Journal of Materials Science Research and Reviews

Volume 7, Issue 1, Page 109-118, 2024; Article no.JMSRR.113342

An Overview of the Application of Magnetic Nanoparticles in the Petroleum Sector

Rawia Mansour [a] and Ali Mohamed Elshafei [b*]

[a] Egyptian Petroleum Research Institute (EPRI), 1 Elzhoor Region, P.O. Box-11727, Cairo, Egypt.
[b] Department of Microbial Chemistry, National Research Centre, 33 El Bohouth St. (Former El Tahrir St.), Dokki, Giza, P.O. Box-12622, Egypt.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/113342

Review Article

Received: 23/12/2023
Accepted: 27/02/2024
Published: 02/03/2024

ABSTRACT

The use of magnetic nanoparticles (MNPs) has gained popularity due to their small size, physico-chemical properties, and cost-effectiveness. When subjected to a magnetic field, MNPs can be used to selectively attach, manipulate, or transfer specific substances to a desired location. This property makes them useful for a variety of applications. The superparamagnetic nature of magnetic nanoparticles arises from their small size. They can be used either uncoated or coated with a functional group and surface coating specifically designed for a given use. In the oil and gas industry, MNPs are utilized in various upstream processes, including enhanced oil recovery, drilling fluids, corrosion control, hydraulic fracturing, and sand control. MNPs have distinct features that make them highly valuable for various applications. These features include their small size, which results in a large contact area due to their large surface-to-area ratio. Additionally, they possess nanoscale properties such as optical, chemical, magnetic, and interfacial properties, which are dependent on their size and can be effectively manipulated to achieve specific outcomes. In the petroleum industry, magnetic nanoparticles (MNPs) have significant potential for directed transport,

---

**Corresponding author: Email: alielshafei@yahoo.com;*

local heating, remote sensing, and targeted adsorption. The dispersity and stability of MNPs in suspension are critical for these applications. The objective of this review is to discuss the latest applications of MNPs in the petroleum industry, as well as understanding the traditional methods employed in the sector.

Keywords: Magnetic nanoparticles; applications; petroleum sector; properties.

1. INTRODUCTION

Magnetic nanoparticles (MNPs) are composed of two constituents: a functional chemical component with biorecognition or bio-catalytic properties and a magnetic component made of iron, nickel, or cobalt [1]. The properties of magnetic nanoparticles differ significantly from those of their bulk materials because of their small size, which allows for an increased surface-to-volume ratio, and their close approach to the domain size [2,3]. Magnetic nanoparticles (MNPs) are widely applied in different sectors including petroleum sector. Applications of magnetic nanoparticles in the petroleum sector have been reported. These include enhanced oil recovery (EOR) [4], heavy oil recovery [5], magnetic separation, enhanced production and drilling operations, imaging and sensing of reservoirs, flow assurance, and configuration control. Numerous techniques have been employed to explore the magnetic characteristics of nanoparticles, one of which is ferromagnetic resonance (FMR). FMR has been extensively researched in bulk magnetic materials, including thin films, and more lately, in magnetic nanoparticles. In these particles of nanoscale size, the FMR behavior can be influenced by a range of factors, such as size, shape, surface effects, and composition [6,7]. Ferroelectric materials are a significant type of electronic materials with the property of spontaneous polarization when exposed to external electric fields. Single crystals of potassium niobate $KNbO_3$ [KN] have attracted considerable attention due to their ferroelectric characteristics and their suitability for applications in non-linear optics, phase hologram storage, piezoelectric instruments, and more [8-10]. Ferroelectric materials with perovskite-type structure, such as KN, are expected to exhibit semi-conductive properties. Their physical characteristics can be influenced by doping. Ferroelectric domain walls are a unique type of interface. They are characterized by their dynamic ferroelectricity, which enables real-time adjustments to the walls' position, density, and orientation [11]. This paper reviews the current state of research on magnetic nanoparticles used in the petroleum industry, assesses the field's current state, and evaluates its future possibilities.

2. CLASSIFICATION OF MNPs

On the basis of their intrinsic magnetic dipoles and net magnetization in the presence and absence of an external magnetic field, MNPs are usually classified as ferromagnetic, ferrimagnetic, antiferromagnetic, diamagnetic, paramagnetic, and superparamagnetic. The maximum magnetization occurs when the magnetic moment of MNPs aligns with an external magnetic field. The maximum magnetization in the presence of an external magnetic field occurs when the MNPs' magnetic moment is oriented in the direction of the magnetic field. When an external magnetic field is removed, MNPs' magnetic moment keeps its previous direction and magnetization. Since their high sensitivity results in increased sensing efficiency, MNPs with high saturation magnetization values are generally chosen for biosensing applications; additionally, saturation magnetization values tend to rise with MNP size (Fig. 1).

Several researchers have reported on the properties of a single crystal of potassium niobate doped with iron, which was produced using a flux method. According to the results obtained from X-ray diffraction (XRD), the sample shows orthorhombic crystal symmetry. The properties studied include structural, dielectric, ferroelectric, and domain properties. When the sample was analyzed using differential thermal analysis (DTA), two peaks were observed. These peaks were endothermic, with the first peak occurring at 224 °C and the second at 425 °C. Additionally, the crystal's dielectric loss was measured and found to be consistent with other dielectric studies. According to the relationship between polarization and electric field (PE), the spontaneous polarization (Ps) and coercive field (Vc) of the doped material are smaller than those of an undoped $KNbO_3$ single crystal. This indicates that the sample has weak ferroelectric properties (Korde et al.) [6]. Korde and colleagues (2022b) utilized the flux method to synthesize a single crystal of potassium niobate (KN) that was doped with aluminum (Al). They used a trinocular microscope to investigate the domain of the prepared crystals. Research was carried out to study the effects of an electric field on the properties of crystal domains. Electric fields ranging from 50 to 100 V/cm were applied during this investigation. This range of electric fields resulted in a modification of the domain's structure [7].

Ferromagnetism: Some materials, like iron, have a property known as ferromagnetism, which can cause them to become permanent magnets. This property gives the material a high level of magnetic permeability and often a high level of magnetic coercivity as well. Therefore, a material can become a permanent magnet due to the presence of ferromagnetism, which is a unique characteristic found in some materials such as iron. [12]. Material magnetism has been classified into several categories. The most common type of magnetism found in magnets used in daily life is called ferromagnetism, which also has the similar effect of ferrimagnetism. Ferromagnetic materials fall into two categories: magnetically hard materials, which tend to remain magnetized, and magnetically soft materials, such as annealed iron, which can become magnetized but do not usually do so [13]. Two naturally occurring ferromagnetic materials are lodestone (or magnetite, an iron oxide, Fe3O4) and pure iron. These materials can acquire strong magnetic properties and are known as natural ferromagnets.

Ferrimagnetism: A ferrimagnetic material is one in which the populations of atoms have opposite magnetic moments, as in anti-ferromagnetism, but the moments are not equal in magnitude, allowing for the persistence of spontaneous magnetization [14]. Similar to ferromagnetic materials, ferrimagnetic materials can be magnetized to create permanent magnets and are attracted to magnets. Among transitionmetal compounds, particularly oxides, antiferromagnetic materials are frequently found. Hematite, metals like chromium, iron manganese (FeMn) alloys, oxides like nickel oxide (NiO), and alloys like these are a few examples. Examples of ferrimagnetic materials include a) Magnetite (Fe3O4) used in magnetic ink, magnetic resonance imaging (MRI) contrast agents, and magnetic drug delivery systems., b) Ferrites belong to a group of ceramic materials made up of metal oxides that include iron (III) oxide (Fe2O3) along with other metallic elements like manganese, nickel, or zinc. Some examples of ferrites are manganese-zinc ferrite (MnZnFe2O4) and nickel-zinc ferrite (NiZnFe2O4). These materials are commonly used in high-frequency transformers, inductors, and antennas due to their low eddy current losses and high resistivity. and, c) Garnets are a type of silicate mineral that have various compositions and magnetic properties. Yttrium iron garnet (YIG, Y3Fe5O12) is one example of these minerals. YIG is a ferrimagnetic material that has low loss characteristics at microwave frequencies. Because of its properties, YIG is widely used in microwave devices such as isolators, circulators, and filters [15].

Antiferromagnetism: Antiferromagnetic materials are commonly found in transition metal compounds, especially in their oxide forms. Examples include hematite, metals such as chromium, alloys of iron manganese (FeMn), oxides such as nickel oxide (NiO), and alloys similar to these [16]. The first demonstration of antiferromagnetic structures was achieved by neutron diffraction of transition metal oxides, including oxides of nickel, iron, and manganese [17]. Examples of antiferromagnetic materials include a) MnO has a rock-salt crystal structure, b) MnO has a rock-salt crystal structure, c) Elemental chromium, d) Transition metal insulators A variety of insulators including copper (II) oxide (CuO) and nickel (II) oxide (NiO) are transition metal insulators.

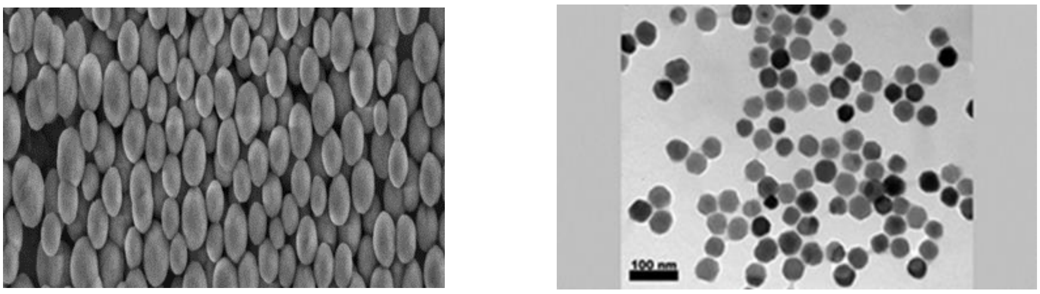

Fig. 1. Examples of magnetic nanoparticles (MNPs)

Diamagnetism: Materials with diamagnetic properties are those that are repelled by magnetic fields; an applied magnetic field induces a magnetic field in them that is directed in the opposite direction, producing a repulsive force [18]. A magnetic field, on the other hand, attracts paramagnetic and ferromagnetic materials. A material is referred to as diamagnetic when diamagnetism is the sole source of magnetism, a quantum mechanical effect present in all materials [19]. The following materials are typical examples of diamagnetic materials: marble, water, glass, copper, zinc, bismuth, silver, gold, and antimony.

Paramagnetism: A kind of magnetism known as paramagnetism occurs when certain materials create internal, induced magnetic fields in the direction of an applied magnetic field despite being only weakly attracted to an externally applied magnetics field [20]. This behavior is in contrast to that of diamagnetic materials, which form induced magnetic fields in the opposite direction of the applied magnetic field and are repelled by magnetic fields. The majority of atoms with partially filled atomic orbitals are paramagnetic because paramagnetic materials have unpaired electrons [21]. Among the paramagnetic materials are uranium, oxygen, lithium, sodium, magnesium, molybdenum, aluminium, and platinum.

Superparamagnetism: MNPs in the superparamagnetic state respond quickly to changes in the magnetic field without coercivity, or the necessary magnetic field to bring the magnetization back to zero, and without residual magnetization. A type of magnetism known as super-paramagnetism can be found in tiny ferromagnetic or ferrimagnetic nanoparticles. Under the influence of temperature, magnetization in sufficiently small nanoparticles can randomly reverse direction [22,23]. Numerous materials, whether inorganic or organic, have been developed that possess sufficient electronic exchange, chemical and thermal stability both at room temperature and higher. Superparamagnetic materials consist of transition metals that are loaded with contrast agents to facilitate imaging of the liver, intestines, and lymph nodes. Other materials include molecules that contain rare earth magnetic materials or transition metals.

3. APPLICATIONS OF MAGNETIC NANOPARTICLES IN PETROLEUM SECTOR (TABLE 1)

Enhanced oil recovery: Enhanced oil recovery (EOR) is one of the most significant areas of application for magnetic nanoparticles since it ensures a quicker return on investment by producing more oil during the extraction process [24-26]. The main advantage of enhanced oil recovery process is to improve traditional surfactant flooding as its acts as a piston and increase the sweep efficiency of oil. Using nanotechnology in the enhanced oil recovery (EOR) process facilitates the extraction of trapped oil that is found below the surface. Certain ultra-fine nanoparticles are both economical and environmentally benign. An environment that is favorable for oil recovery is produced by the injected fluid's interactions with the rock/oil system [27,28]. There are three phases or categories of oil recovery - primary, secondary, and tertiary. Primary oil recovery involves using the oil layer's original energy to drive oil production without the need for additional fluid injection. Specifically, the elastic energy of the oil layer, the potential energy of water, and the volumetric energy of gas expansion are used. On the other hand, when general fluids such as gas and water are injected into the oil recovery process, it is called secondary oil recovery. Finally, tertiary oil recovery involves injecting special fluids, such as steam, CO2, polymer solution, alkali solution, or surfactant solution, to recover oil after the secondary oil recovery phase. In general, primary oil recovery can extract 10-25% of crude oil from underground, and secondary oil recovery can extract an additional 10-25%. This means that after both of these phases of oil recovery, only 25-50% of crude oil underground can be recovered. Enhanced oil recovery (EOR) is a process that involves both tertiary and secondary oil recoveries. It produces higher recovery factors than primary oil recovery. Tertiary oil recovery plays a significant role in EOR, but they are not conceptually identical. EOR involves the development of a higher level of oil recovery, such as quaternary oil recovery, after tertiary oil recovery. However, it is only feasible if the price of oil is high enough [27].

Heavy oil recovery: This process helps to upgrade heavy oil by reducing its viscosity through the use of magnetic induction heating and prevents the viscoelastic network from forming by adhering asphaltenes [22,29]. There are various forms of naturally occurring crude oil. The most well-known to most people is light crude oil, which flows easily at room temperature and is less dense than water. The most promising and easily accessible oil resource to meet energy demands in the upcoming decades is heavy oil, which is estimated to make up roughly 70% of the remaining oil reserves [27, 29]. The high mobility of injected fluids, polymer degradation, surfactant adsorption, significant chemical consumption, significant energy and water consumption, significant greenhouse gas emissions, high operation costs, and the requirement for sturdy facilities pose significant challenges to conventional enhanced oil recovery (EOR) methods for heavy oil [30]. The technology of nanoparticles has emerged as a viable substitute for improving heavy oil recovery in recent years. This is because of their exceptional features, which include ultra-small size, high surface area to volume ratio, cost-effectiveness, and environmental tolerance [30]. Two main categories of nanoparticle applications for improving heavy oil recovery are hybrids of conventional EOR techniques and nanofluid flooding. The different uses of nanofluid flooding are summarised up in terms of EOR mechanisms and incremental oil recovery performance [30]. The second category highlights new developments in the study of hybrids between nanoparticles and conventional EOR techniques, such as gas injection, chemical, and thermal injection [31]. To fulfill the energy demands in the coming years, heavy oil is considered to be the most promising and easily accessible oil resource. It constitutes around 70% of the remaining oil reserves. However, traditional enhanced oil recovery (EOR) methods face significant challenges while dealing with heavy oil. These challenges include high fluid mobility, degradation of polymers, surfactant adsorption, large chemical consumption, high energy and water consumption, high greenhouse gas emissions, high operational costs, and the need for robust facilities. Thermal EOR methods are currently being used to improve fluid flow in porous media. These methods involve heating heavy and bituminous oils to a lower viscosity. However, they have several shortcomings that cause significant hazardous gas emissions and environmental contamination. Recently, nanoparticle technology has been introduced as a viable substitute for heavy oil recovery enhancement. This technology has distinctive features such as ultrasmall size, high surface area to volume ratio, affordability, and environmental friendliness [32].

Drilling and completion improvement: This application uses filter cakes to stop the formations from being invaded by excess filtrate, increase the spacer fluids' cleaning effectiveness, preserve the drilling fluids' stability and rheological integrity in challenging reservoir conditions, and improve the rheological characteristics of the drilling fluids [33,34]. Recently, artificial Intelligence (AI) is becoming a necessary tool for the petroleum industry. AI is regarded as an innovative technology in drilling and completion engineering that can save costs and greatly increase drilling efficiency (DE). The number of artificial intelligence (AI) tools used in the petroleum industry has rapidly increased in recent years, indicating their enormous potential [35]. Artificial Intelligence (AI) has been applied to many problems in the oil and gas industry, such as the identification of seismic patterns, characterization of reservoirs, prediction of permeability and porosity, prediction of PVT properties, diagnosis of drill bits, estimation of pressure drop in pipelines and wells, optimization of oil well production, performance of oil wells, portfolio management, and general decision-making operations [36].

Flow assurance and conformance control: This application reduces the incremental water production from the mature reservoirs by controlling the formation of gel or magnetic solid-like structures, and it also prevents the deposition of wax and the formation of methane hydrates by heating the production tubing. Oil companies are facing a critical operational challenge of one or more fluid-flow assurance issues during pipeline production and transportation in cold environments as a result of increasing hydrocarbon production from conventional and unconventional reservoirs in harsher environments. Therefore, a detailed explanation of the fluid flow assurance problems is necessary to overcome these operational difficulties [37,38]. The application of flow assurance is needed to ensure the smooth and cost-effective transportation of hydrocarbons from the reservoir to the point of sale. Applications from several fields are needed in order to solve these flow assurance problems, especially production chemistry, multi-phase hydrodynamics, thermodynamics, and materials science. All phases of the petroleum flow path's production, including system selection, thorough design, monitoring, troubleshooting operational issues, and enhanced recovery, are subject to flow assurance [39]. The production of multiphase flow through pipelines and risers in offshore or onshore oil and gas field developments requires careful consideration of several flow assurance issues, including hydrates, waxing, asphaltenes, slugging, naphthenates, scales, corrosion, erosion, and emulsions [40].

Magnetic separation: The magnetic separation process has the advantage to separate oil or injected polymer from the produced water, remove emulsified water from the crude oil and bitumen, in addition to the removal of divalent cations. The discharge of oily wastewater from industrial activities and the frequency of oil spill accidents have drawn a lot of attention to oil-water separation recently [41]. Before releasing oily wastewaters, it is essential to remove any oil-containing materials because they can pose a major threat to human health by entering the food chain and causing serious environmental problems [42,43]. Under some circumstances, flocculation has been suggested in recent years to be a helpful technique for removing emulsified oil droplets; however, the flocculation process is costly and the resulting flocs have a tendency to float, which reduces the effectiveness of oil-water separation. Therefore, it is imperative to create new materials or technologies for treating emulsified oil wastewaters at a reasonable cost. Magnetic nanoparticles (MNPs) have garnered particular attention in the last ten years because of their surface characteristics and possible for recycling. The hydrophobicity or amphiphilicity of MNPs can be modified via a variety of surface modification techniques to enhance their sorption at oil-water interfaces and/or within dispersed droplets, giving the dispersed oil droplets magnetic properties. Consequently, an external magnetic field can be used to easily separate the magnetically tagged oil droplets from the continuous phase [44,45].

Table 1. Applications of the MNPs in petroleum sector

Specific area	Application & Properties	Reference
Enhanced oil recovery	• Increases the oil's sweep efficiency by acting as a piston. • Enhance conventional surfactant flooding.	Anirbid et al., 2022; Ehsan et al., 2018a; Ehsan et al., 2018b
Heavy oil recovery	• Reduce heavy oil viscosity via magnetic induction heating. • Adsorb asphaltenes to their surface and therefore inhibit the formation of the viscoelastic network. • Help to the upgrading of heavy oil.	Goma et al., 2023; Wei et al., 2023.
Drilling and completion improvement	• Enhance the drilling fluids' rheological characteristics. • Increase the spacer fluids' cleaning effectiveness. • Create filter cakes to stop the formations from being invaded by excess filtrate. • Keep the drilling fluids stable and rheologically sound under challenging reservoir circumstances.	Li et al., 2022; Tran et al., 2020; Yin et al., 2017; Mohaghegh, 2005.
Flow assurance and conformance control	• Stop the development of gel or magnetic solid-like structures to minimize the additional water production from the mature reservoirs. • Use heat to stop the production tubing from accumulating wax and forming methane hydrates.	Asheesh, 2023; McMullen, 2006; Joshi et al., 2003.
Imaging and sensing reservoirs	• Monitor the source of crude oil. • Produce distinct and highly contrasted signal regions within the fractures. • Enhance the interpretation of NMR data for the evaluation of porosity distribution • Establish the fluid front's magnetic-permeability-contrast zones.	Tesfaye et al., 2023; Nasser et al., 2020.
Magnetic separation	• Separate the produced water from the injected polymer or oil. • Take the emulsified water out of the bitumen and crude oil. • Divalent cation removal.	Bowman, 2023; Yi et al., 2022; Kaibo et al., 2020.

Reservoir sensing and imaging: This application is designed to establish zones of magnetic permeability contrast at the fluid front, monitor the source of crude oil, create distinct and highly contrasted signal regions within fractures, improve the interpretation of NMR data for evaluating porosity distribution, and establish zones of magnetic permeability contrast at the fluid front [46]. Soil erosion in the reservoir's watershed areas, which is nearly infinitesimal at the source, has become a serious issue for dams. This erosion is responsible for sedimentation in the reservoirs [47]. Routinely applying nuclear magnetic resonance (NMR) spectroscopy can facilitate the in situ analysis of nanoparticle formation and morphology in both the solution and solid phase. NMR spectroscopy offers direct molecular-scale analysis, and there is a growing body of research suggesting that it can provide an exciting supplement to the current standard tools for characterizing nanoparticles, such as optical absorption spectroscopy and electron microscopy [48].

4. CONCLUSION

Applications for MNPs in the petroleum industry have shown them to be extremely promising, and during the last ten years, some progress has been made. The behavior of MNPs can be remotely controlled by an external magnetic field due to their special magnetic properties. This has several potential applications in the fields of magnetic separation, enhanced oil recovery, heavy oil recovery, flow assurance, conformance control, reservoir sensing, and imaging. Moreover, because of their size effects, MNPs have been developed as injected fluid additives to enhance rheological behavior in the absence of a magnetic field. The use of MNPs offers exciting opportunities for the development and improvement of the petroleum industry. Nevertheless, these applications continue to face a number of significant obstacles. The development of novel MNP modification materials, the enhancement of MNP synthetic routes, and additional investigation into the distinct properties and mechanisms of MNPs are among the fundamental research attempts that hold the answers to overcoming the pivotal challenges. It has been demonstrated that Iron Magnetic Nanoparticles (IMNPs) hold a lot of potential for various applications in the petroleum industry such as directional transport, local heating, remote sensing, targeted adsorption, and more. However, to ensure success in these applications, it is crucial to maintain the stability and dispersity of the MNPs in suspension.

ACKNOWLEDGEMENT

Authors acknowledge the support provided by the Egyptian Petroleum Research Institute (EPRI) and the National Research Centre (NRC), Egypt.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Alagiri M, Muthamizhchelvan C, Ponnusamy S. Structural and magnetic properties of iron, cobalt and ncikel nanoparticles. Synth. Met. 2011;161(15-16):1776-1780. synthmet.2011.05.030. Available:https://doi.org/10.1016/j.
2. Akbarzadeh A, Samiei M, Daravan S. Magnetic nanoparticles: Preparation, physical properties, and applications in biomedicine. Nanoscale Res. Lett. 2012; 7:1-13. Available:https://doi:10.1186/1556-276X-7-144.
3. Reddy LH, Arias JL, Nicolas J, Couvreur P. Magnetic nanoparticles: Design and characterization, toxicity and biocompatibility, pharmaceutical and biomedical applications. Chem. Rev. 2012; 112:5818-5878. Available:https://doi:10.1021/cr300068p.
4. Pirizadeh M, Alemohammad N, Manthouri M, Pirizadeh M. A new approach for ranking enhanced oil recovery methods based on multi-gene genetic programming, Pet. Sci. Technol. 2023;41(1):64-85. Available:https://doi:10.1080/10916466.2022.2030752.
5. Xue L, Liu P, Zhang Y. "Development and research status of heavy oil enhanced oil recovery", Geofluids. 2022;13. Article ID 5015045. Available:https://doi.org/10.1155/2022/5015045.
6. Korde V, Shamkuwar S, Patil N. Analytical study of the ferroelectric properties of Fe-doped KNbO3 single crystal. Journal of Physics and Chemistry of Solids. 2022a; 167:110712. ISSN 0022-3697. Available:https://doi.org/10.1016/j.jpcs.2022.110712.

7. Korde V, Patil N, Shamkuwar S. A critical field study of ferroelectric domain in Al-doped KNbO3 single crystal. Ceramics International. 2022b;48(7):9172-9179. ISSN 0272-8842.
Available:https://doi.org/10.1016/j.ceramint.2021.12.102.
8. Korde VB, Patil NM. Synthesis, structural, dielectric and domain properties of Al-doped KNbO3 single crystal. J Mater Sci: Mater Electron. 2019a;30:6910–6919.
Available:https://doi.org/10.1007/s10854-019-01006-8.
9. Korde VB, Patil NM. Domain imaging in Fe-doped KNbO3 single crystal via trinocular microscopy and scanning electron microscopy. Materials Chemistry and Physics. 2019b;226:230-234. ISSN 0254-0584.
Available:https://doi.org/10.1016/j.matchemphys.2018.12.071.
10. Korde VB, Patil NM. Kinetics of ferroelectric domains investigated by etching technique in Al-doped KNbO3 single crystal. Optik. 2020;221:165343. ISSN 0030-4026.
Available:https://doi.org/10.1016/j.ijleo.2020.165343.
11. Meier D, Selbach SM. Ferroelectric domain walls for nanotechnology. Nat Rev Mater. 2022;7:157–173.
Available:https://doi.org/10.1038/s41578-021-00375-z.
12. Coey JMD. Ferromagnetism and exchange. In: Magnetism and Magnetic Materials. Cambridge University Press. 2010;128-194.
Available:https://doi.org/10.1017/CBO9780511845000.006.
13. Chikazumi, Sōshin. Physics of ferromagnetism. English edition prepared with the assistance of C. D. Graham, Jr. (2nd ed.). Oxford: Oxford University. Press. 2009;118. ISBN:978-0-19-956481-1.
Available:https://doi.org/10.1093/oso/9780198517764.001.0001.
14. Li C, Zhang J, Wang Y et al. Emergence of Weyl fermions by ferrimagnetism in a noncentrosymmetric magnetic Weyl semimetal. Nat. Commun. 2023;14:7185.
Available:https://doi.org/10.1038/s41467-023-42996-8.
15. Spaldin, Nicola A. Magnetic materials: Fundamentals and applications (2nd ed.). Cambridge: Cambridge University Press; 2011. ISBN 978-0-521-88669-7. OCLC 607986416.
Available:http://www.cambridge.org/9780521886697.
16. Du A, Zhu D, Cao K et al. Electrical manipulation and detection of antiferromagnetism in magnetic tunnel junctions. Nat. Electron. 2023;6:425-433.
Available:https://doi.org/10.1038/s41928-023-00975-3.
17. Forrester M, Kusmartsev F. "The nano-mechanics and magnetic properties of high moment synthetic antiferromagnetic particles". Physica Status Solidi A. 2014; 211(4):884–889. Bibcode:2014PSSAR. 211. 884F. S2CID 53495716.
Available:https://doi:10.1002/pssa.201330122.
18. Laumann D, Ries M, Heusler S. Everything can be magnetized: Simulating diamagnetic and paramagnetic response of everyday materials in magnetic balance experiments. Phys. Educ. 2023;58(2):58 025012.
Available:https://doi:10.1088/1361-6552/acad58.
19. Beatty, Bill. Neodymium supermagnets: Some demonstrations—Diamagnetic water. Science Hobbyist; 2005. Retrieved 26 September 2011.
Available:http://amasci.com/neodemo.html.
20. Man, Huiyuan, Ghasemi Alireza, Adnani Moein Siegler, Maxime A, Anber, Elaf A, Li Yufan, Chien Chia-Ling, Taheri, Mitra L, Chu Ching-Wu, Broholm Collin L, Koohpayeh, Seyed M. Quantum paramagnetism in a non-Kramers rare-earth oxide: Monoclinic Pr2Ti2O7. Phys. Rev. Mater. 2023;7(6): 063401.
Available:https://link.aps.org/doi/10.1103/PhysRevMaterials.7.063401.https:// doi:10.1103/PhysRevMaterials.7.063401.
21. Miessler GL, Tarr DA. Inorganic Chemistry 3rd ed., Pearson/Prentice Hall publisher; 2010. ISBN 0-13-035471-6.
Available:https://doi.org/10.1007/s00897990322a.
22. Zhao W, Liu Z, Sun Z et al. Superparamagnetic enhancement of thermoelectric performance. Nature. 2017; 549:247–251.
Available:https://doi.org/10.1038/nature23667.
23. Kryder MH. Magnetic recording beyond the superparamagnetic limit. Magnetics Conference. INTERMAG 2000 Digest of Technical Papers. 2000 IEEE

International. 2000;575. ISBN:0-7803-5943-7. Available:https://doi:10.1109/INTMAG.2000.872350.

24. Sircar A, Rayavarapu K, Bist N, Yadav K, Singh S. Applications of nanoparticles in enhanced oil recovery. Petroleum Research. 2022;7(1):77-90. Available:https://doi.org/10.1016/j.ptlrs.2021.08.004.
25. Esmaeilnezhad E, Van SL, Chon BH, Choi HJ, Schaffie M, Gholizadeh M, Ranjbar M. An experimental study on enhanced oil recovery utilizing nanoparticle ferrofluid through the application of a magnetic field. J Ind Eng Chem. 2018;58(25):319-327. Available:https://doi.org/10.1016/j.jiec.2017.09.044.
26. Nourafkan E, Hu Z, Wen D. Controlled delivery and release of surfactant for enhanced oil recovery by nanodroplets. Fuel. 2018;218:396-405. Available:https://api.semanticscholar.org/CorpusID:103799268.
27. Gomaa S, Salem KG, El-hoshoudy AN. Enhanced heavy and extra heavy oil recovery: Current status and new trends. Petroleum; 2023. ISSN 2405-6561. Available:https://doi.org/10.1016/j.petlm.2023.10.001.
28. Gbadamosi AO, Junin R, Manan MA et al. An overview of chemical enhanced oil recovery: Recent advances and prospects. Int Nano Lett. 2019;9:171–202. Available:https://doi.org/10.1007/s40089-019-0272-8.
29. Mirzayi B, Younesi M, Nematollahzadeh A. A New investigation on asphaltene removal from crude oil: Experimental study in flow–loop system using maghemite nanoparticles. Nanoparticles. Pet. Chem. 2021;61:640–648. Available:https://doi.org/10.1134/S0965544121060037.
30. Zhou W, Xin C, Chen Y, Mouhouadi RD, Chen S. Nanoparticles for enhancing heavy oil recovery: Recent progress, challenges, and future perspectives. Energy & Fuels. 2023;37(12):8057-8078. Available:https://doi:10.1021/acs.energyfuels.3c00684.
31. Alsaba MT, Dushaishi MA, Abbas AK. A comprehensive review of nanoparticles applications in the oil and gas industry. Vol.:(0123456789)1 3 J Pet Explor Prod Technol. 2020;10:1389–1399. Available:https://doi.org/10.1007/s13202-019-00825-z.
32. Wu R, Wei B, Li S, Zhang Y, Luo Q. Enhanced oil recovery in complex reservoirs: Challenges and methods. Advances in Geo-Energy Research. 2023;10(3):208-212. Available:https://doi.org/10.46690/ager.2023.12.07.
33. Li G., Song X., Tian S., Zhu Z. Intelligent drilling and completion: A review. Engineering. 2022;18. Available:https://doi.org/10.1016/j.eng.2022.07.014.
34. Tran NL, Gupta I, Devegowda D et al. Application of interpretable machine-learning workflows to identify brittle, fracturable, and producible rock in horizontal wells using surface drilling data. SPE Reservoir Evaluation & Engineering. 2020;23(4):1328–1342. https://doi:10.2118/202486-PA.
35. Mohaghegh Shahab D. Recent developments in application of artificial intelligence in petroleum engineering. J Pet Technol. 2005;57(04):86-91. Available:https://doi:10.2118/89033-JPT.
36. Yin Q., Yang J., Liu S., et al. Intelligent method of identifying drilling risk in complex formations based on drilled Wells data. In: SPE Intelligent Oil and Gas Symposium. OnePetro; 2017. Available:https://doi.org/10.2118/187472-MS.
37. Kumar A. Perspectives of Flow Assurance Problems in Oil and Gas Production: A Mini-review. Energy & Fuels. 2023;37(12): 8142-8159; Available:https://doi:10.1021/acs.energyfuels.3c00843.
38. Joshi NB, Moin M, Louis CJ, McFadden J. "Flow Assurance: A challenging path to well completions and productivity." Paper presented at the Offshore Technology Conference, Houston, Texas; 2003, may. Available:https://doi.org/10.4043/15185-MS.
39. McMullen N.D. "Flow-Assurance Field Solutions (Keynote)." Paper presented at the Offshore Technology Conference, Houston, Texas, USA; 2006, May. Available:https://doi.org/10.4043/18381-MS.
40. Shayan NN, Mirzayi B. Adsorption and removal of asphaltene using synthesized maghemite and hematite nanoparticles. Energy Fuels. 2015;29(3):1397–1406.

Available:http://dx.doi.org/10.1021/ef502494d.

41. Yi Kang, Shuo Shi, Hao Sun, Jie Dan, Yanmin Liang, Qiuping Zhang, Zehui Su, Jianlong Wang, Wentao Zhang. Magnetic Nanoseparation Technology for Efficient Control of Microorganisms and Toxins in Foods: A Review. J. Agric Food Chem. 2022;70(51):16050-16068. Available:https://doi:10.1021/acs.jafc.2c07132.
42. Bowman, Frank. “Magnetic Separation: A Comprehensive Overview.” Ind Eng Manag. 2023;12:195. Available:https://doi:10.37421/2169-0316.2023.12.195.
43. Zhou K, Zhou X, Jie Liu J, Huang Z. Application of magnetic nanoparticles in petroleum industry: A review. J. Pet. Sci. and Eng. 2020;188:106943. Available:https://doi.org/10.1016/j.petrol.2020.106943.
44. Lü T, Zhang S, Qi D, Zhang D, Vance GF, Zhao H. Synthesis of pH-sensitive and recyclable magnetic nanoparticles for efficient separation of emulsified oil from aqueous environments. Appl. Surf. Sci. 2017;396:1604-1612. https://doi.org/10.1016/j.apsusc.2016.11.223.
45. Wu L, Zhang JP, Li BC, Wang AQ. Magnetically driven super durable superhydrophobic polyester materials for oil/water separation. Polym. Chem. 2014; 5:2382-2390. Available:https://doi.org/10.1039/C3PY01478A.
46. Tesfaye AT, Moges MA, Moges MM et al. Reservoir sedimentation evaluation using remote sensing and GIS approaches for the reservoirs in the upper Blue Nile Basin. Sustain. Water Resour. Manag. 2023;9:23. Available:https://doi.org/10.1007/s40899-022-00792-0.
47. Kazemi N, Nejadi S, Auriol J, Curkan J, Shor RJ, Innanen KA, Hubbard SM, Ian D, Gates ID. Advanced sensing and imaging for efficient energy exploration in complex reservoirs. Energy Rep. 2020;6:3104-3118. Available:https://doi.org/10.1016/j.egyr.2020.11.036.
48. Lauren E. Marbella, Jill EK. NMR Techniques for Noble Metal Nanoparticles. Millstone Chemistry of Materials 2015;27 (8):2721-2739. Available:https://doi:10.1021/cm504809c.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/113342