



# Nanoparticles as Depressurization and Augmented Injection Agents to Facilitate Low Permeability Reservoir Exploitation: Potentials and Risks

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## INTRODUCTION

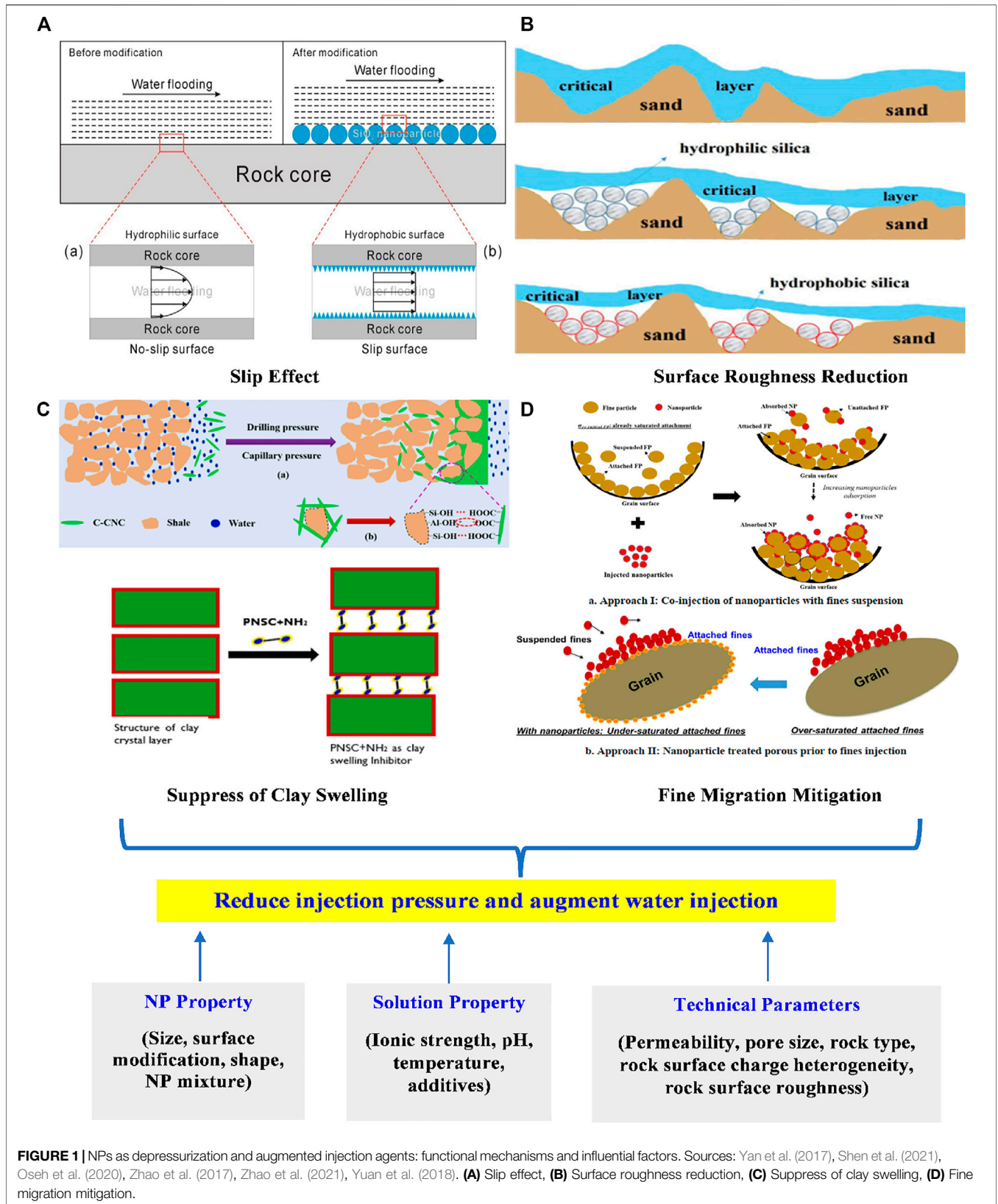
According to the recent report released by International Energy Agency (IEA), the global demand for energy would increase by 4.6% in year 2021. The proportion of proved low permeability oil/gas in total annual proved reserves is now around 70.0%, but the current average recovery is just 23.3%. Since the steady oil production could not be ensured in most mature reservoirs, effective development of low permeability reservoirs becomes the mainstay to mitigate the great gap between energy supply and consumption and also to ensure the national energy security (Hu et al., 2018; Xu et al., 2019; Li et al., 2021). Water flooding is the most popular energy supplement technology. However, due to the nature of narrow throats, poor connectivity, high clay content, etc., low-permeability reservoirs usually exhibit high injection pressure and insufficient injection volume. Traditional depressurization and augmented injection technologies such as acidizing/fracturing (Wang et al., 1999; Al-Harbi et al., 2006), surfactant and membrane technology (Qu et al., 2012) are either with short validity or complicate process design. The advances in nanoscience offer a new insight to mitigate the problems confronted with water injection in low/ultra-low permeability reservoirs.

Nanoparticles (NPs) are nanosized (1–100 nm) particles with high surface area, strong interfacial effect and prominent adsorption ability. According to Roco (2011a, 2011b), the overall market value of products concerning nanotechnology was about three trillion dollars by the year 2020. NPs are good depressurization and augmented injection agents with huge potential. This report reviews the opportunities and challenges of using NPs for depressurization and augmented injection based on what has been accomplished in both lab and the field. The driving forces and the influential factors that affect NP performance are analyzed to accelerate NPs selection, as shown in **Figure 1**. At last, the potential risks and possible solutions encountered by NPs are also discussed.

## FUNCTIONAL MECHANISMS

After long-time water washing and immersion, the porous media surround the wellbore become more water-wet, resulting in thicker water films and narrower water flowing paths. NPs function through multiple mechanisms. The admitted ones include,

**Wettability Alteration and Slip Effect:** Hydrophobic NPs can form stable hydrophobic films on pore surfaces, replace the hydration layer, expand the flowable path, increase water relative permeability and decrease the flow resistance, thereafter, the high injection pressure problem can be resolved (Wang et al., 2018). Furthermore, hydrophobic surfaces demonstrate impressive



**FIGURE 1** | NPs as depressurization and augmented injection agents: functional mechanisms and influential factors. Sources: Yan et al. (2017), Shen et al. (2021), Oseh et al. (2020), Zhao et al. (2017), Zhao et al. (2021), Yuan et al. (2018). (A) Slip effect, (B) Surface roughness reduction, (C) Suppress of clay swelling, (D) Fine migration mitigation.

drag reduction effect which is beneficial to induce a larger pressure drop. In Wuqi Oilfield, polysilicon adsorption decreased the thickness of water film, and the effective porosity increased from 22.22 to 37.14% (Qi, 2014). Moreover, acidification pretreatment is conducive to NPs performance, with which effective water permeability increases by 458.3%, comparing to that of 160.0% without pretreatment (Liu et al., 2019).

**Clay Swell Suppression:** The volume of clay minerals could increase by up to 20 times when water layers are inserted, leading to decreased pore/throat size and increased water injection pressure especially in tight and low permeability reservoirs (Amorim et al., 2007). Hu et al. (2020) indicated that with a clay anti-swelling rate of 42.0%, the subsequent water injection pressure in tight sandstone reduced by 23.0%. By forming a water-resisting layer or narrowing down the interspaces between clay platelets, adsorbed NPs can reduce the clay swelling index by 1.1–3.2 times, comparing to that of 0.42–0.66 times with potassium chloride solution.

**Fine Migration Mitigation:** Fine migration during water injection causes permeability impairment and poses a great threat to the subsequent water injection. NPs with high surfaces areas can easily adsorb on migrating fines or rocks. NP on migrating fines reduces the repulsive forces between modified fines and rocks, while NP on rocks decreases surfaces energy, enhances heterogeneities and increases the adhesion forces. Yuan et al. (2018) indicated that NPs adsorb on pore surfaces is better preferred to control fine migration than NPs adsorb on migrating fines. Zhao et al. (2021) found that the fine control efficiency of Al<sub>2</sub>O<sub>3</sub>-treated porous media was over 60%, and the injection pressure dropped by 33.3% at an ionic strength (IS) of 500 mmol/L.

**Surface Roughness Reduction:** Rock surface roughness has a significant impact on phase distribution and fluid flow pattern (Cousins et al., 2018; Yi et al., 2019). Generally, an increase in rock surface roughness increases two-phase interference and flow resistance. By occupying the spaces between sands, NP adsorption can effectively decrease rock roughness and thickness of water film, therefore, to reduce the flow resistance and augment water injection. With a NP concentration of 0.15 wt %, the surface roughness reduced by 16.67% and the pressure decreased by around 17.0% (Zhao et al., 2017).

## INFLUENTIAL FACTORS

NPs performance as depressurization and augmented injection agents highly depends on their retention in porous media, and any factors that affect NP transportation and adsorption behaviors would have an impact. Possible influential factors may include,

**NP Properties:** NP properties influences the rock-NP interactions and impose impacts on NP transportation and retention. He et al. (2019) found that NP retention in saturated porous media increased with decreasing NP concentration and increasing NP size, but Wang et al. (2012) and O'Carroll et al. (2013) believed that the more intensive

Brownian movement and higher collision probability of smaller particles might reduce the trap possibility. In addition, when different NPs are mixed, behaviors may change. For instance, TiO<sub>2</sub> could significantly increase GO retention at varying NaCl and CaCl<sub>2</sub> cases (Zhang et al., 2017; Xia et al., 2019).

**Solution Properties:** NP stability has a close relationship with NP mobility. In general, more NPs could be recovered with higher repulsion between NPs and rocks. An increase in IS will promote particle aggregation and weaken the repulsion, thereafter, result in a considerable reduction of recovered NPs. For example, TiO<sub>2</sub> recovery rates in distilled water, 500 mM NaCl and 10 mM MgCl<sub>2</sub> were 72.2%, 17.6 and 26.1%, respectively. Changes in solution pH also has similar impacts. The impacts of temperature are IS-dependent, but NPs retention generally increases at higher temperatures (Bayat et al., 2014).

**Reservoir Properties:** NPs are selective to reservoir permeability. If the permeability is too high, NP adsorption may show a noticeable decrease. While when the permeability is too low, NPs may hardly enter into the narrow pores to take effect. When particle size (*d*) is larger than 0.59 times of the pore throat size (*D*), pore throat clogging would occur, when  $d < 0.59 D$ , individual particle would easily pass through the pores and possibly deposit on rock surfaces. When *d* is far smaller than *D*, for example  $d/D < 0.01$ , the interactions between particles and porous media can be neglected (Feng et al., 2020). In general, NPs show higher adsorption on heterogeneous tight porous media with opposite charge. For instance, SiO<sub>2</sub> NPs tend to adsorb on limestone instead of sandstone, while TiO<sub>2</sub> NPs prefer to adsorb on sandstone rather than on limestone. In Yu's case (Yu et al., 2012), NPs recovered from 33 mD sandstone, 57.6 mD sandstone and 132 mD limestone 5.29 mD dolomite were 23.0%, 86.0 and 32.6%, respectively. The influences of rock surface roughness are still controversial. Bayat et al. (2014) believed that NPs may easily trapped by irregular dents and bumps, but Zhou et al. (2021) and Suri et al. (2020) suggested that the increases in energy loss, turbulence might promote NP migration in fracture center rather than deposition in grooves.

**Technological Parameters:** Increases in NP dosage and injection volume give different results. Phenrat et al. (2009) found the impacts of NP dosage were negligible, Feng et al. (2020) stated NP retention increased, and Sun et al. (2015) reported increased NP mobility thanks to the faster occupation of attachment sites. A rise in flow rate also demonstrates different impacts, either accelerate the particle bridging or wash away the reversibly and loosely attached NPs.

## POTENTIAL RISKS AND POSSIBLE SOLUTIONS

The potential of NPs as depressurization and augmented injection agents is huge, but there are also some risks confronted with this treatment. Such as,

**Pore Plugging:** NP adsorption not only produces slip effects, but also narrows the flowing channels. NP blocking takes place when NP diameter is larger than the size of pore throats or when NP aggregation/bridging occurs. The performance of NP

formulas highly depends on the net effects and the change in effective permeability. Synthesis of smaller NPs such as silicon dots and carbon dots (Rao et al., 2018; Zhou et al., 2020) may be a feasible solution.

**Involvement of Organic Solvents:** Hydrophobic NPs demonstrate excellent pressure reduction capability by generating slip effect. However, NPs alone can hardly be dispersed in water if no other additives are introduced, so organic solvents are required. The usage of organic solvents not only increases the cost, but also leads to environmental pollution. Two possible methods to reduce the risks are 1) apply dispersants, such as surfactants, 2) develop Janus, responsive and amphiphilic NPs.

**Conditions Applicable:** Limited by NP stability or severe NP aggregation/retention, Feng et al. (2020) claimed that the calcium and magnesium ions in injection water should be no higher than 300 mg/L. Given the fact that many oilfields worldwide are featured by high temperature and high salinity with huge amounts of multivalent cations, developing NPs with good salt and temperature tolerance is of crucial importance. To cater for the requirements of high salinity and high temperature conditions, endow NPs with steric repulsion is the key, verified NP surface modifiers are zwitterionic polyelectrolyte, copolymers, highly soluble silanes, etc.

**Material Cost and Safety:** At the present stage, the investment for NP manipulation and fabrication is relatively high than conventional materials, therefore, increasing NP performance is necessary and important to reduce the required dosage and the cost. In addition, the adverse impacts of NPs on human beings as well as the environment are still unclear. From the perspective of diffusivity, we highly suggest using NP dispersion instead of NP powder in daily experiment to minimize the risks. A comprehensive study concerning NP safety is required and a

well-defined protocol involving materials, engineering, humanity and the environment should be defined.

## CONCLUSION

NPs functioned through different mechanisms including wettability alteration and slip effect, clay swell suppression, fine migration mitigation and surface roughness reduction. A comprehensive understanding of NPs transportation in wellbores and subsurface porous media is essential for successful NP applications, and the performance of NPs for depressurization and augmented injection highly depends on their transportation and retention in complex underground porous media. However, NP applications may confront with the risks of pore plugging, usage of organic solvents, low NP stability, etc. Possible solutions to mitigate these risks are developing novel small, and highly stable responsive/amphiphilic/Janus NPs, construct surfactant-NP augmented systems, etc.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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