STEPHY Publishers

Trends in Petroleum Engineering

Review Article

ISSN: 2771-2494

The Impact of Electromagnetic Waves Propagation to the Dielectric Nanoparticles on Crude Oil Interfacial Tension Reduction for Oil Recovery: A Review

Yarima Mudassir Hassan,[1]* Beh Hoe Guan,[2] Lee Kean Chuan[2]

[1]Faculty of Computing and Sciences, Azman University Kano, Nigeria

[2]Department of Fundamental and Applied Sciences, Universiti Teknologi Petronas, Malaysia

Abstract

The presence of interfacial tension (IFT) force between crude oil and other fluids in reservoirs is one of the critical parameters that restrict the effective mobility of the oil and is continuously entrapped in reservoir pores. Reducing binding forces between oil and such fluids is one of the methods employed to improve oil productivity known as enhanced oil recovery (EOR). Various nanoparticles (NPs) have been utilized to reduce IFT. However, NPs encountered a challenge in terms of successful operation under a high temperature. Consequently, the NPs tend to segregate at the oil/water interface which diminishes the IFT influences and more oil continuously entrapped. Recently, an innovative approach to enhance oil mobility was proposed by activating the charges of the NPs via electromagnetic (EM) wave propagation. Few analyses were reported using dielectric NPs with reasonable reductions to IFT. The dielectric properties of NPs are essential attributes corresponding to EM waves. During the EM wave exposure, the extra disruptions were generated at the fluid/oil interface that function as activating agents for the NPs resulting in the additional reduction for IFT. The present study provides a comprehensive review of the few results available, challenges that confronted the success of this novel approach, and admirable recommendations to improve the process in the future.

Keywords: EM waves, Dielectric nanoparticles, Interfacial tension (IFT)

Introduction

One of the major sources of global energy production is crude oil extraction.[1-3] Regrettably, oil reservoirs around the world are suffering from persistent entrapment of crude oil within reservoir rock holes, and more than 70 % of the crude oil across the globe cannot be recovered.[2] Oil removal from reservoirs was formerly accomplished by using primary and secondary recovery technologies. The primary approach entails oil extraction from the reservoir using the crude oil's natural mobility without employing external equipment to improve oil mobility. Nevertheless, in certain situations, the primary recovery was artificially boosted by adding rod pumps to increase pressure within the reservoir. Only 15 % of the residual oil could be extracted using this procedure. Subsequently, a secondary recovery method was implemented by injecting gas or flooding the reservoir with water to maintain reservoir pressure and increase crude oil mobility. More oil was examined to be recovered superior to the primary methods. However, additional obstacles to oil mobility still exist in such a manner that 55 to 70% of the oil cannot be recovered using a secondary method due to the high viscosity of the crude oil and low viscosity of the injected fluids. Thus, less viscous fluids like water cannot displace a plentiful amount of crude oil, it could rather slide beyond the oil front which resulted in fingering and diminishing the recovery factor.[1] Meanwhile, the EOR method was invented to alleviate the problem and increase oil production. EOR is categorized into three approaches, the first one is a chemical injection which entails injecting chemicals into a reservoir to enhance crude oil mobility. The second is thermal processing which has to do with heating

Quick Response Code:

***Corresponding author:** Yarima Mudassir Hassan, Faculty of Computing and Sciences, Azman University Kano, Nigeria

Received: 24 February, 2024 **Published:** 05 March, 2024

Citation: Yarima Mudassir Hassan, Beh Hoe Guan, Lee Kean Chuan. The Impact of Electromagnetic Waves Propagation to the Dielectric Nanoparticles on Crude Oil Interfacial Tension Reduction for Oil Recovery: A Review: Review Article. *Trends Petro Eng.* 2024;4(1):1–6. DOI: 10.53902/TPE.2024.04.000534

reservoirs to reduce crude oil viscosity for easy withdrawal. The third category, known as gas miscible flooding, involves injecting CO_2, hydrocarbon gases, or nitrogen into the reservoir to reduce the oil viscosity that helps to displace oil efficiently.[2] There are some factors responsible for improving the stated objective of EOR, and by enhancing them, the condition of the reservoirs could be restructured to achieve oil recovery. These are rock wettability alteration, oil viscosity reduction, and reducing interfacial tension (IFT) between crude oil and other fluids.

The small size of NPs compared to reservoir rock holes enhances their smooth flow through reservoir formation with minimal disruption.[2,4] Various NPs were reported to have shown an encouraging change in improving reservoir characteristics by reducing the negative influence of the IFT effect. IFT is the adhesive force that occurs between the molecules at the interface of two liquid phases.[2] The natural existing IFT between crude oil/fluids interface reduces the simple and flexible mobility of the oil, and therefore reducing the intensity of this force could certainly advance the oil mobility which in turn enhanced oil recovery.

Different NPs were studied to have shown positive results in reducing the IFT of the crude oil/fluids which included ZnO,[5-8] Ferrite NPs,[9] TiO_2,[10,11] Al_2O_3,[10-13] ZrO_2,[12] Fe_2O_3/Fe_3O4,[13-15] and SiO_2.[11,13] Despite the significant effort indicated by these NPs, it has been observed that NPs tend to isolate at the oil/fluid interface due to the reservoir's high temperature which limits the NPs' application.[2] Meanwhile, Haroun[16] presented a novel approach to employ energy in a reservoir using an electrical method to active fluid mobility. Afterward, the EM waves driving approach was introduced which entails activating NPs movement by propagating energy to the nanofluids, and positive enhancement was examined for improving crude oil mobility. Some of the NPs reported are ZnO and Al_2O_3,[6,17-19] Cobalt ferrite ($CoFe_2O_4$),[20] yttrium iron garnet (YIG) ($Y_3Fe_5O_{12}$),[21] ZnO,[22] Fe_2O_3-Al_2O_3,[23] Nickel-zinc ferrite ($Ni_{1-x}ZnxFe_2O_3$),[24] and $Co^{2+}_{0.75}Fe^{2+}_{0.25}Fe^{3+}_{2}O_{4}$.[25] The present study summarizes and evaluates the influence of employing EM waves using dielectric NPs to improve IFT which in turn enhances oil productivity. The merit and challenges confronting the newly innovative approaches and possible solutions to the problems is briefly highlighted.

Discussion on the Effect of Dielectric NPs Propagated by EM Waves

Certain ions are naturally present in the earth's crust, including reservoir holes.[26-28] Unfortunately, when nanofluids are injected into the reservoir the naturally existing ions stocked on the rock surfaces attract the moving particles within the fluids and consequently resist the effective functionality of the NPs. Introducing energy to the reservoir via EM waves could significantly activate the mobility of the NPs and reduce the attraction of such ions onto the suspended particles within the nanofluids. Hence, the effective operations of the NPs will be improved. The charge distribution of ions for the nanofluids is the driving force for the effective mobility of the fluids when endorsed by EM waves. The ions are atoms or molecules with an electrical charge solubilized material in a particular fluid. It is made up of two charges, either positive or negative. The negative charge ions are referred to as anions while the positive charge ions as cations. It is essential to understand the processes that regulate the ion distribution and concentration in the electric double layer within the porous media for us to fully comprehend how cation and anion reactions affect objects. The ions dissolve in the fluids can move around freely within the fluids. However, the mobility of the particles could be improved upon the EM wave exposure on account of the polarization and alignment of the particles. The ions' types, concentration, and particle size can all have an impact on the fluid characteristics.[29] The use of EM waves depends on how electromagnetic materials interact with EM waves within a given medium. It is necessary to maintain control over the electric and magnetic elements present in the porous medium so that they can interact with the time-varying electric and magnetic field components which allow proper EM wave propagation. The characteristics of the medium's surroundings will dictate the kinds of interactions that occur and the frequency range over which EM waves will propagate. The high energy stimulus of dielectric NPs makes them a perfect candidate to be used under EM wave propagation which could encourage NP's mobility in the reservoir. The EM waves generator applies the required energy to the nanofluids which could enhance extra agitation within the fluids and result to cause crude oil deformations and consequently decrease the IFT. When EM waves are applied to the nanofluids that contain dielectric behavior, the dielectric loss of the fluids makes ions polarize and align to the direction of the applied EM waves. Thus, crude oil deformation is said to occur for easy displacement due to the aggregation of the particles at the oil/fluid interface.[30] Additionally, the IFT reduction under the EM waves endorsement is attributed to the hydrodynamic sizes of the fluids. The impact of EM waves on the oil/nanofluid interface lowers IFT, resulting in a single layer of NPs packed in a liquid-like form at the interface.[31,32] The oil droplet is distorted when the EM waves are delivered, which causes the surface area of the droplet to develop, reducing the assembly of the NPs. The increased surface area allows the accumulation of more NPs at the oil/nanofluid interface, resulting in a further drop in IFT.

The well-known equipment used for IFT measurement is a goniometer using a method of pendant drop or sessile drop. It was recently reported that a goniometer has been used to test the IFT performance under the influence of EM waves Figure 1. The radiofrequency (RF) signal generator is the EM waves equipment used to generate the energy in the form of waves and propagate it through the solenoid coil connected to the fluid's container which enhances the fluid operational activation. The nanofluids could be poured into the experimental chamber that was enclosed by the solenoid's coils. The crude oil is injected onto the rock sample (for the sessile drop technique) that was settled on a metal platform in the center of the chamber using an inverted syringe. The light source can be used to flash across the container to ensure that the image can be seen, and the computer is connected to display images of the crude oil versus injected fluids.

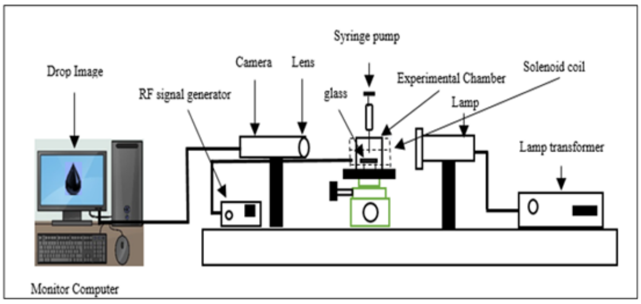

Figure 1: Goniometer with EM waves connection for IFT measurements.[30]

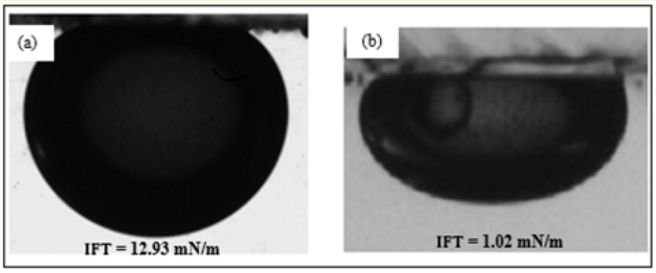

Figure 2: (a) Crude oil/brine (b) ZnO/SiO_2 NPs/crude oil.[45]

The Influence of EM Waves Propagation on IFT Reduction

A unique method for triggering the activation of NPs applications using EM waves in porous media was recently introduced. Yet, the majority of the EM wave incidents that were recorded supported the use of NP for oil recovery. The NPs that have been described include cobalt ferrite ($CoFe_2O_4$),[20] $Co^{2+}_{0.75}Fe^{2+}_{0.25}Fe^{3+}_2O_4$,[25] yttrium iron garnet (YIG) ($Y_3Fe_5O_{12}$),[21] nickel-zinc ferrite ($Ni_{1-x}ZnxFe_2O_3$)[24] and ZnO.[22] In addition to oil recovery studies, it's critical to look at how EM waves affect NPs activation to change the connection between the oil and fluids interface. Yet, there weren't many reports in the literature. NPs with magnetic or dielectric properties are the most appropriate nanomaterials employed due to their excellent electrical conductivity under EM waves.[30] As a result, NPs' ability to absorb energy is a key element that promotes their aggregation at the oil/fluid interface, which lowers IFT.

The function of EM waves on IFT reduction was determined using dielectric nanofluids of ZnO and Al_2O_3 at the voltage of 3.5 V and frequency of 18.8 MHz.[33] The dielectric loss of the nanofluids caused rotational polarization that introduced additional agitation within the fluids, resulting in a reduction in the IFT. Some previous reports have equally shown significant reductions in IFT using ZnO and Al_2O_3 NPs under EM wave inducement,[5,6,33] the same was equally reported for yttrium iron garnet (YIG) NPs.[34-36] Recently, Hassan YM studied the influence of EM waves applied to activate the dielectric composite nanofluids of ZnO-SiO_2 using a voltage of 4.5 and frequency of 20 MHz. A significant reduction was observed when EM waves were induced and the IFT of the nanofluid reduced from 16.70mN/m to 0.002mN/m. The individual nanofluids of ZnO and SiO_2 were also reported and correlated with their respective composite NPs.[37] In a different study by Yarima[38] the IFT was found to have significantly reduced when hybrid NPs of Fe_2O_3-SiO_2 were used. Thus, IFT reduced from 17.39mN/m to 0.21mN/m. The authors concluded that the influence of Fe_2O_3-SiO_2 hybrid NPs performance for IFT reduction was attributed to the amalgamation of magnetic and dielectric attributes in a prepared nanofluid considering their immensive reaction towards EM waves. ZnO-SiO_2 were equally reported to have shown a reducing trend in IFT when subjected to EM waves.[39] Figure 2(a) shows the image of crude oil injected in brine activated by EM waves, in which the IFT value was 12.93mN/m. However, when ZnO-SiO_2 NPs were introduced, the crude oil was considerably deformed as shown in Figure 2(b), and IFT was lowered from 12.93mN/m to 1.02mN/m which made the crude oil easy to displace across reservoir roots.[39] Additionally, IFT reduction was recently reported using dielectric nanofluids in a hybrid form activated with EM waves, and additional improvement considering IFT reduction was equally reported above their constituents, the NPs including ZnO-SiO_2[37] and ZnO-Fe_2O_3-SiO_2.[39] Some recent experiment has reported a significant reduction in IFT when nanocomposite materials were used even without recognition of EM waves such as ZnO-SiO_2,[40] Fe_2O_3-SiO_2,[15,41,42] TiO_2-Quartz,[43] TiO_2-SiO_2,[41] and NiO-SiO_2.[44-50]

Challenges and Recommendations

The Materials and Methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited Table 1.

Despite the significant outcome examined while using various NPs on IFT reductions, the following challenges diminish the development of the process:

- Most of the experiments using NPs under EM wave exposure were laboratory-scale research and are yet to have practical application.
- Calculations of the required frequency and

Table 1: Previous Experimental results for the Influence of various NPs on reducing Interfacial tension (IFT).

Nanoparticles (NPs)	NPs Size (nm)	(IFT) (mN/m)		Base-fluids	Remark	References
		Fluids (F)	F + NPs			
SiO_2	20	16.5	8.47	Brine	EM waves enhance small reduction for IFT	[39]
SiO_2	20	12.5	3.38	Brine	EM waves were propagated to SiO_2 nanofluids which enhance IFT reduction	[30]
SiO_2	10–30	39	1.5	Propanol	IFT reduced when SiO_2 was supported with saline	[46]
SiO_2	40	20	18	Brine	IFT has shown a poor reduction	[11]
SiO_2	20	3.5	2.7	Brine	The IFT performance was relatively low	[47]
SiO_2	10 - 150	27.1	5.6	Distilled water	IFT was rationally reduced	[48]
ZnO	20	16.5	6.84	Brine	IFT was reasonably reduced when EM waves were delivered to the nanofluids	[39]
ZnO	20	12.5	4.45	Brine	IFT was reasonably reduced	[30]
ZnO	-	27	19	Surfactant (SDS)	Adsorption analysis of ZnO on calcite was examined	[49]
ZnO	-	20	2.8	Surfactant (SDS)	Nano-surfactant fluids enhance the IFT reduction	[50]
Fe_2O_3	20	16.5	7.41	Brine	IFT was further reduced when EM waves were incorporated into the nanofluids	[39]
Fe_2O_3	20	12.5	1.16	Brine	IFT was considerably reduced upon EM wave exposure	[30]
ZnO	117	13	12	Brine	IFT slightly changed when EM waves were induced	[5]
ZrO_2	30	8.45	1.85	Cetyl Trimethyl Ammonium Bromide (CTAB)	Adding CTAB to ZrO_2 nanofluids enhances a reasonable IFT reduction	[12]
TiO_2	10–30	21.1	17.5	Brine	The low performance of TiO_2 NPs was due to a lack of fluid adsorption on the surface.	[10]
TiO_2	21	19.2	-	Brine	The IFT reduction was not counted	[11]
Al_2O_3	40	26.5	18	Brine	The charge distribution of Al_2O_3 NPs was examined	[10]
Al_2O_3	20	8.46	1.65	(CTAB)	Nano-surfactant-based fluids reported significant results for IFT reduction	[12]
ZrO_2	40	9.88	2.78	sodium dodecyl sulfate (SDS)	The performance of ZrO_2 on IFT was considerable despite a limited report on it	[12]
TiO_2-quartz	-	36.4	3.5	Distilled water	The results for IFT reductions were highly significant	[43]
NiO_2-SiO_2	-	29.2	1.28	Distilled water	When composite nanofluids of NiO_2-SiO_2 were utilized, IFT was considerably reduced	[44]
ZnO-SiO_2	-	19.68	9.45	Seawater	ZnO-SiO_2 hybrid nanofluids improved IFT reduction	[40]
ZnO-SiO_2	20	16.5	0.02	Brine	Forming hybrid nanofluids of different dielectric NPs under EM waves exposure enhances the IFT reduction by 99 %	[37]
ZnO-Fe_2O_3-SiO_2	20	16.5	1.27	Brine	The EM wave propagation to a hybrid of magnetic and dielectric nanofluids enhances a sufficient reduction in IFT	[39]
Fe_2O_3-SiO_2	20	17.39	1.03	Brine	The composite nanofluids influence IFT reduction without EM waves exposure	[15]

- heat disaffection to the reservoir that are precise and faultless are necessary to implement EM waves in the field reservoir.
- A large quantity of NPs is required for oil and gas industrial companies; hence, the high cost of NPs remains a challenge.

Recommendations

- The thermal stability of the NPs needs to be evaluated, thus, the IFT and nano-flooding experiment should be done at high temperatures.
- Further research into theoretical and analytical modeling is recommended to generate precise estimations about the required heat and frequency that favors the reservoir situation

The high cost of NPs can be addressed by enhancing the key sources of NPs formation. This could provide innovative approaches to form NPs with lower-cost raw materials and EM wave responsiveness.

Conclusion

Various NPs have exhibited a powerful role in reducing IFT that existed within crude oil/fluids boundaries which in turn enhanced oil productivity. Recently, the concept of operating EM waves to provide energy to dielectric nanofluids for IFT evaluation was brought out. A meaningful outcome was observed during the EM wave exposure which enhances ions of the NPs to be polarized and aligned to the EM wave propagation point. Consequently, the crude oil deforms and causes IFT reduction for oil recovery. More experiments are recommended to be done in the future using various NPs at reservoir conditions. implementing the proposed idea appropriately is anticipated to enhance oil removal from the reservoir's environment.

Acknowledgements

None.

Funding

This Review Article received no external funding.

Conflicts of Interest

Regarding the publication of this article, the authors declare that they have no conflict of interest.

References

1. Hassan YM, Guan BH, Chuan LK, et al. Effect of annealing temperature on the rheological property of ZnO/SiO_2 nanocomposites for Enhanced Oil Recovery. *Materials Today: Proceedings.* 2021;48(4):905-910.
2. Hassan YM, Guan BH, Zaid MH, et al. Application of magnetic and dielectric nanofluids for electromagnetic-assistance enhanced oil recovery: a review. *Crystals.* 2021;11(2):106.
3. Adam AA, Ojur Dennis J, Al Hadeethi Y, et al. State of the Art and New Directions on Electrospun Lignin/Cellulose Nanofibers for Supercapacitor Application: A Systematic Literature Review. *Polymers.* 2020;12(12):2884.
4. Hassan Y. Effect of annealing temperature on the crystal and morphological sizes of Fe_2O_3/SiO_2 nanocomposites. in IOP Conference Series: Materials Science and Engineering. IOP Publishing. 2021.
5. Adil M, Lee K, Mohd Zaid H, et al. Experimental study on electromagnetic-assisted ZnO nanofluid flooding for enhanced oil recovery (EOR). *PLoS One.* 2018;13(2):e0193518.
6. Lee K. Wettability, interfacial tension (IFT) and viscosity alteration of nanofluids under electromagnetic (EM) waves for enhanced oil recovery (IFT) applications, in Engineering Design Applications. 2019:pp.305-311.
7. Zaid HM, Ahmad Latiff NR, Noorhana Yahya, et al. Application of electromagnetic waves and dielectric nanoparticles in enhanced oil recovery. *Journal of Nano Research*. 2014.
8. Lee KC, bin Saipolbahri ZA, Soleimani H, et al. Effect of zinc oxide nanoparticle sizes on viscosity of nanofluid for application in enhanced oil recovery. *Journal of Nano Research.* 2016;38:36-39.
9. Esmaeilnezhad E, Van SL, Hyun Chon B, et al. An experimental study on enhanced oil recovery utilizing nanoparticle ferrofluid through the application of a magnetic field. *Journal of Industrial and Engineering Chemistry.* 2018;58:319-327.
10. Esfandyari Bayat A, Junin R, Samsuri A, et al. Impact of metal oxide nanoparticles on enhanced oil recovery from limestone media at several temperatures. *Energy Fuels.* 2014;28(10):6255-6266.
11. Hendraningrat L, Torsæter OJAN. Metal oxide-based nanoparticles: revealing their potential to enhance oil recovery in different wettability systems. *Applied Nanoscience.* 2015;5(2):181-199.
12. Moslan M, Sulaiman W, Ismail A, et al. Applications of aluminium oxide and zirconium oxide nanoparticles in altering dolomite rock wettability using different dispersing medium. *Chemical Engineering Transactions.* 2017;56:1339-1344.
13. Joonaki E, Ghanaatian S. The application of nanofluids for enhanced oil recovery: effects on interfacial tension and coreflooding process. *Petroleum Science and Technology.* 2014;32(21):2599-2607.
14. Rezvani H, Riazi M, Tabaei M, et al. Experimental investigation of interfacial properties in the EOR mechanisms by the novel synthesized Fe3O4 @Chitosan nanocomposites. *Colloids and Surfaces A: Physicochemical and Engineering Aspects.* 2018;544:15-27.
15. Hassan YM, Guan BH, Chuan LK, et al. The synergistic effect of Fe_2O_3/SiO_2 nanoparticles concentration on rheology, wettability, and brine-oil interfacial tension. *Journal of Petroleum Science and Engineering.* 2021;210:110059.
16. Haroun MR, Al Hassan S, Ansari A, et al. Smart nano-EOR process for Abu Dhabi carbonate reservoirs. in Abu Dhabi international petroleum conference and exhibition. *Society of Petroleum Engineers*. 2012.
17. Adil M, Zaid MH, Chuan LK, et al. Effect of EM propagation medium on electrorheological characteristics of dielectric nanofluids. *Journal of Dispersion Science and Technology.* 2017;38(4):570-576.
18. Primo VA, Rosa DP, García B, et al. Evaluation of the stability of dielectric nanofluids for use in transformers under real operating conditions. *Nanomaterials.* 2019;9(2):143.
19. Ali AM, Yahya N, Qureshi S. Interactions of ferro-nanoparticles (hematite and magnetite) with reservoir sandstone: implications for surface adsorption and interfacial tension reduction. *Petroleum Science.* 2020;17:1-19.
20. Yahya N, Kashif M, Nasir N, et al. Cobalt ferrite nanoparticles: an innovative approach for enhanced oil recovery application. *Journal of Nano Research.* 2012;17:115-126.

21. Soleimani H, Ahmad Latiff NR, Yahya N, et al. Synthesis and characterization of yttrium iron garnet (YIG) nanoparticles activated by electromagnetic wave in enhanced oil recovery. *Journal of Nano Research.* 2016;38:40-46.

22. Latiff NRA, Yahya N, Zaid HM, et al. Novel enhanced oil recovery method using dielectric zinc oxide nanoparticles activated by electromagnetic waves. 2011 National Postgraduate Conference. 2011.

23. Soleimani H, Latiff NRA, Yahya N, et al. Effect of annealing temperature on the crystallization of Hematite-Alumina (Fe_2O_3-Al_2O_3) nanocomposite and Its influence in EOR application. *Journal of Nano Research*. 2014;29:105-113.

24. Zaid HM, Wan Azahar WA, Soleimani H, et al. Effect of Nickel: Zinc Ratio in Nickel-Zinc-Ferrite Nanoparticles as Surfactant on Recovery Efficiency in Enhanced Oil Recovery. *Journal of Nano Research.* 2014;29:115-120.

25. Soleimani H, Yahya N, Ahmad S, et al. Novel enhanced oil recovery method using $CO^{2+}_x\ Fe^{2+}_{1-x}Fe^{3+}_2O_4$ as magnetic nanoparticles activated by electromagnetic waves. *Journal of Nano Research*. 2014;26:111-116.

26. Hassan YM, Zaid HM, Guan BH, et al. Radioactivity in staple foodstuffs and concomitant dose to the population of Jigawa state, Nigeria. 2021;178:108945.

27. Nadhiya A, Khandaker MU, Mahmud S, et al. Radiation dose to maldivians via the consumption of tuna fish caught from the coastal waters of indian ocean. *Radiat Prot Dosimetry.* 2019;184(3-4):302-306.

28. Yarima MH, Khandaker MU, Nadhiya A, et al. Assessment of natural radioactivity in maize and estimation of concomitant dose to nigerian via ingestion pathway. *Radiat Prot Dosimetry.* 2019;184(3-4):359-362.

29. Buschow KHJ, Boer FR. Physics of magnetism and magnetic materials. Springer. 2003;7.

30. Hassan YM, Hoe Guan B, Chuan LK, et al. Interfacial tension of brine-oil interface using Fe_2O_3, ZnO, and SiO_2 nanoparticles endorsed. *Electromagnetic Waves.* 2022;8:100083.

31. Ali AM, Yahya N, Mijinyawa A, et al. Molecular simulation and microtextural characterization of quartz dissolution in sodium hydroxide. *Journal of Petroleum Exploration and Production Technology.* 2020;10:1-16.

32. Sikiru S, Afolabi LO, Borhana Omran A, et al. Ionic Surface Dielectric Properties Distribution on Reservoir Sandstone. *International Journal of Integrated Engineering*. 2021;13(7):258-265.

33. Adil M, Zaid HM, Chuan LKJF. Electromagnetically-induced change in interfacial tension and contact angle of oil droplet using dielectric nanofluids. 2020;259:116274.

34. Lau ZY, Lee KC, Soleimani H, et al. Experimental study of electromagnetic-assisted rare-earth doped yttrium iron garnet (YIG) nanofluids on wettability and interfacial tension alteration. *Energies.* 2019;12(20):3806.

35. Lee KC, Mohd Sukri MN, Guan BH, et al. Interfacial Tension and Viscosity Alteration of Samarium Doped Yttrium Iron Garnet (YIG) Nanofluid under the Presence of Electromagnetic Waves. *Defect and Diffusion Forum.* 2019;390:64-70.

36. Lee K, Shuhaili FM, Zaid HM, et al. Neodymium (Nd) Doped Yttrium Iron Garnet (YIG) Nanofluid Activated By Electromagnetic Waves for Enhanced Oil Recovery (EOR). *Journal of Physics: Conference Series.* 2018; 012011.

37. Hassan YM, Guan BH, Chuan LK, et al. Electromagnetically Modified Wettability and Interfacial Tension of Hybrid ZnO/SiO_2 Nanofluids. *Crystals.* 2022;12(2):169.

38. Hassan YM, Hoe Guan B, Chuan LK, et al. The synergistic effect of Fe_2O_3/SiO_2 nanoparticles concentration on rheology, wettability, and brine-oil interfacial tension. *Journal of Petroleum Science and Engineering.* 2022;210:110059.

39. Hassan YM, Hoe Guan B, Chuan LK, et al. Interfacial tension and wettability of hybridized $ZnOFe_2O_3$/SiO_2 based nanofluid under electromagnetic field inducement. *Journal of Petroleum Science and Engineering.* 2022;211:110184.

40. Ali JA, Kolo K, Manshad AK, et al., Potential application of low-salinity polymeric-nanofluid in carbonate oil reservoirs: IFT reduction, wettability alteration, rheology and emulsification characteristics. *Journal of Molecular Liquids.* 2019;284:735-747.

41. Kazemzadeh Y, Sharifi M, Riazi M, et al. Potential effects of metal oxide/SiO_2 nanocomposites in EOR processes at different pressures. *Colloids and Surfaces A: Physicochemical and Engineering Aspects.* 2018;559:372-384.

42. Kazemzadeh Y, Dehdari B, Etemadan Z, et al. Experimental investigation into Fe_3O_4/SiO_2 nanoparticle performance and comparison with other nanofluids in enhanced oil recovery. *Petroleum Science.* 2019;16(3):578-590.

43. Zargar G, Arabpour T, Manshad AK, et al. Experimental investigation of the effect of green TiO_2/Quartz nanocomposite on interfacial tension reduction, wettability alteration, and oil recovery improvement. *Fuel.* 2020;263:116599.

44. Dahkaee KP, Sadeghi MT, Fakhroueian Z, et al. Effect of NiO/SiO_2 nanofluids on the ultra interfacial tension reduction between heavy oil and aqueous solution and their use for wettability alteration of carbonate rocks. *Journal of Petroleum Science and Engineering.* 2019;176:11-26.

45. Hassan YM, Hoe Guan B, Chuan LK, et al. The Influence of ZnO/SiO2 nanocomposite concentration on rheology, interfacial tension, and wettability for enhanced oil recovery. *Chemical Engineering Research and Design.* 2022;179:452-461.

46. Joonaki E, Ghanaatian S. The application of nanofluids for enhanced oil recovery: effects on interfacial tension and coreflooding process. *Petroleum Science and Technology.* 2014;32(21):2599-2607.

47. Ahmed A, Saaid IM, Pilus RM, et al. Development of surface treated nanosilica for wettability alteration and interfacial tension reduction. *Journal of Dispersion Science and Technology.* 2018;39(10):1469-1475.

48. Jiang R, Li K, Horne R. A mechanism study of wettability and interfacial tension for EOR using silica nanoparticles. *SPE Annual Technical Conference and Exhibition.* 2017.

49. Soleimani H, Baig MK, Yahya N, et al. Synthesis of ZnO nanoparticles for oil–water interfacial tension reduction in enhanced oil recovery. *Applied Physics A.* 2018;124(2):1-13.

50. Zaid HM, Ahmad Latiff NR, Yahya N. The effect of zinc oxide and aluminum oxide nanoparticles on interfacial tension and viscosity of nanofluids for enhanced oil recovery. *Advanced Materials Research.* 2014;1024:56-59.