Environmental effects of enhanced oil recovery methods

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Journal of Advanced Environmental Research and Technology

Vol. 1, No.1
page 39-48 ,winter 2023
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Received 5 November 2022
Accepted 18 February 2023

Abstract

Nowadays, application of enhanced oil recovery methods has increased; therefore it's necessary to determine their impacts on environment and human life. So, this research investigates the environmental impacts of conventional enhanced oil recovery methods and new methods such as using electromagnetic waves, ultrasound waves, and nanoparticles. The investigations show that electromagnetic waves and ultrasound can effectively remove many environmental pollutants. Characteristics of the wave and the type of formation determine that these waves have different effects on the formation, and efforts should be made to understand these effects to prevent damage to the formation. Nanoparticles can also reduce the quantity of pollutants in the environment. According to the mechanisms of entrapment of nanoparticles in the porous medium, they may remain in the reservoir and find their way to the underground water over time, so their environmental effects should be considered in the long term. A better knowledge of new methods of increasing oil extraction will lead to the identification and use of more suitable methods with less environmental effects (compared to conventional methods).

key words

environmental effects

enhancing oil recovery

heavy oil upgrading

electromagnetic waves

ultrasound waves

nanoparticles

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[DOI: 10.22034/jaert.1.1.39]

1. Introduction

Nowadays, energy production is one of the most critical issues in the world. With the advancement of technology, in addition to fossil fuels, other sources of energy production have also been used, and the amount of energy from fossil fuels has decreased in recent years. However, a large part of the energy needed in the world is still provided through fossil fuels and mainly from crude oil. On the other hand, considering the decrease of light crude oil resources, it is necessary to use more heavy and extra heavy oil reservoirs. The use of heavy crude oil is not desirable due to its high viscosity and high amounts of sulfur, heavy metals, and nitrogen. For this reason, many heavy crude oil reservoirs have remained untouched. The high viscosity of heavy oil causes friction between the oil and the reservoir's wall and pipe, resulting in a pressure drop in the pipe and transmission lines. As a result, due to the low driving force in heavy oil reservoirs to overcome the pressure drop induced by the high viscosity of the fluid, the recovery factors in such reservoirs are deficient, and oil transmission would be associated with some problems and difficulties [1]. Heavy oil recovery is more complicated than conventional oil reservoirs due to the inherent characteristics of these reservoirs, such as very high viscosity, low oil mobility, high ratio of carbon to hydrogen, and a high number of heteroatoms [2]. So far, heat recovery methods such as thermal EOR methods, including steam flooding, cyclic steam stimulation, In-situ combustion and steam assisted gravity drainage have been used. Although these methods are technically successful, there are still economic and environmental challenges because they are expensive and emit many greenhouse gases, such as carbon dioxide, into the environment. The abovementioned obstacles have all become a driving force for a better solution for oil recovery in these reservoirs [2]. The use of new methods of enhancing oil recovery, such as electromagnetic and ultrasound heating, could warm the oil, decrease viscosity, improve its physical properties and upgrade the quality. Heavy oil has a low ability to absorb these waves, so the use of nanoparticles improves this process and absorbs these waves. On the other hand, there is evidence that the combination of ultrasonic methods and catalytic nanoparticles due to the cavitation phenomena and the combination of catalytic nanoparticles and electromagnetic wave radiation increases electromagnetic heating and the efficiency of nanocatalysts [3],[4]. Enhancing oil recovery and heavy oil upgrading through the simultaneous using waves and nanocatalysts or nanoparticles has the advantages of thermal recovery and in-situ upgrading. Furthermore, these approaches are economical and environmentally friendly since, in this research, the effects of these processes have been investigated. In general, the various methods of enhancing oil recovery should have the least adverse environmental effects. Also, these methods do not endanger the ability of future generations to meet their needs, so evaluating the environmental effects of various processes of enhancing oil recovery before and after accomplishing them is critical. The various parameters examined in assessing environmental effects are shown in Figure 1. Since many aspects of these methods have not been fully investigated, investigating environmental effects is needed for a more reasonable and practical understanding of these processes. Therefore, this research investigates the environmental effects of current enhancing oil recovery processes [4 -5].

Therefore, the environmental effects of conventional methods of enhanced oil recovery are briefly and usefully discussed. Then the environmental effects of new techniques for enhancing oil recovery are discussed and investigated. The methodology of environmental impact assessment of enhanced oil recovery methods in this research is depicted in Figure 2.

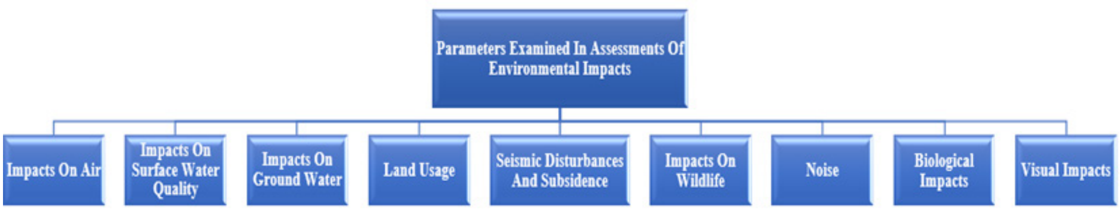

Figure1-The parameters examined in the assessment of environmental effects

1.1. Environmental effects of conventional methods of enhancing oil recovery

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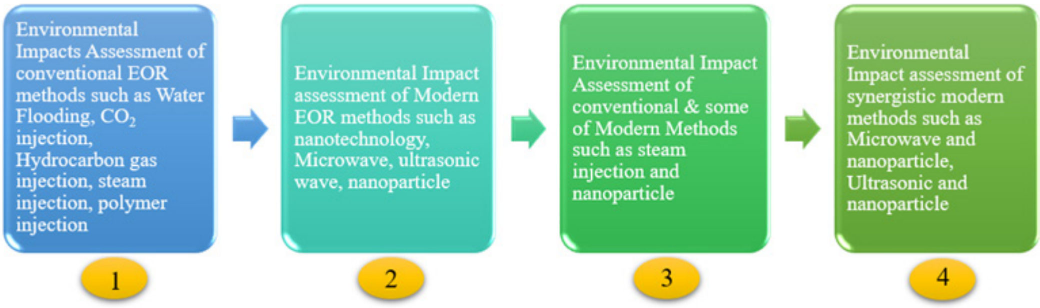

Figure2- The methodology of environmental impact assessment of enhanced oil recovery methods

- Water Flooding

The first environmental effect of water flooding is the risks caused by corrosion and leakage; of course, these risks are attending in all recovery processes. As a result of this process, large amounts of water are produced and consumed; the produced water needs to be treated and handled. Storage of this water has little safety, and its treatment or purification for other uses is often expensive. This amount of water could later cause more pollution, especially on the earth's surface. Also, this process is caused to sinkhole formation and the collapse of some formations due to water movement through the water wells; an example of the formation of this sinkholes has been observed in West Texas [7].

-Immiscible CO_2 injection

When CO_2 reacts with water in oil formations, it produces carbonic acid, lowering the formation's pH and creating a corrosive environment that can increase the risk of subsurface issues such as leaks and blowouts. Also, the blowout can create more leakage paths to subsurface water. In addition, the built acidic environment (with low pH) can cause the irritation and dissolution of some rare and polluting elements such as barium, calcium, chromium, strontium, and iron in the underground and produce hydrogen sulfide. It is a very toxic gas that may be present in the reservoir before injecting CO_2. If there is a leak, there is a possibility of its release, and it can cause underground water pollution and even the death of people in the oil well derrick [7]. The explosion in the injection well causes the release of CO_2 into the air. The release of this gas and air pollution can harm wild animals and people in that area. In 2011, a 37-day-long explosion at Tinsley Field, Mississippi, poisoned the oil field workers and choked animals in the area. In addition to the mentioned cases, explosions near the surface can cause environmental pollution due to the entrance of production fluids, oil, and drilling mud to the surface. As a result of the Tinsley Field explosion, Danbury Resources Company was forced to clean 27,000 tons of contaminated soil and 32,000 barrels of liquid from the environment [7].

- Thermal method (steam injection)

The most significant environmental effect of the thermal method of enhancing oil recovery could be the consumption of a considerable amount of energy and fuel to produce and refine a relatively small amount of oil. However, recently solar energy has been utilized in some thermal processes to reduce fossil fuel consumption in steam injection. However, the energy consumption of this approach is still elevated. Like other recovery methods, this method also has the risk of corrosion and destruction, which can cause the well to fail and eventually leak and explode. Since some formations may contain more acidic compounds, the risk of corrosion and hydrogen sulfide production depends on the location of the well compared to the CO_2 injection method. The high temperature of the injected steam causes additional pressure on the wells, so the wells must be built to resist temperature-related destruction. Construction is the most critical factor in preventing leakage and explosion in enhancing oil recovery. A miserable example of safety issues and surface contamination from a blowout during the thermal recovery process occurred in June 2011 in California's oldest oil field[7].

- Thermal method (in situ combustions)

In the in-situ combustion method and during the combustion process at high temperatures, water-soluble secondary chemical compounds (for example, metals and metal oxides) are formed. Excessive heating of sand can cause corrosion in wall of pipes and fluid leakage. Also, it's difficult to remove produced water with acidic properties and containing petroleum and pollutant metals. In short, the possibility of groundwater pollution in

[DOI: 10.22034/jaert.1.1.39]

enhancing oil recovery, particularly in areas where underground water is the primary source of water production, should be considered [5].

2. Environmental effects of the method of enhancing oil recovery by electromagnetic waves

Electromagnetic waves include very low frequency, low frequency, radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays [9]. Bara and Babadagli, (2015) stated that in this method, fewer greenhouse gases are emitted compared to other methods of steam-based oil recovery. Also, less water is needed than the steam injection method, so it is more acceptable from an environmental issue. Microwave waves can cause the destruction of bacteria in the soil and reservoir areas affected by the waves [10]. Microwave heating is used to clean environments contaminated with volatile organic compounds (such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenols, etc.). Volatile organic compounds are converted into lighter and more volatile compounds during microwave radiation and can be removed from the environment or contaminated soil. In this process, the temperature increase causes the pollutants to enter the vapor phase and exit the soil [11]. The results of the research of Falciglia et al., (2017). show that the removal rate of PAH pollutants in microwave heating with 1000 W and time irradiation over 10 minutes is about 70-100%. The four primary effective mechanisms in removing PAHs are thermal desorption, molecular bond cracking, selective thermal evaporation, and removal of contaminants due to steam distillation processes, which are presented in Figure 3. Selective heating occurs when soil and pollutants convert the absorbed microwave energy into heat due to their different dielectric properties. Generally, the solubility of organic compounds in the water rises with increasing temperature. At the same time, water vapor can modify the soil structure and increase its porosity, which is favorable for pollutant mass transfer. Moreover, the more significant difference between pollutant boiling point and soil temperature caused the more significant effect of pollutant polarity in selective heating on pollutant removal efficiency. Finally, considering the adequate removal of pollutants in wet soil samples (10%) compared to dry soil samples, it can be said that water significantly increases the effectiveness of soil cleaning due to distillation and the removal of pollution [12].

Some ionizing waves, such as X-rays and gamma waves contain a level of electromagnetic energy that could destroy the atoms and molecules in the body's organs and change the chemical reactions inside the body. During that, the molecules are partially or completely converted into ions. These waves could cause damage to the human body. Non-ionizing waves include the range of low frequencies in the spectrum of electromagnetic waves. In this category of waves, the energy of electromagnetic waves is less than the amount that can leave effects on atomic levels, but these waves can only create thermal effects.

Typical sources producing these waves usually do not have enough energy to damage human tissues. However, at higher power waves that occur in high-voltage power and transmitters, there is a possibility that they could have long-term effects on human health. Some researchers have stated that exposure to non-ionizing waves with high power density can cause risks such as cancer, tumor, headache, fatigue, Alzheimer's, and Parkinson's disease. However, until now, researchers have not discussed the effects of long-term exposure. Exposure to non-ionizing radiation is not

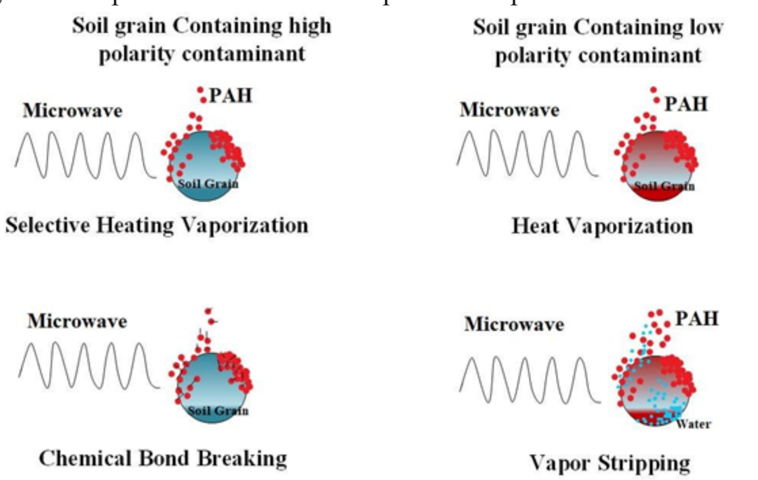

Figure 3- Mechanisms for removing polycyclic aromatic hydrocarbons from soil

[DOI: 10.22034/jaert.1.1.39]

safe. Radio waves cover waves with a frequency of 30-300 GHz. These waves can heat human body tissue, and in case of prolonged exposure, they may cause damage to body tissues. Also, there is a possibility that injuries such as skin burns, deep burns, heat exhaustion, and heatstroke may occur. The eye is also vulnerable to these waves because the lack of blood flow to cool the cornea can lead to cataracts [9].

Researchers have also investigated the impact of microwave heating on different minerals and formations. Wang et al., (2016). investigated the effects of microwave heating on tight sandstone. The results revealed that depending on dielectric properties, the temperature of tight sandstone could rise to 400°C. Thermal expansion gradient and water loss in clays could cause fractures and increase permeability and porosity. Furthermore, Calcite and Feldspar disappeared as the primary cement in sandstone [13].

Zhu et al., (2018). indicated that microwave heating could develop the pore structure of oil shales through Kerogen decomposition, jet flow pressure, evaporation of volatile material, and thermal stress depending on the output power and irradiation time [14]. Hu et al., (2018), examined the effects of microwave heating with an output power of 1000w and irradiation time of 3 minutes on different formations, including tight sandstone, sandstone, shale, and carbonate. The results indicate that the shales have higher temperatures due to the high pyrite, clay, and organic material content. Microwave heating could cause an increase in shale flow ability, and shales could crumble into pieces under microwave heating, while the impacts of microwave heating on other samples were negligible. In addition, the pores of shale could be enlarged due to clay shrinkage. Bitumens could block pores of shales with low thermal maturity under microwave heating. Microwave heating has negligible influence on sandstone and carbonate samples because their main components, including quartz and Calcite, are transparent to microwave heating. In tight sandstones, evaporating of water and pore enlargement could cause fractures [15]. Furthermore, the results of Lu et al., (2017). experiments on different minerals revealed that the zones of Ferrum rich could absorb more microwave heating and have more temperature rise [16].

3. Environmental impacts of the method of enhancing oil recovery by ultrasonic waves

Ultrasonic waves are the form of energy generated via a longitudinal mechanical wave with a frequency higher than 20 KHz and are classified into low frequency (20 KHz – 1 MHz) and high frequency (above 1 MHz) [17]. Ultrasonic technology is a clean and green technique for degrading organic pollutants and could remove persistent organic pollutants, petroleum hydrocarbons, and heavy metals from the soil. The investigations demonstrated that the ultrasonic technique is most useful when utilized with other techniques, such as Electrokinetic Remediation and soil washing. Ultrasonic irradiation in several mechanisms based on acoustic cavitation could cause inactive microorganisms in water [18]. The ultrasonic wave could also be used effectively in oil well cleaning, removing or preventing asphaltene deposition in the porous medium, removing formation damages caused by drilling and completion fluids, etc. [19].

Wag et al., (2020). investigated the impacts of ultrasonic waves on cores. They observed that ultrasonic waves could improve the cores' permeability depending on the wave's frequency and power. However, formation damage could also occur in wave frequencies above 40 KHz [20]. Ghamartale et al., (2019). investigated the effects of an ultrasonic wave with a frequency of 20 kHz and power of 300 W for 1 minute (7 seconds and 3 minutes pause) to investigate the impact of ultrasonic wave on flow behavior and pore structure. The Scanning Electron Microscope (SEM) results showed that ultrasonic waves could alter rock morphology by causing microfractures and separating rock particles. Creating microfractures could result in permeability increment, while particle separation could increase or decrease permeability. In Dolomite samples, ultrasonic waves cannot cause fracture propagation and permeability increment because of their heterogeneity, crystalline, and compact texture. In other words, if microfractures were created, it could not result in effective permeability due to high heterogeneity and unsuitable connection. Also, due to their brittle texture, ultrasonic waves could have more substantial effects in Limestone samples than in dolomite samples. Furthermore, existing sand and Lithic as loose elements in these rock samples could cause acceptable migration, while ultrasonic irradiation can result in pore throat plugging and permeability reduction [21].

4. Environmental impacts of the method of enhancing oil recovery by nanoparticles

Nanoparticles due to their small sizes in the na-

[DOI: 10.22034/jaert.1.1.39]

noscale could penetrate the reservoir and interact with oil molecules and decompose them into smaller and lighter molecules. They can also have interactions with rock surfaces and fluid, and consequently alter some of their properties including heat conductivity, density, surface tension reduction, wettability, and specific heat improvement and demulsification [22]. The high surface-to-volume ratio of nanoparticles and their reactivity enabled them to remove heavy metals, colors, organochlorines, organophosphorus, volatile organic materials, bacteria, viruses from the environment. Some of the nanoparticles such as Carbon nanotubes, ZVI nanoparticles, and Silver nanoparticles could be utilized for water treatment. Besides, nanoparticles such as Zinc Oxide, Titanium Oxide, and Tungsten Oxide can be applied as a photocatalyst, and change organic pollutants into harmless materials. Nanoparticles can also remove oil leakages from water and remove toxic gases from the air [23].

The interactions between the injected nanoparticles and reservoir pore throat walls or between nanoparticles could cause considerable retention of nanoparticles in a porous medium and finally result in wettability alteration of the rock surface and permeability reduction. Some metal nanoparticles due to larger sizes in comparison with the pore throats might plug the pore throats (Mechanical plugging). The main mechanism of interaction between nanoparticles and porous medium is surface deposition and plugging by nanoparticles (mono-particle or multi-particles). This mechanism mainly depends on the surface charge and roughness of the rock or porous medium, the surface charge of nanoparticles, nanoparticle size to pore size ratio (separation distance), nanoparticle concentration, and salinity, temperature, and injection rate [24].. Figure 4 depicts different interactions between nanoparticles and porous medium during the flow of nanoparticles in the porous medium.

Guo et al., (2016). showed that in-situ catalysts combined with thermal injection methods could result in the reduction of environmental impacts on oil production. Besides, Hashemi et al., (2014). revealed that when metal nanoparticles are added to thermal injection methods, greenhouse gases release especially CO_2 reduces to 50% compared with the case without nanoparticles. However, in the same process, the production of total gases such as CO_2, CO, H_2S, and hydrocarbon gases are doubled in the presence of nanoparticles indicating that more H2S might have been produced [2]. Montgomery et al., (2015). showed that H2S production only occurs within a special temperature and pressure window, in other words, H2S production could be minimal if the process was controlled within a specific operating window [2]. Despite the positive environmental impacts of nanoparticles, their toxicity should be determined. The toxicity of nanoparticles depends on different parameters including source, dose, dimension, durability, mass, number, surface area, size, surface chemistry, aggregation of nanoparticles, aspect ratio, surface-coating, and function [25]. To construct a more helpful comparison and create a more proper arrangement between the new methods and the conventional methods of enhancing oil recovery, according to the research conducted and the classification of the resulting information was done. This dialogue is presented in Table 1.

5.Challenges & future work

There are several fundamental issues associated with the environmental impacts of enhanced oil recovery methods that need to be addressed in the future:

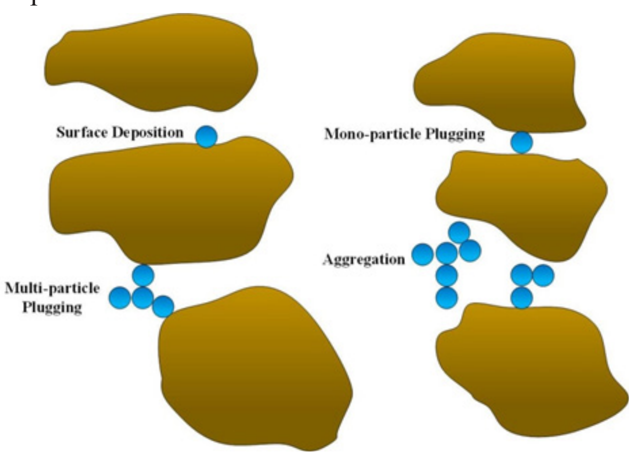

Figure 4- Different interactions between nanoparticles and porous medium

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Table 1 – Comparison between environmental impacts of conventional enhanced oil recovery methods and new methods[8].

Main Environmental impacts	Water Flooding	Substance injection (steam, polymer, CO_2 or Hydrocarbon gas)	Ultrasonic irradiation	Microwave irradiation	Nanoparticle
Impact on air	Emissions of SO2, NOx and dust from the equipment and vehicles used to clean, pressurize and inject water, Emissions of CO2 from the equipment used to pressurize and clean injection water.	Emissions of SO_2, NOx and dust from the equipment and vehicles used to transport, pressurize and injection substances (and/or heat steam).	Ultrasonic enhanced oil recovery method has less negative impact on air quality	less emission of greenhouse gases in comparison with the steam injection as thermal enhanced oil recovery method and other conventional EOR methods.	- Could result in reduction in greenhouse gases when it used steam based EOR methods.
Impact on water resources	Consuming large amount water	Chemicals penetrating subsurface and groundwater due to the proximity of the wellbore to groundwater. Polymers and gases are often injected alongside water, additionally, steam is produced using local water resources, which causes a slight risk of consuming local water resources.	Ultrasonic irradiation has no negative impact on water resource, - It can cause inactive microorganism in water in several mechanisms based on acoustic cavitation. - Consuming less amount water.	-Consuming less water in comparison with steam injection method. -Microwave irradiation could remove some of pollutants in water resourced based on wave characteristics and distance from wave source.	-consuming amount water in case of nanoparticle flooding -It could have negative impact on water resources in case of reaching to water resource. So it›s necessary to determine their toxicity.
Land usage	Increased land take resulting from the need to store water/demineralization equipment in addition to the equipment required for pressurization, injection and injection wells.	Increased land take resulting from the need to store water /demineralization equipment in addition to the equipment required for pressurization, injection and injection wells.	increased land take resulting from the need to install equipment required to irradiate ultrasonic wave	Increased land take resulting from the need to install equipment required to irradiate microwave	Increased land take resulting from the need to install equipment required to inject nanoparticle with fluid
Visual impacts	Visual impact due to physical presence of water storage and injection equipment	Visual impact due to physical presence of fluid storage and injection equipment	Visual impact due to physical presence of equipment for irradiation of ultrasonic wave	Visual impact due to physical presence of equipment for irradiation of microwave	Visual impact due to physical presence of equipment for injection of nanoparticles with fluid
Seismic disturbance and subsidence	Small risk of induced seismicity from the pressures applied during injection	Small risk of induced seismicity from the pressures applied during injection	Laboratory results showed that ultrasonic waves could cause micro fracture propagation and expansion based on wave characteristics and formation type. However, there is small risk of induced seismicity	Laboratory results showed that microwave irradiation could cause micro fracture propagation and expansion based on wave characteristics and formation type. However, there is small risk of induced seismicity	Small risk of induced seismicity from the pressures applied during injection
Noise	Noise resulting from equipment used to pressurize and inject the water	Noise resulting from equipment used to pressurize and inject the substance	noise generated from related equipment	noise generated from related equipment	Noise resulting from equipment used to pressurize and inject the fluid and nanoparticle

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* It is essential to conduct more investigations on the simultaneous impacts of nanoparticles and electromagnetic or ultrasonic waves on the environment in different aspects including the numeral of greenhouse gases released, removing pollutants from the environment, retention of nanoparticles in the porous medium, and impacts of electromagnetic and ultrasonic waves on the formation in the presence of nanoparticles.

* It is also necessary to prepare comprehensive information on the toxicity and non-toxicity of nanoparticles. Furthermore, it's important to do more studies on the environmental impacts of conventional EOR methods and novel EOR methods such as adding nanoparticles to steam-based methods, water flooding, gas injection, etc.

6- Conclusion

According to the novelty of the new approach of heavy oil upgrading and enhanced oil recovery such as electromagnetic waves, Ultrasonic waves, and nanoparticles, there are still undiscovered performances of the mentioned methods and it's necessary to determine their environmental impacts.

Based on the studies it can be deduced that:

1- Novel enhanced oil recovery methods seem to be more eco-friendly and have fewer negative environmental impacts.

2- Impacts of electromagnetic and ultrasonic waves on different formations depending on the formation type and wave characteristics could result in improvement or deterioration of formation quality.

3- A combination of novel EOR methods with conventional methods may result in a decrease in the negative environmental impacts of conventional EOR methods. For example, adding metal nanoparticles to steam-based EOR methods could result in a reduction in CO_2 production compared with the case without nanoparticles. However, it is necessary to do more investigations into the simultaneous impacts of novel and conventional EOR methods on the environment.

4- Based on the different Mechanisms of retention of nanoparticles in the porous medium, nanoparticles could remain in pores and reach the ground waters. Furthermore, nanoparticles could enter the human body while operations, therefore it's essential to determine their environmental impacts in the long term, their toxicity, and their non-toxicity.

5- It is possible for the nanoparticles used to stick to the formation of the reservoirs and get trapped in some holes. Therefore, the optimal amount of nanoparticles to enhance oil recovery and also prevent damage to the formation should be taken into consideration.

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[DOI: 10.22034/jaert.1.1.39]