concluded that more than 25% of the original oil in place has been recovered after conventional water flooding. In another study, Bera et al. (2013) investigated the adsorption of surfactants onto the reservoir rock and the effect in performing a practical application of surfactant flooding. It has been found from their experiments that the adsorption of cationic surfactant on the sandstone surface is more than an anionic surfactant, while nonionic surfactant shows intermediate behavior. X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) have been used to determine the main components present in the sand particles and examine the interaction between them and surfactants tested before and after aging with a surfactant, respectively.

In this review, a comparison between ASP and nanoparticle flooding technologies will be explored in some detail then the recovery factor for some of these flooding techniques will be mentioned. Finally, an outlook on the difficulties and challenges of applying each technique will be

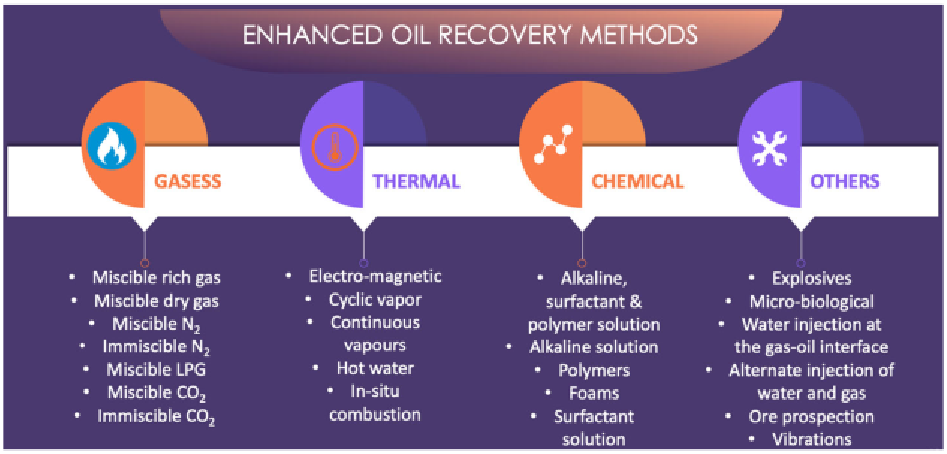


Figure 1. Classification of some major EOR processes (Olajire 2014).

demonstrated for optimum oil production. Figure 1 illustrates some of the general enhanced oil recovery (EOR) methods.

2. ASP projects

Currently, there are 32 global ASP projects in the world where 19 of them were applied in China alone. Table 1 shows typical costs per barrel for a standard ASP operation, and Figure 2 demonstrates the incremental oil recovery for 21 global projects and their average value and locations.

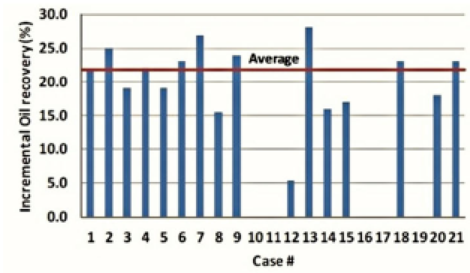
ASP flooding can be developed technically so that the oil recovered is 10% higher than polymer flooding and 20% higher than waterflooding. There are currently more than (83×10^8) tons of reserves that can be produced by injecting ASP flood from which over (14×10^8) tons of reserves can be extracted for Daqing oil field alone in China (Yang et al. 2019). ASP flooding has economic limitations due to the large volumes of chemicals injected. Therefore, the technical and economic feasibility of ASP flooding must be considered for the effective use of injected chemicals and slug formulation.

3. Effect of alkaline, surfactant, and polymer

There are different opinions about the alkaline used in ASP formulations. Some studies found that using strong alkali like caustic soda (NaOH) could significantly improve oil recovery (Zuo et al. 2012; Arvis et al. 2017). Other studies stated that using a weak base like sodium carbonate (Na_2CO_3) was more effective in recovering oil (Yin et al. 2017; Guo et al. 2018; Huang 2020). Yin et al. (2017) performed several experiments to obtain the optimal concentration of alkali that may lead to the best results. They observed that IFT decreased to a low value of 1.13 mN/m when using Na_2CO_3 at concentration 1.2 wt.%. This is achieved because Na_2CO_3 alkali has ions of

Table 1. Chemical cost estimates for a standard protocol of ASP (Sheng 2014)

		Slugs due to chemicals		
Investigated variables	Unit	Main slug	Pre-flush	Post-flush
Pore volume of slug	a-unit volume	0.308	0.097	0.242
Alkaline agents	%	1.25		
Polymer	ppm	1350	1450	800
Surfactants	%	0.27		
HPAM cost	USD per lb	1.03		
Alkaline cost	USD per lb	0.12		
Surfactant cost	USD per lb	2.2		
Incremental oil	%OOIP	21.8		
Individual chemical slug cost	USD per bbl	4.37	0.23	0.32
Total chemical cost including oil	USD per bbl	4.93		



Case #	Field	Country	Start date	P*	I*
1	Daqing Sa-zhong-xi (S-ZX)	China	01-09-1994	9	4
2	Daqing Xing-wu-Zhong (X5-Z)	China	29-01-1995	4	1
3	Daqing Xing-2-xi (X2-X)	China	28-09-1996	9	4
4	Daqing Sa-bei-1-xi (S-B)	China	15-12-1997	4	3
5	Daqing Xing-bei-xing-2-zhong (X2-Z)	China	01-04-2000	27	17
6	Daqing Sabei-bei-2-dong (SB-B2-D)	China	03-10-2004	4	3
7	Shengli Gudong	China	01-08-1992	9	4
8	Shengli Gudao-xi	China	01-05-1997	13	6
9	Karamay	China	22-07-1996	9	4
10	Jilin Hong-gang	China	01-09-1997		
11	Zhong-yuan Hu-zhuang-ji	China	12-01-2000	5	5
12	Yumen Lao-jun-miao	China	01-03-1994	4	1
13	Cambridge	USA	01-02-1993		
14	West Kiehl	USA	03-12-1987		
15	Tanner	USA	01-05-2000	2	1
16	Mellot Ranch	USA	01-08-2000	3	2
17	Lawrence	USA	01-08-2010	6	12
18	Sho-Vel-Tum	USA		4	1
19	Lagomar	Venezuela			
20	Viraj	India	10-08-2002	9	4
21	Jhalora	India	07-02-2010	6	1

P and I* mean the number of producers and injectors, respectively.*

Figure 2. Incremental oil recovery for 21 worldwide ASP projects (Sheng 2014).

OH^- that reacted with the molecules of petroleum acid (HA) found in the crude oil to produce the so-called "soap" or natural surfactant (A^-) according to the following equation:

$$\text{HA (acid)} + OH^- \rightarrow A^-(\text{Soap}) + H_2O \tag{1}$$

Khan et al. (2009) performed an experimental investigation to find the best combination for ASP flooding. They tested two cores for this purpose. The first one is devoted to 0.1 wt.% sodium dodecyl sulfate (SDS) surfactant, 2000 ppm HPAM polymer and 0.7 wt.% NaOH alkali. The second core is used for 0.075 wt.% sodium dodecylbenzene sulfonate (SDBS), 2000 ppm HPAM and 0.7 wt.% NaOH. It was possible to recover an additional 24% OOIP from the first core and about 22% OOIP from the second one. The excess recovery has been achieved due to the significant interfacial tension reduction, which decreased to 30–35 mN/m compared to waterflooding (72 mN/m).

4. Application of nano-fluids in EOR

NPs have two unique properties that make them attractive for many industries. First, they have a small particle size (1–100 nm) which enables them to transport to pores not accessible to large particles. Secondly, they have a large surface to volume ratio. When these two main benefits are combined, they can be effectively involved in many industries, not only EOR (Esfandyari Bayat et al. 2014; El-Diasty and Aly 2015; Oseh et al. 2020a, b).

Many researchers investigated TiO_2 polymeric nano-fluid (PNF), and an improvement in oil recovery was reported. Nonetheless, the data obtained is insufficient to authenticate TiO_2 NPs as an efficient additive for polymeric flooding. This is due to the titanium metal itself, which is listed as a transition metal. Besides that, TiO_2 NPs are classified to have variable oxidation. Hence, it is considered unstable.

Al_2O_3 NPs is one of the most widely used NPs as well. High temperatures are found to have a small effect on fluids containing Al_2O_3 NPs. Moreover, Al_2O_3 NPs play an important key role in slowing down polymer's degradation upon effective shear forces. The existing oxygen atom in its chemical structure helps counter the cations found in saline water and can withstand in the saline environment.

5. Challenges for ASP flooding operations

Some challenges need to be faced with making ASP flooding a more efficient and economical process. First, to obtain a higher incremental recovery, the oil–water interfacial tension must reach a magnitude of 10–3 mN/m, which cannot be easily achieved depending on the surfactant concentration. Secondly, it was found that adding more alkali will help in reducing the interfacial tension to the ultra-low value (magnitude of 10^{-3} mN/m), but at the same time, this may lead to some problems like decreasing the viscosity of ASP solution. To fix this additional problem, a substantial amount of polymer is recommended to substitute for the decreasing viscosity. Moreover, adding a high alkali concentration may cause technical scaling problems in the piping system and instruments. Therefore, the alkali concentration must be tailored to an appropriate quantity to avoid these problems and reduce the utilization of the chemical.

6. Mechanisms of nano-fluid flooding

The implementation of nanoscale entity can increase oil recovery considerably through achieving the following:

I. Enhancing the viscosity of fluid acting as an injectant and decreasing the oil viscosity.
II. Decreasing the interfacial tension and improving the emulsion formation.
III. Modifying the wettability from oil-wet to water-wet by decreasing the contact angle between the rock surface and oil.

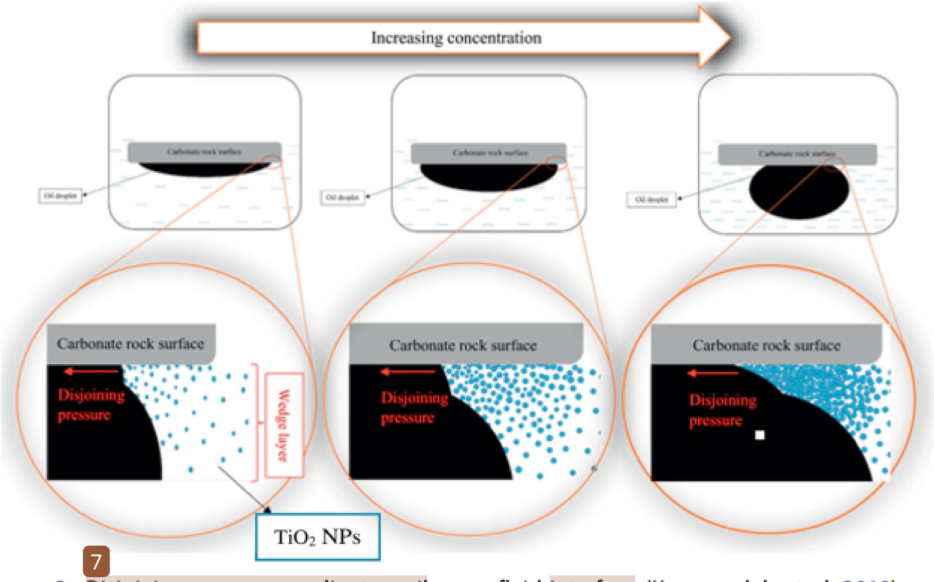


Figure 3. Disjoining pressure gradient at oil–nano-fluid interface (Kazemzadeh et al. 2019).

IV. Diminishing the reservoir formation damage by reducing the chemicals adsorbed on the rock matrix.

NP suspension is determined through the regulation of electrostatic repulsion force between its particles. As the repulsion force becomes more prominent, the more stable will be the NPs suspension, and the NPs will not aggregate. Generally, three mechanisms have been proposed to explain the formation activity of NPs. The first theory is related to what is called the "disjoining pressure". This pressure prevents the fluid from sticking to the solid surface and it is the difference in pressure between the fine fluid layer and the fluid bulk. NPs make the interface between discontinuous fluids through this mechanism in the form of wedge film. The disjoining pressure is formed due to energies found in the Brownian motion of the particles and the electrostatic repulsion forces between them (El-Diasty and Aly 2015). Figure 3 shows the representation of this principle.

The second mechanism is called the "density difference". This process is correlated with the density difference between the water and NPs, which agglomerate at the entrant of the pore throats. This agglomeration permits the fluid to flow to the neighboring pores and causes the oil to move and be produced in the adjacent pores (El-Diasty and Aly 2015). The third mechanism is related to the wettability alteration and interfacial tension reduction. This mechanism explains that oil is recovered due to the wettability alteration from oil-wet to neutral or water-wet, and therefore the IFT will be reduced at the interface region between the oil and water. Figure 4 shows a schematic view of these three mechanisms.

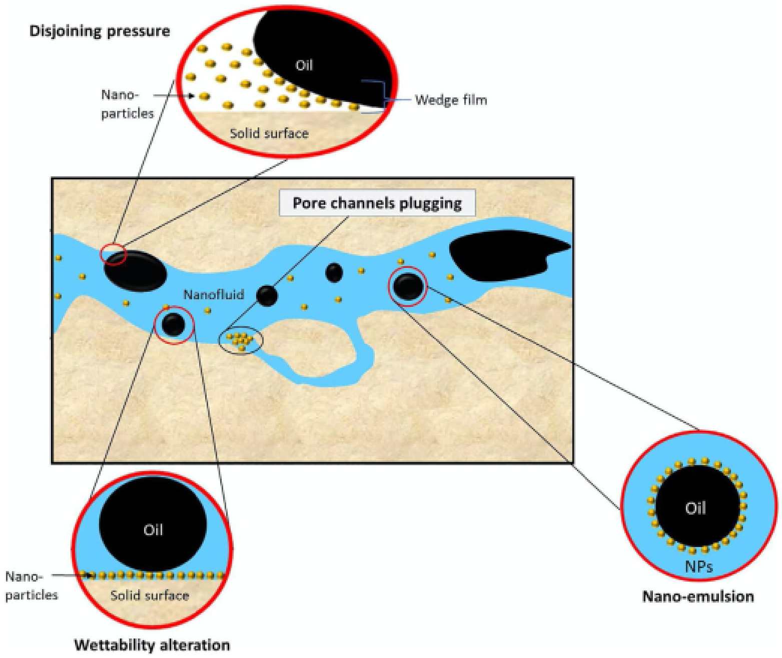


Figure 4. EOR mechanisms of nano-fluids within the porous media (Ali et al. 2018).

The increase of salinity leads to nanoparticle agglomerating. However, increasing salt ions does not prevent the movement of NPs, but it facilitates the accumulation of NPs on the surfaces of the rock. The temperature also affects the NPs so that when the temperature increases, the NPs agglomeration begins, which diminishes its stability. Injection rate, from the other part, also effects on the performance of NPs. Small molecules of water move at a high injection rate faster than suspended NPs and this leads a high injection rate faster than suspended NPs, leading to the agglomeration of NPs, which block the pore throats and cause the decrease of oil recovery. Table 2 summarizes some previous studies on the application of NPs in EOR experiments.

Polymers may be added to the injected water to increase its viscosity. Therefore, polymer flooding can be considered as one of the most prevalent chemical operations of EOR. The injection of polymer solutions will minimize water mobility, increase sweeping performance, and recover more oil (Ogolo et al. 2012). The primary polymers injected in chemical flooding include PAM, HPAM, xanthan gum, biopolymers (Zolfaghari et al. 2006; Hu et al. 2017).

7. Nanoparticles in oil recovery

Agi et al. (2019) synthesized crystalline starch NPs (CSNP) from plant and fruit extracts using weak ascorbic acid. The rheological formation of CSNP

Table 2. A summary of some studies for EOR processes using nanofluids

Seq.	Author	Method	Receiver rock	Scope of work
1	Agi et al. (2019)	Core flooding	Sandstone	Synthesizing crystalline starch nanoparticles from plant and fruits extracts and by using weak ascorbic acid and comparing the performance of manufactured NPs with native cassava starch and polymer xanthan
2	Aminzadeh Goharrizi (2013)	Core flooding	Boise sandstone	Multi-phase displacement experimental calculation of the sweep efficiency with NPs
3	Cheraghian et al. (2017)	Core flooding		Improvement of oil recovery through the application of TiO_2 polymeric nanofluid (PNF)
4	Assef et al. (2016)	Core flooding	Sandstone	Controlling the colloidal and porous media's interactions during low-salinity flooding of water and alkaline MgO NPs
5	Cheraghian et al. (2014)	Core flooding		Evaluating the addition of nano-clay to improve the rheology properties of polyacrylamide solutions used in enhanced oil recovery
6	Bagaria et al. (2013)	Chemical method		Weakly adsorbed nano-silica and Iron oxides NPs grafted in concentrated salt at high temperatures with sulfonated copolymers
7	Greff and Babadagli (2011)	Thermal		Nano-sized metal ion 's catalytic impact in asphalt molecules during heavy oil thermal recovery
8	Huang and Clark (2015)	Core flooding		Improvement of oil recovery with specified NPs through the control of migration from sources to reservoirs by flooding
9	Cieśliński and Krygier (2014)	Contact angle	Plates made of glass	Water–TiO_2, water–Al_2O_3, and water–Cu nanofluids increase critical heat flux
10	Ehtesabi et al. (2015)	Core flooding		Evaluating the deposition during transport in the core plug by TiO_2 NPs in the recovery of heavy oil
11	Kazemzadeh et al. (2015)	Interfacial tension		Impact of Fe_3O_4 nanoparticles on asphaltene precipitation during CO_2 injection
12	Hamedi-Shokrlu and Babadagli (2014)	Micromodel		Stabilization and interaction of nonmetal catalysts with an oleic phase during EOR in porous media
13	Zhang et al. (2010)	Emulsion		NP with stabilized emulsions applications in EOR
14	Mintsa et al. (2009)	Thermal		New thermal conductivity data for water-based nanofluids contingent on temperatures
15	Khalilinezhad et al. (2017)	Core flooding		Checking the influence on heavy oil recovery during the flooding of hydrophilic nanosilica
16	Li et al. (2013)	Adsorption and wettability	Berea sandstone	Influence of adsorption of nanosilica on Berea sandstone wettability index

(*continued*)

Table 2. Continued

Seq.	Author	Method	Receiver rock	Scope of work
17	Kjøniksen et al. (2008)	Chemical method		Modified polysaccharides application in EOR
18	Singh and Mohanty (2015)	Core flooding	Berea sandstone	The synergy between surfactants and NPs in foams stabilization for EOR
19	Shokrlu and Babadagli (2014)	Thermal		The reduction in viscosity of heavy oil and bitumen in aqueous and non-aqueous thermal applications by micro-nano metal particles
20	Skauge et al. (2010)	Core flooding	Berea sandstone	NPs for EOR
21	Zhang et al. (2014)		Berea sandstone	NP dispersions for EOR: mechanism and experiment with imbibition
22	Youssif et al. (2018)	Core flooding	Sandstone	Assessing the impact on oil recovery of nanosilica
23	Vafaei et al. (2008)	Contact angle	Glass and silicon wafers	NPs impact on contact angle through the sessile droplet method
24	Shamsi Jazeyi et al. (2014)	Chemical method		Coated NPs with polymer for EOR

performance was compared with native cassava starch (CS) and polymer xanthan. Three techniques were adopted in performing CSNP in extracting oil. These techniques include weak-acid hydrolysis, ultrasonic treatment, and nano-precipitation. These techniques were found satisfactory in producing polygonal and spherical NPs with an average diameter of 100 nm. The concentration, morphology, and surface charge of the solution are the main factors that affected the rheology of the system produced.

Their study stated that the viscosity of NPs solutions increases with the increase of NPs surface area and the increased temperature of CS and CSNP. In contrast, the viscosity of the solution decreases with the increased temperature of polymer xanthan. Figure 5 shows a TEM analysis for CSNP produced.

8. Prospects for efficient ASP and nano-fluid flooding

Since 2014, ASP flooding in Daqing Oilfield in China has officially started its commercial production and oil produced in 2015 was about 3.5 million tons. The quantity of oil produced by this technique was approximately 9% of total production for that oilfield. Despite that, ASP flooding has some limitations in field applications due to the large volumes of chemicals injected. The technical feasibility of ASP flooding depends mainly on the economical use of injected chemicals.

ASP flooding is applied after the reservoir has been water flooded or polymer flooded for a long time. Most oil reservoirs contain gas-phase trapped in between the rock's matrix. In areas where gas flaring is not allowed and no modern infrastructure deals with gas transportation, the

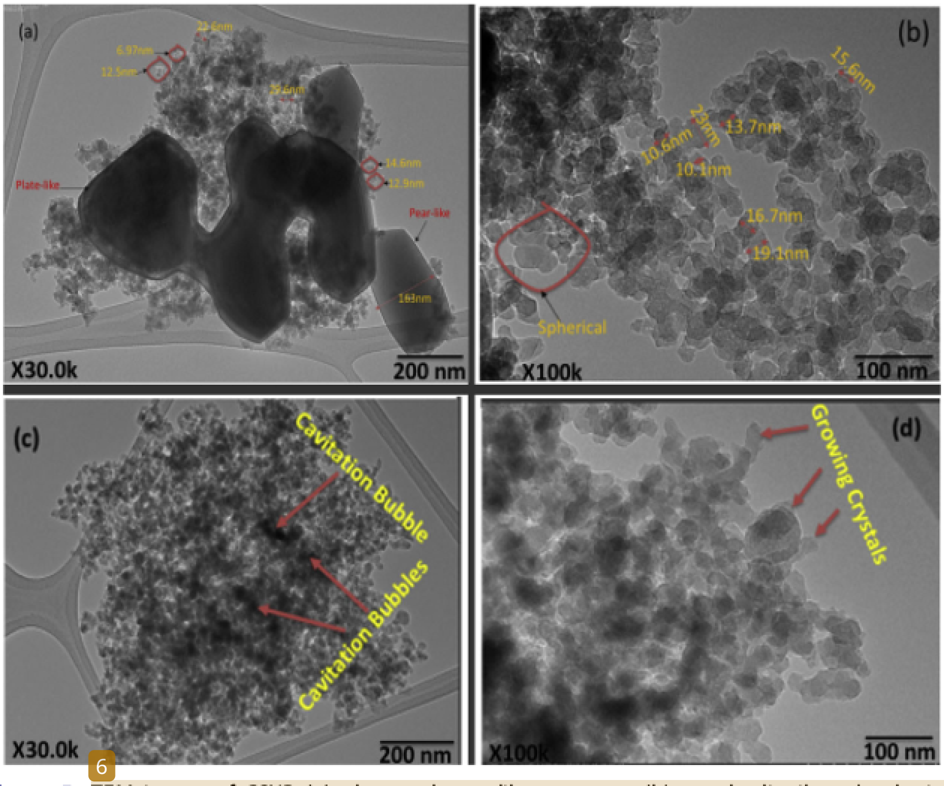


Figure 5. TEM image of CSNP (a) platy and pear-like structure, (b) evenly distributed spherical crystals, (c) nucleation due to cavitation bubbles, (d) secondary nucleation and crystal growth (Agi et al. 2019).

reinjection of the produced gas may be the final possible solution. Nonetheless, no precise data are available in the literature about the direct influence of in situ gas (trapped or continuous) on the performance of ASP flooding.

Low concentrations of alkali and surfactant is considered enough to achieve low interfacial tension between oil and water. From another aspect, ASP flooding is considered as an expensive operation, and an optimization approach has to be performed before commencing with the production operation. To maintain an economic operation, this is considered necessary to account for all controlling variables, including oil prices. Therefore, extensive laboratory floods, approximate numerical simulations, and pilot tests must be operated before moving to the commercial production level.

Although NPs floods have shown significant benefits in laboratory scale in extracting more oil, the drawbacks concerns cannot be ignored. One of these drawbacks is the high cost of manufacturing NPs and their compatibility to be operated under actual reservoir conditions. Generally, the synthesis and managing operation in EOR process can be costly and large injection volumes of NPs may be required. Besides that, each oilfield's

Table 3. Summary of reported nanofluids field trials

Used nanoparticles	Application	Location	Results	References
Aluminum oxide nano-silica	Inhibition and remediation of formation damage	Columbia	After 18 months of injecting aluminum oxide, the oil rate has increased by 300 bbl/day. Another trial using nano-silica resulted in an oil rate increase of 134 bbl/day.	Franco et al. (2017)
Carbon-based fluorescent nanoparticle named "A-Dots"	Evaluating the stability of nanoparticles in harsh formation environment as water injection tracers	Saudi Arabia	The results showed a high recovery percentage up to 86% suggesting their high stability.	Kanj et al. (2011), Kosynkin and Alaskar (2016)
Unnamed	Enhancing the mobility ratio of heavy oils	Columbia	An immediate increase in the oil production rate was observed along with a reduction of 11% in the basic sediment and water.	Zabala et al. (2016)
Unnamed	Stabilizing shale formation using water-based drilling fluid containing nanoparticles	Brazil	The results showed good performance in terms of shale hydration inhibition and wellbore stability. The same fluid was stored and used to drill another section in a different well after almost 3 months, which resulted in a 15% reduction in the well cost.	Barroso et al. (2018)

conditions and unique properties may not be suitable for certain NPs which in turn add, each oilfield's conditions and unique properties may not be suitable for specific NPs, which adds more challenges to this issue. High temperature and salinity conditions in some formations may decrease the efficacy of the NPs as these environments can be destructive for NPs structures. It is worth mentioning that only a few field trials have been reported in the literature. A summary of field trials for nanoparticles and nano-fluids are given in Table 3.

9. Conclusions

This study shed light on essential technologies involved in EOR processes: ASP and nano-fluid flooding. The recovery criteria depend on wettability alteration of the rock surface from oil-wet to water-wet and reduction in IFT between the oil and water phases. The increase in the macroscopic displacement efficiency and the decrease in mobility ratio between the water and the oil also significantly increase oil recovery. Despite that, ASP flooding has some limitations in field applications due to the large volumes of chemicals injected. The technical feasibility of ASP flooding depends mainly on the economical use of injected chemicals.

Nano-fluid flooding has been applied as a pilot process in some countries like China, Saudi Arabia, and Columbia and showed promising results in enhancing oil recovery. Many flooding experiments have revealed that NPs can reduce the IFT and the contact angle between the oil and rock surface. NPs are mixed with polymers, surfactants and alkalis to improve recovery and reduce chemicals in the injection stream. NPs suspension and its stability in any fluid are determined by the electrostatic repulsion forces between its material particles. If the repulsion forces are big enough, the suspended NPs become more stable and will not aggregate. The inclusion of NPs in chemical agents like polymer can significantly increase the recovery ratio.

Although NPs floods have shown significant benefits in laboratory scale in extracting more oil, the drawbacks concerns cannot be ignored. One of these drawbacks is the high cost of manufacturing NPs and their compatibility under natural reservoir conditions. It is found that nanoparticles are effective to recover at least 10% additional oil from sandstone cores. The right choice of nanoparticles in EOR operations also depends on the kind and nature of the oil reservoir being inspected. The future work of NPs applications should address the following gaps: the accurate capture of aging time of NPs in the base fluid and the exploring of balance between the rock surface and NPs charge while maintaining their effectiveness as interfacial tension modifiers.

Authorship contribution statement

Agus Arsad: Conceptualization, Resources, Supervision, Validation, Writing – review and editing, Visualization, Hasanain A. Al-Jaber: Conceptualization, Information and data collection, Formal analysis, Writing – original draft, Radzuan Junin: Supervision, Methodology, Project administration, Funding acquisition, Sulalit Bandyopadhyay: Supervision, Data curation, Writing – review and editing, Abdulmunem R. Abdulmunem: Formal analysis, Writing – review and editing, Investigation, Jeffrey Onuoma Oseh: Writing – review and editing, Data curation, Agi Augustine: Writing – review and editing, Resources, Muslim Darbi Abdurrahman: Funding acquisition, Evizal Abdul Kadir: Funding acquisition, Sharul Kamal Abdul Rahim: Funding acquisition.

Conflict of interest

The authors would like to declare that there is no potential conflict of interest during the preparation of this paper.

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Nomenclature

IFT	Interfacial tension, mN/m

Abbreviations

EOR	Enhanced oil recovery
ASP	Alkali–surfactant–polymer
SP	Surfactant polymer
NPs	Nanoparticles
OOIP	Original oil in place
HPAM	Partially hydrolyzed polyacrylamide PAMpolyacrylamide
PNF	Polymeric nano-fluid
SDS	Sodium dodecyl sulfate
SDBS	Sodium dodecyl benzene sulfonate
TEM	Transmission electron microscopy
CFD	Computational fluid dynamics
CSNP	Crystalline starch Nanoparticles
CSNF	Crystalline starch Nano-fluid
CS	Cassava starch

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