Al-Qadisiyah JournalFor Engineering Sciences 19 (2026) 211 – 218

Contents lists available at: http://qu.edu.iq

Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: https://qjes.qu.edu.iq

Research Paper

Performance evaluation of titanate nano structures on enhancement of oil recovery

Zainab M. Mahdy , ***Abdulwahid A. Al-Hajjaj*** , ***and Shaima Albazzaz***

Department of Chemical Engineering, College of Engineering, University of Basrah, Al-Basrah, Iraq.

ARTICLE INFO

Article history:
Received 13 July 2024
Received in revised form 13 October 2025
Accepted 10 March 2026

keyword:
Oil recovery
Rheological
Titanate
Nanoparticles
Nanotubes
Crude oil

ABSTRACT

As global energy consumption increases, there is an increasing desire to investigate nanotechnology-based approaches for enhancing oil recovery. Integrating nanostructures has shown an augmentation in the rate of crude oil recovery. This study used Iraqi crude oil obtained from well-known fields in Basra, such as Majnoon, Zubair1, North Rumaila, Nahran Omar, and West Qurna1, which feature unique attributes. Titanate nanoparticles (TiNP) and titanate nanotubes (TiNT) were employed as additives to enhance various properties of Iraqi heavy crude oil, including viscosity, API, specific gravity, surface tension, and interfacial tension. These additives were used either as enhancers or for advanced treatment purposes. The research examined the influence of various concentrations of nanoparticles (ranging from 0.01 to 0.1 wt%) on the efficiency of systems developed for crude oil characteristics. TiNT exhibited outstanding performance in the face of a 37% fall in the viscosity of Majnoon crude oil, surpassing the performance of other fields to a greater extent. The surface tension of Zubair1, North Rumaila, Nahran Omar, and West Qurna1 fields fell by 15.5%, 14.5%, 15.1%, 18.6%, and 15.7%, respectively. Similarly, the addition of 0.1 wt% of TiNT resulted in reductions of 26.07%, 19.7%, 23.4%, 23.6%, and 19.6% for the aforementioned areas. The impact of TiNT on IFT was reduced by up to 22.3%. However, TiNP demonstrated more efficacy than TiNT in decreasing the specific gravity by 4.3% in crude oil from the Majnoon field. The inclusion of titanate nanostructures resulted in the following API values: 23.5%, 19.5%, 17%, 22.4%, and 21.2% with TiNP; and 15.15%, 14.8, 15.4%, 15.6%, and 8.2% with TiNT at a concentration of 0.1 wt%.

1. Introduction

Rheology is the scientific study of how crude oil flows and changes shape, and it examines the relationship between force, deformation, and time. Understanding the flow properties of reservoir fluids such as brine, crude oils, and other fluids utilized in enhanced oil recovery (EOR) is of utmost importance in the oil and gas industry. This area plays a critical role in analyzing and studying these features [1,2]. Crude oil is an intricate mixture of hydrocarbons, Sulphur, nitrogen, oxygen, and organometallic compounds. It may be classified into four categories: saturates, aromatics, resins, and asphaltenes [3–6]. It is essential for countries with urgent fuel requirements, particularly in the industrial, energy, and transportation sectors [7–10]. The increase in specific gravity and viscosity hinders the manufacture, transportation, and processing of the substance [11].The exhaustion of traditional oil reserves and increasing energy requirements have prompted the investigation of innovative methods to improve oil extraction from mature regions. Methods for Enhanced Oil Recovery (EOR) have been devised to reduce the mobility ratio and interfacial tension [12]. Tertiary recovery, commonly referred to as enhanced oil recovery (EOR), involves a range of processes including thermal flooding, miscible flooding, and chemical flooding. Enhanced oil recovery technologies are sophisticated methods used in mature oil fields to improve the viscosity of crude oil, hence facilitating its extraction. When choosing the optimal technique for enhancing oil recovery, several elements like reservoir formation, oil composition, rock characteristics, and other criteria are meticulously taken into account. Among all the enhanced oil recovery (EOR) methods, the majority of them have not attained economic viability. Moreover, the selection of a suitable applicable methodology mostly depends on the kind of reservoir and the composition of hydrocarbons, in addition to several other parameters. Heat-based recovery methods, such as Cyclic Steam Stimulation (CSS) and steam flooding, have been shown to be very effective in recovering heavy oil and bitumen. Gas injection methods, including both miscible and immiscible gas flooding, may be used to extract light oil. Enhanced oil recovery (EOR) techniques that use chemical processes, such as surfactant flooding, polymer flooding, and surfactant-polymer flooding, have shown significant promise in reducing the residual oil content in crude oil reservoirs [13]. Studies on nanoparticle suspension for enhanced oil recovery (EOR) have shown advantages, such as remarkable stability attributed to surface forces prevailing over gravity and reliance on nanoparticle size and form [14]. Various nanoparticles have been shown to improve recovery and increase hydrocarbon output in experimental tests [15]. For instance, the rheological properties of heavy crude oils (HO) when ultrasonic cavitation is combined with NiO-functionalized SiO_2 nanoparticle have been investigated by Daniel et al [16]. The results showed significant changes in HO rheology, including reduced viscosity by 50%-60%, reduced power per unit volume wasted during a hysteresis cycle by around 70%, and decreased sample elasticity. In another study, Harshkumar et al. examined the effect of three metal oxide nanoparticles (Fe_2O_3, CuO, and NiO) on heavy oil viscosity. It found a significant decrease in viscosity for both samples, with a 50-70% decrease for each type of nanoparticle. The optimal concentration of nanoparticles was determined by the metal type and fluid temperature [17].

*Corresponding Author.
E-mail address: zainab.mohammed98@uobasrah.edu.iq ; Tel: (+964) 782-265 5319 (Zainab Mahdi)

https://doi.org/10.30772/qjes.2024.151866.1311

Nomenclature

API	American Petroleum Institute gravity	*FTIR*	Fourier transform infrared
IFT	American Petroleum Institute gravity	*HO*	Heavy oil
SFT	Surface tension (mN/m)	*NP*	Nano particle
$S_p.gr$	Specific gravity	*PFA*	Polytetrafluoroethylene round-bottom flask
Greek Symbols		*TEM*	Transmission electron microscopy
v	Kinematic Viscosity *Cst*	*TiNP*	Titanate nanoparticle
Subscripts		*TiNT*	Titanate nanotube
CSS	Cyclic Steam Stimulation	*XRD*	X-Ray Diffraction
EOR	Enhanced oil recovery		

On the other hand, S. Afzal et al [18]. has been investigating the effect of different metal oxide concentrations on heavy oil viscosity at different temperatures. Results show that certain concentrations of these nanoparticles reduce viscosity by less than 50%, with Fe_2O_3, NiO, and WO_3 being the most optimal. The maximum reduction is achieved at 0.2% and 0.5%, with the impact being more pronounced in thermal process recovery at elevated temperatures. Also studied the effect of nanoparticles on aquathermolysis by Ronal et al., a process that increases cracking and reduces crude oil viscosity. The study used a high-viscosity oil and found that the addition of (Mg, Ni)O and TiO-NiO, TiO_2 nanoparticles led to similar decreases in viscosity and sulphur content. The study suggests that TiO_2 nanoparticles can improve oil quality by reducing heavy components and lowering viscosity by up to 13.4% [19]. While Sarah et al. [20]. Examined three pipes with varying inner diameters, concentrations, and flow rates. Results showed superior drag reduction performance in larger pipes. Titanium dioxide nanoparticle (TiO_2NP) significantly impacted RCR viscosity, resulting in a maximum deviation of 1.6% and decreased pressure drop, Drag Reduction %, and shear stress. In contrast, Amin et al. have investigated the impact of graphene oxide nanosheet (GO)/and TiO_2 nanocomposite on Oil recovery in Cedr extraction solutions. The GO/TiO_2-augmented solution showed the lowest interfacial tension, achieving 65% oil recovery compared to 56% and 40% in bare Cedr solutions [21]. Furthermore, Iman et al [22] utilized nanoparticles in carbonated water to improve carbon dioxide solubility in salty water. The carbonated Nano fluids, containing TiO_2, $\gamma - Al_2O_3$, and MgO, achieved the lowest contact angle values and recovered significant amounts of primary oil, resulting in a 30%, 25%, and 18% increase in solubility. While Jagar et al. presented a nano-enhanced Oil recovery agent using TiO_2/SiO_2/poly(acrylamide) nano composites derived from pomegranate seed extract. The nano-smart solutions, created by dispersing NCs into smart water, showed reduced. IFT, increased wettability, and increased oil recovery. The best performing smart-Nano fluid, Nano-OSS3, increased oil recovery from 36.0% to 46.53%[23]. The objective of this work is to evaluate the potential uses of Nano materials, especially of (TiNP) and (TiNT), for different types of Iraqi oils that can be collected from petroleum fields in Basra and other regions of Iraq In EOR. The material, Titanium dioxide nanotube (TiNT), will be synthesized using an innovative hydrothermal process.

2. Materials and methods

The crude oil used in this study was acquired from the major oil reservoirs in Basra, Majnoon, Zubair 1, North Rumaila, Nahran Omar, and West Qurna1. Table 1 provides a comprehensive characterization of the crude oil sample taken from the above fields. The TiNP with a particle size of 10 ± 30 *nm* used in the experimental study was supplied from SkySpring Nanomaterials, Inc., USA. The properties are shown in Table 2. The chemicals used in this study (sodium hydroxide, potassium hydroxide, and hydrochloric acid) were obtained from the USA, INDIA and their specifications are listed in Table 2.

3. Experimental work

3.1 Synthesis of titanate nanotubes

Titanate Nanotubes (TiNTs) in protonated form were synthesized using an alkaline hydrothermal process at a pressure of 10 atmospheres, using an aqueous solution of NaOH and KOH. A combination including 25 gr of TiO, NaOH, and 10 cm^3 of powder was dispersed in a solution consisting of 240 cm^3 of 10 molar concentration KOH aqueous solution. The dispersion was carried out in a PFA round-bottom flask, and the mixture was refluxed for a duration of 72 hours at about 110 °C and atmospheric pressure. The final product was cooled to ambient temperature and subjected to several water washes until the pH of the wash water was within the range of 7 to 8. To convert TiNTs into its protonated form (H-TiNT), a 0.1 *mol* dm HCI solution was added gradually until a stable pH value of 2 was reached. The resulting mixture was then washed with water to obtain a pH of 5. The specimen was subjected to filtration and thereafter subjected to vacuum drying for an extended period of time at room temperature [24, 25]. Figure 1 shows the synthesis of Titanate Nanotubes procedures.

Table 1. Crude oil properties of the major fields in Basra.

Field	Properties				
	SP.GR	**API**	**Viscosity** *Cst*	**SFT** mN/m	**IFT** mN/m
Majnoon	0.9089	25.27	25.390	27.46	35.76
Zubair1	0.8893	27.6	21.055	26.58	34.89
North Rumaila	0.8802	29.03	15.5	26.58	33.06
Nahran Omar	0.8952	26.33	13.34	26.48	34.69
West.Qurna1	0.9051	24.62	20.26	27.70	34.97

Table 2. List of materials used and their specifications.

Material	Specifications	Supplier
Titanium dioxide	Formula: TiO_2 Molecular Weight: 79.90 g/mol Purity: 99.5% Form: powder Color: White	SkySpring Nanomaterials, Inc. USA
Sodium Hydroxide	Formula: NaOH Molecular Weight: 40.00 g/mol Purity: 97.5% Form: Pellets Color: White	INDIA
Potassium Hydroxide	Formula: KOH Molecular Weight: 56.11 g/mol Purity: 85% Form: Flakes Color: White	INDIA
Hydrochloride acid	Formula: HCL Molecular Weight: 36.46 g/mol Purity: 36.5-38.0% Form: Liquid Color: Light yellow	USA

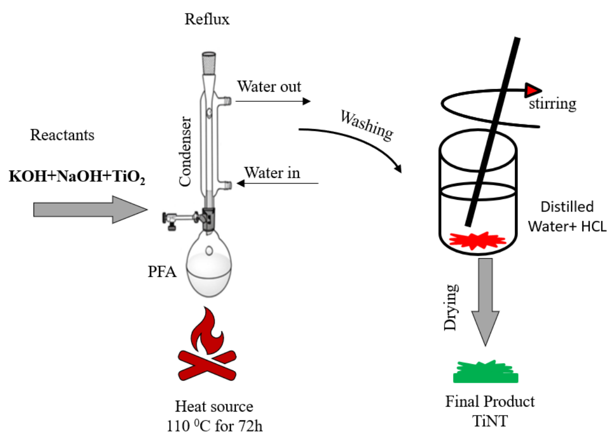


Figure 1. Synthesis of Titanate Nanotubes procedures.

3.2 Characterization of the nanostructures

The study analyzed TiNP and TiNT powders using surface analysis techniques and traditional characterization procedures. Techniques used included transmission electron microscopy (TEM), Fourier transform infrared (FTIR) spectroscopy, and X-Ray Diffraction (XRD). TEM was performed using a JEOL 3010 microscope, while FTIR spectra were recorded using a JASCO FTIR-4100 instrument. XRD was performed using a PAN alytical X-Pert Pro instrument, using $CuK\alpha_1$ radiation at a current of 30 mA and voltage of 40 kV. The XRD measurements were taken within an angular range of 5°to 60°(2θ) using Cu K radiation. The results provide valuable insights into the nanostructures of these powders. The study highlights the importance of characterization in the development of nanomaterials.

3.3 Experimental procedure

Before the addition of TiNP and TiNT, the physical characteristics of the crude Oil were measured. The included properties are Viscosity, specific gravity, API, SFT, and IFT subsequently, 500 *ml* of Crude Oil was extracted from each sample and introduced into a beaker. Additionally, various proportions of titanium nanoparticles and nanotubes were quantified, namely 0.001%, 0.002%, 0.003%, 0.004%, 0.005%, and 0.1%. Notably, the first concentration of titanium nanoparticles was added to the crude oil. The crude oil and titanium nanoparticles were mixed for 5 to 10 minutes for a homogeneous combination. Then the properties of the mixture were measured.

3.4 Tests of crude Oil properties

3.4.1 SP.GR, and API measurement

A density metre was used to measure the specific gravity and API. The ASTM D1298 standard measures specific gravity and API gravity at a temperature of 15 °C (60 °F). The property values of density are expressed in g/cm^3 at a temperature of 20 °C, but the actual gravity, known as API gravity, is indicated with respect to a certain reference temperature.

3.4.2 Viscosity measurement

The viscosity of the crude Oil sample was determined using the ASTM D 446 method. The capillary viscometer equipment, which includes a glass capillary with a regulated aperture, was placed in a water bath with controlled temperature. To determine the viscosity of the sample, the fluid was transferred from one container to another by passing it through one of the capillary tubes that were placed. After the flow achieves a state of equilibrium, the time is recorded. SFT and IFT measurement Tensiometer with a Display panel was used to measure surface and interfacial tensions in mN/m according to the ASTM D971-12 method.

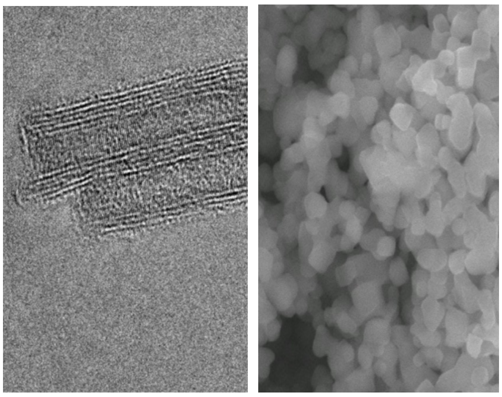
3.4.3 SFT and IFT measurement

A tensiometer with a Display panel was used to measure surface and interfacial tensions in mN/m according to the ASTM D971-12 method.

4. Results and discussion

4.1 Results of characterization of nanostructures

Figure 2 shows TEM images of titanate nanotubes and titanate nanoparticles, illustrating their characteristic wall structure. In Figure Fig. 2a, the nanotubes have four walls with a gap of 0.72 *nm* in the protonated state. They have an inner diameter of 10 *nm* and are open at both ends. The interior diameters in the sample show significant variation compared to nanotubes created using templating techniques. The radial cross-section of a specific nanotube has a prominent seam, while the axial cross-section of another nanotube has an uneven number of walls [26]. Nanotubes can reach lengths of several microns, resulting in large aspect ratios [27]. They are haphazardly arranged into clusters of particles, and their characteristics are determined by the size and form of the synthetic conditions. Agglomerates typically have a size in the range of several microns. The synthesised TiO2 nanoparticles have a well-defined crystalline structure, spherical form, and morphology, with a size of 100 *nm* [28].
Figure 3 shows the FTIR spectra of protonated TiNT that was synthesised using hydrothermal methods. The FTIR spectra provide valuable information about the properties of the generated substance. that display transparency in the spectral band from 2040 to 2200 cm^{-1}. The graph illustrates the spectrum of vibrations exhibited by the TINT. The sample has a band at 2154 cm^{-1} within the wavenumber range of 2200 to 2000 cm^{-1} regarding the (O), the position of this band is shifted towards lower energy levels, namely at 2152 cm^{-1}. The TiNTs sample is transparent over the analysed range of wavenumbers. The TiNT produced with this method demonstrates exceptional quality and is well-suited for several future applications [29, 30]. Figure 4 shows the X-ray diffraction (XRD) patterns of the original titanium nanotubes (TiNTs). The sample's diffraction pattern exhibits clear reflections that originate from TiNT. These findings indicate that the crystal structure of the TiNTs stays mostly unaltered throughout reversible ion exchange processes. The composite consists of O-Ti, which creates a highly organised phase on the surfaces of TiNT [31].



(a) Model 01-TiNT (10 nm) (b) Model 02- TiNP (100 nm)

Figure 2. TEM image of models.

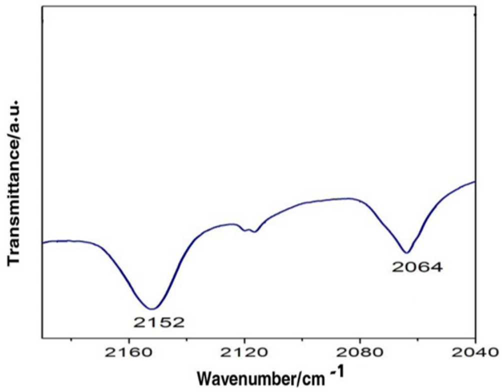


Figure 3. Infrared spectra (FTIR) of TiNT composite.

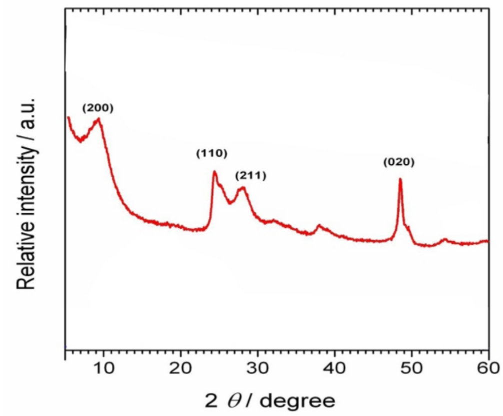


Figure 4. XRD patterns of TiNT.

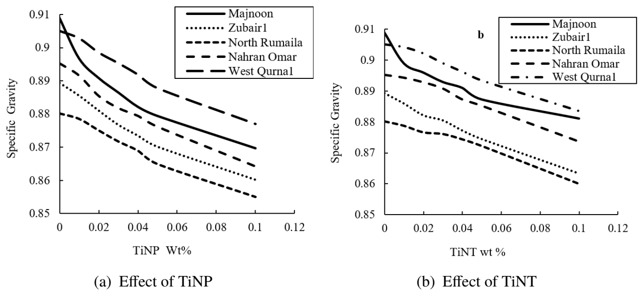
4.2 Effect of TiO_2 nanostructures on crude oil properties

Chemical enhanced oil recovery often involves the addition of chemicals, such as surfactants, polymers, macromolecules, and nanomaterials. Herein, we will represent the effect of titanate nano particles (TiNPs) and titanate nanotubes (TiNTs) on improving oil recovery for a crude oil sample taken from different oil fields at Basrah area. This is achieved by enhancing specific properties, such as rheological properties(Sp.gr, API, Viscosity, SFT, and IFT).

4.2.1 Specific gravity, API gravity

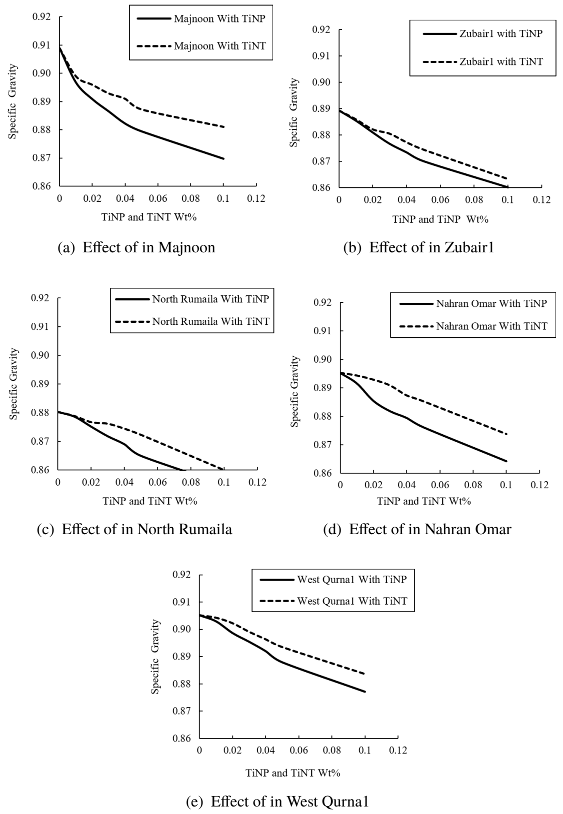
The addition of TiNP and TiNT results in a reduction in specific gravity, as seen in Figs. 5a and b. Since specific gravity (sp.gr) directly correlates with density, it decreases as the rate of nanomaterial incorporation increases. The addition of TiNP and TiNT to crude oil results in the breakdown of heavy crude oil molecules, namely, asphalt and resins. This breakdown causes the molecules to fragment into smaller units, which in turn decreases the density and specific gravity of the crude oil. Also The interaction between the nanostructures and the crude oil molecules is responsible for the decrease in specific gravity. This interaction alters the crude oil's fine structure, resulting in more porous structures with a lower density and specific gravity [32].

The results are shown for the main regions of Majnoon, Zubair 1, North Rumaila, Nahran Omar, and West Qurna 1. As mentioned, the addition of 0.1 wt% of TiNP results in drop percentages of 3.1%, 2.9%, 2.3%, 2.4%, and 2.4%. The addition of the same proportion of TiNT resulted in drop percentages of 3.1%, 2.9%, 2.3%, 2.4%, and 2.4%. This study provided evidence that the Majnoon field is subject to the most significant level of impact and subsidence due to additional causes, which may be related to its distinct features. The comparison of each primary category with TiNP and TiNT is shown in Fig. 6. Prior to the addition, Majnoon and West Qurna 1 had identical specific gravity values.



(a) Effect of TiNP (b) Effect of TiNT

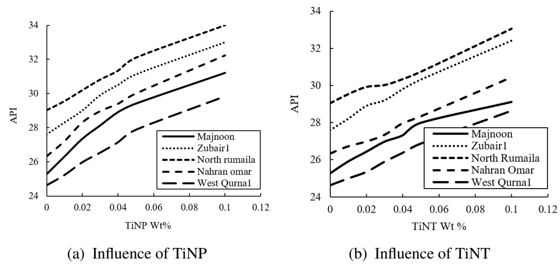
Figure 5. Effect of items concentration on specific gravity.



(a) Effect of in Majnoon (b) Effect of in Zubair1 (c) Effect of in North Rumaila (d) Effect of in Nahran Omar (e) Effect of in West Qurna1

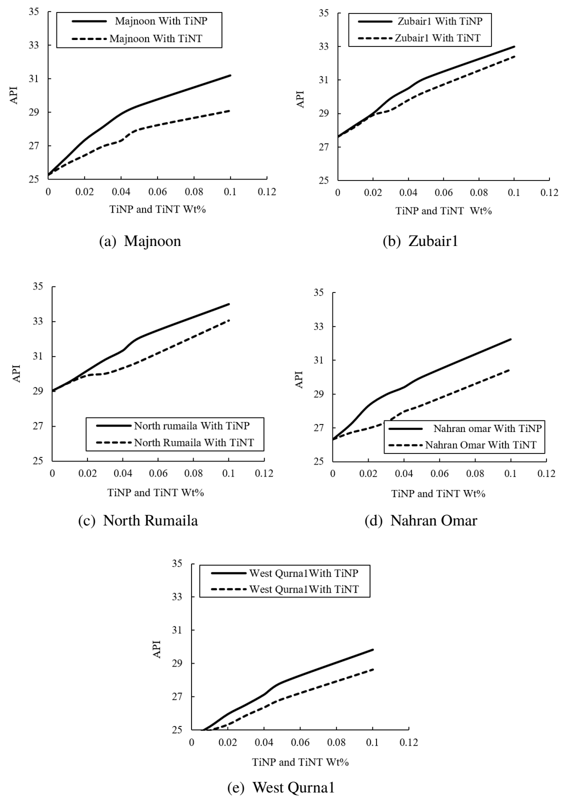
Figure 6. Comparison between the effect of concentration of TiNP and TiNT on Crude Oil Specific gravity in five locations.

Nevertheless, after the inclusion, it became apparent that Majnoon experienced a greater adverse effect and exhibited a lower specific gravity. However, Omar and West Qurna showed comparable results due to the unique qualities specific to each area .Figure 7 shows the effect of nanoparticle and nanotube concentration on the increase in API value at a temperature of 15°C [33]. The highest API value was observed at a concentration of 0.1% for both TiNP and TiNT. However, the effect of temperature on the API was negligible. Increasing the percentages of TiNP and TiNT in the crude oil resulted in an increase in the API value because. Adding this nanostructure into crude oil results in the decomposition of the heavier components of the crude oil, the absorption of heavy contaminants, better dispersion, and increased thermal impacts. These modifications result in a decrease in density and specific gravity, thereby causing a rise in the API value, which is inversely related to density and specific gravity. This rise was beneficial for the oil industries, making the oil more usable. The concentration of TiNP and TiNT in the API at Majnoon, Zubair1, North Rumaila, Nahran Omar, and West Qurna1 was 0.1%. Specifically, the percentage of TiNP was 23.5%, 19.5%, 17%, 22.4%, and 21.2%, respectively, while the percentage of TiNT was 15.15%, 14.8%, 15.4%, 15.6%, and 8.2% .Figure 8 shows the comparison between each field using TiNP and TiNT. The API values of each field, Majnoon and West Qurna1, are in close proximity.



(a) Influence of TiNP (b) Influence of TiNT

Figure 7. Influence items concentration on API.



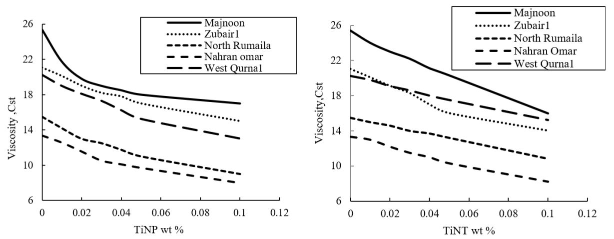
(a) Majnoon (b) Zubair1 (c) North Rumaila (d) Nahran Omar (e) West Qurna1

Figure 8. Comparison between the effect of concentration of TiNP and TiNT on Crude Oil API in the tested areas.

By introducing TiNP and TiNT at a concentration of 0.1% in the Majnoon field, a more substantial increase in the API value is seen compared to West Qurna1. This is due to the fact that the initial API value of Majnoon is higher than that of West Qurna 1 because of the specific properties of majnoon oil field.

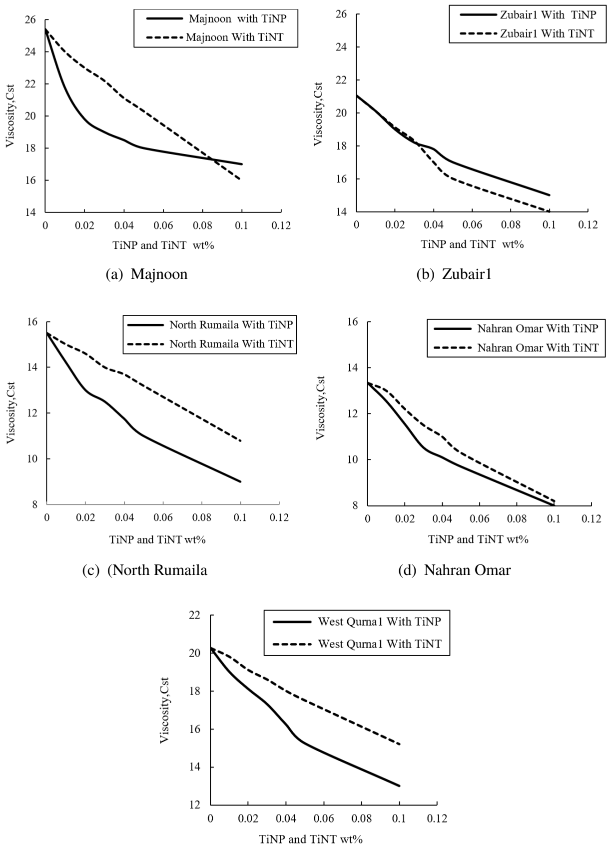
4.2.2 Crude Oil viscosity

Figure 9 shows the results of a rheological investigation carried out on Crude oil with varying concentrations of TiNP and TiNT at a temperature of 40 °C. A higher concentration of TiNP and TiNT in the crude oil leads to a decrease in viscosity. The addition of the substance at a concentration of 0.001% had a notable effect on the Majnoon field, resulting in a decrease in viscosity of 14% and 5.5%. The viscosity of the nano is more than the viscosity of crude oil, which leads to an escalation as the concentration of TiNP and TiNT increases. Figure 10 the comparison between each field with TiNP and TiNT reveals that TiNT has a greater impact on lowering viscosity in a and b, whereas TiNP is more effective in reducing viscosity in Fig. 10c, d, and e.



(a) Impact of TiNP (b) Impact of TiNT

Figure 9**.** Impact of items concentration on crude oil Viscosity.



(a) Majnoon (b) Zubair1

(c) (North Rumaila (d) Nahran Omar

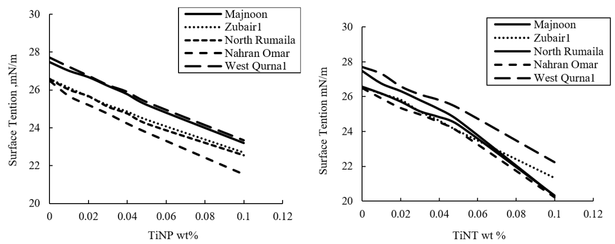
(e) West Qurna1

Figure 10**.** Comparison between the effect of concentration of TiNP and TiNT on Crude Oil viscosity in testing areas.

The outcome indicates the Majnoon field. The drop in viscosity is particularly pronounced in this sector compared to others, with a 37% reduction seen when TiNT was applied at a concentration of 0.1%. Each field has unique characteristics, and the Majnoon field exhibits a greater viscosity compared to other fields. The decrease in viscosity may be ascribed to the addition of TiNP and TiNT, which can disturb the intermolecular interactions among the bulky hydrocarbon molecules present in crude oil. This decreases the collective molecular interactions that lead to the elevated viscosity of the crude oil. Also, incorporating nanostructures into crude oil causes the dispersion of clumps formed by heavy and complex molecules, such as asphaltene, resulting in a decrease in viscosity [34].

4.2.3 SFT and IFT

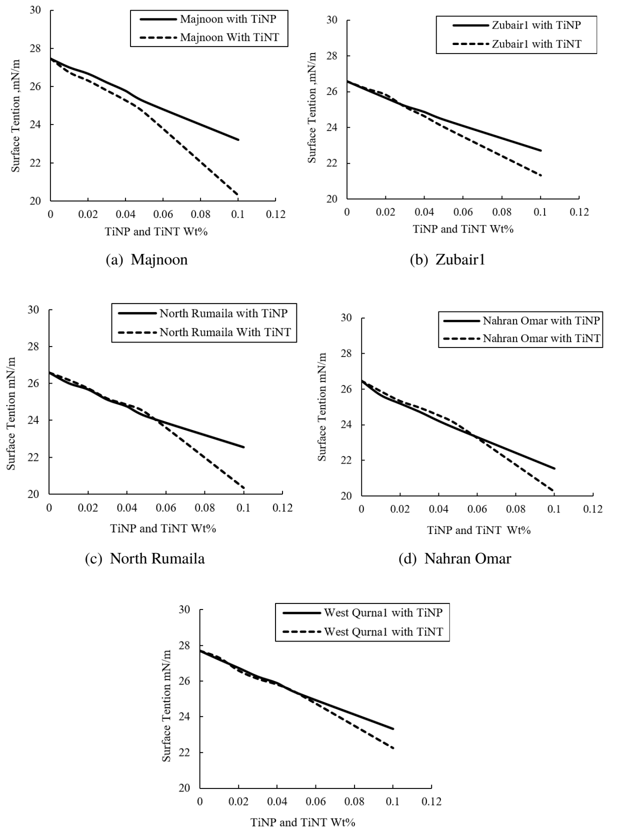
Figure 11 indicates the results of SFT. As the concentration of TiNP and TiNT rises, the SFT of crude oil decreases due to the disturbance of molecular forces, adsorption occurring at the interface, surfactant-like properties, and alteration of the oil's microstructure. TiNP and TiNT have different properties that contribute to reducing the SFT of crude oil. TiNP has a high surface area, while TiNT has a high aspect ratio and the ability to form systems. These properties enhance the wettability alteration of oil wet surface. The addition of TiNP decreases the contact angles between the oil and the surface, and alters the surface wettability towards being more water-wet when the concentration of TiNP is increased. This leads to an increase in the alteration of the oil wet surface towards being more water-wet [35], dispersion of additives, and flow properties of crude oil. In the major oil fields, namely Majnoon, Zubair1, North Rumaila, Nahran Omar, and West Qurna1, the SFT was reduced by 15.5%, 14.5%, 15.1%, 18.6%, and 15.7% respectively when 0.1wt% of TiNP was used. Similarly, when 0.1 wt% of TiNT was used, the reduction in SFT was 26.07%, 19.7%, 23.4%, 23.6%, and 19.6%, respectively. The comparison between each major field using TiNP and TiNT is shown in Fig. 12. The findings clearly demonstrate that TiNT is more effective in lowering SFT because the special characteristics of the Majnoon oil field include its unique qualities, chemical composition, thermal chemical conditions, greater initial surface tension, and restricted interactions with the nanostructure. The presence of these components renders the Majnoon field more susceptible to the influence of the nanostructure, resulting in a reduction in surface tension compared to other fields.



(a) Effect of TiNP (b) Effect of TiNT

Figure 11**.** Effect of items concentration on SFT.

Figure 12b and c displays identical SFT values in Zubair1 and North Rumaila. Nevertheless, the decline in SFT is more pronounced in North Rumaila compared to Zubair, primarily because of the distinct characteristics shown by each region. The findings indicated that the Majnoon field exhibits the lowest SFT and is susceptible to changes when nanomaterials are introduced, owing to its unique characteristics. Furthermore, the initial surface tension value of the Majnoon field is greater compared to the other fields[36]. Furthermore, the oil-water interfacial tension was assessed using different weight percentages of TiNP and TiNT (0.01, 0.02, 0.03, 0.04, 0.05, and 0.1 wt%) at the standard temperature of 25 °C. The IFT between the oil and water, with varying concentrations of TiNP and TiNT (0.01, 0.02, 0.03, 0.04, 0.05, and 0.1 wt%) are shown in Fig. 13. It is evident that the IFT dropped as the concentration of TiNP and TiNT increased. This phenomenon is caused by the augmentation of Brownian motion as a consequence of repulsive forces. The addition of TiNP and TiNT may have a substantial impact on wettability. This suggests that the texture and porosity of the reservoir rock can be altered and enhanced when TiNP and TiNT are present. The findings suggest that the optimal reduction rate for the IFT value is 0.1 wt% for both nanoparticles and nanotubes, resulting in a drop in the major fields as follows: The percentages with TiNP are 21.7% in Majnoon, 13.7% in Zubair1, 15.2% in North Rumaila, 14.8% in Nahran Omar, and 15.3% in West Qurna1, whereas the percentages with TiNT are 22.3%, 14.5%, 18.2%, 16.1%, and 17.9%. The interfacial tension value drops at a minimum rate of 0.04 wt% for both NPS and NTS [37].

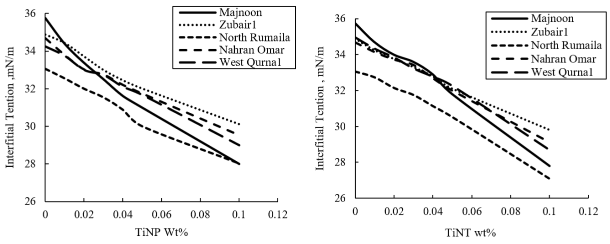


(a) Majnoon (b) Zubair1

(c) North Rumaila (d) Nahran Omar

(e) West Qurna1

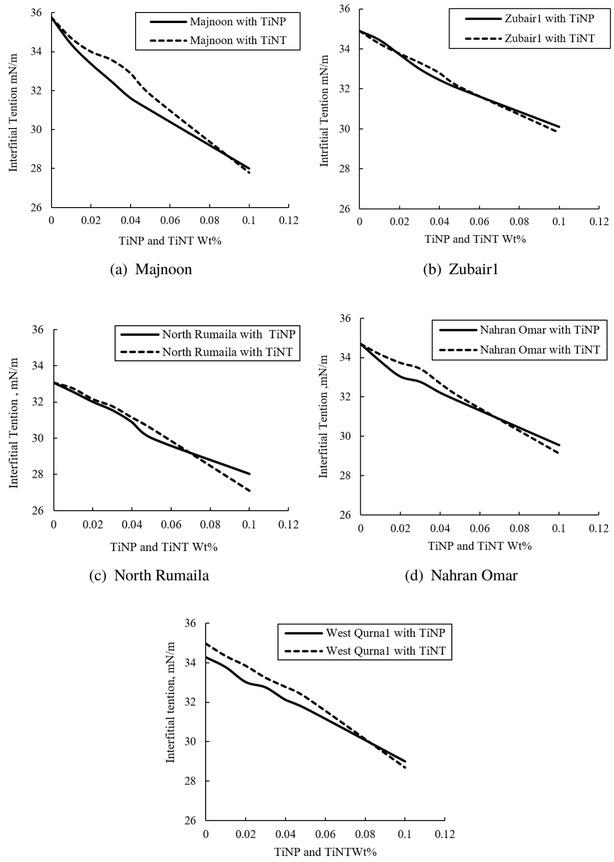
Figure 12**.** Comparison between the effect of concentration of TiNP and TiNT on Crude Oil Specific gravity in five study zones.



(a) Impact of TiNP (b) Impact of (TiNT

Figure 13**.** Impact the items' concentration on IFT.

The comparison of important fields using TiNP and TiNT is shown in Fig. 14. The findings demonstrated that TiNT is superior to TiNP in decreasing IFT in all domains, owing to its elevated aspect ratio, improved adsorption capacity, superior interaction with oil constituents, capability to establish stable networks at the interface, and potential for surface functionalization. These characteristics allow TiNP to more effectively weaken the attractive interactions between oil molecules, resulting in a greater decrease in the tension between different surfaces and enhancing the overall effectiveness in applications such as increased oil recovery and emulsion stabilization. Fig. 14b and d depict The interfacial tension values of the Zubair1 and Nahran Omar fields were similar before the addition. However, after the addition, the Nahran Omar field exhibited a lower IFT value. This is attributed to its unique characteristics. Crude oil's hydrocarbon composition of Nahran Omar is highly influenced by the active surface features of nanostructures, resulting in a significant reduction in interfacial tension. In addition, Nahran omar has some contaminants which is not found in the Zubair1 field. These contaminants function as reducing agents, rendering it more susceptible to decline. Furthermore, the physical and chemical features of Nahran Omar facilitate the dispersion of the nanostructure, resulting in a more uniform contact with the surface components. As a result, the terfacial tension is reduced more compared to the Zubair1 field. On the other hand, the Majnoon field was more significantly influenced by nanomaterials, resulting in a lower IFT value. It is important to note that each field possesses its own unique properties [38].



(a) Majnoon (b) Zubair1

(c) North Rumaila (d) Nahran Omar

(e) West Qurna1

Figure 14**.** Comparison between the effect of concentration of TiNP and TiNT on Crude Oil Specific gravity in different zones.

5. Conclusion

The crude oil included a comprehensive characterization process. The rheological characteristics of the material were thoroughly examined. TiNT was synthesised via hydrothermal synthesis. This experimental investigation explored the effects of TiNP and TiNT on the rheological properties of crude oil. It has a notable capacity to decrease specific gravity, viscosity, surface tension, and interfacial tension in the analysed crude oil samples. The Majnoon oil field saw a more significant decline in production compared to other fields, with a fall of 4.3%. The use of nanoparticles is superior in efficiency compared to TiNT. Majnoon had the most significant drop in viscosity, with a reduction of 23.5%. Zubair 1 had a decrease of 19.5%. Both occurred at a TiNT content of 0.1 wt% and a temperature of 40 °C. Nevertheless, the addition of TiNP resulted in much more significant decreases in viscosity in North Rumaila, Nahran Omar, and West Qurna1. The maximum API value was discovered at a concentration of 0.1 weight percent, notably when TiNP was used. The proportions of oil output in Majnoon, Zubair1, North Rumaila, Nahran Omar, and West Qurna1 were 23.5%, 19.5%, 17%, 22.4%, and 21.2%, respectively. Furthermore, the API values were selected using TiNT. The percentages were 15.15%, 14.8%, 15.4%, 15.6%, and 8.2%. The surface tension of these fields decreased by 15.5%, 14.5%, 15.1%, 18.6%, and 15.7% accordingly when 0.1wt% of TiNP was used.

Authors' contribution

In this research, Zainab M. Mahdy conducted all practical work, performed data analysis, wrote the original draft, and contributed to conceptualization and data curation. Then Abdulwahid A. Al-Hajjaj and Shaima Albazzaz Revised and critically reviewed the results, supervised the overall study, contributed to data curation and validation, and edited the manuscript. All authors contributed to the analysis/conceptualization/data curation, and writing/reviewing of the manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] S. Sarmah *et al.*, "Study on the effects of the rheological properties for flow behaviour of assam crude oil with various chemicals," in *Contemporary Issues in Geoenvironmental Engineering: Proceedings of the 1st GeoMEast International Congress and Exhibition, Egypt 2017 on Sustainable Civil Infrastructures*, vol. 1. Springer, 2018. [Online]. Available: https://doi.org/10.1007/978-3-319-61612-4_12

[2] E. Taborda *et al.*, "A new model for describing the rheological behavior of heavy and extra heavy crude oils in the presence of nanoparticles," *Energies*, vol. 10, no. 12, p. 2064, 2017. [Online]. Available: https://doi.org/10.3390/en10122064

[3] C. Perles, V. Guersoni, and A. Bannwart, "Rheological study of crude oil/water interface–the effect of temperature and brine on interfacial film," *Journal of Petroleum Science and Engineering*, vol. 162, pp. 835–843, 2018. [Online]. Available: https://doi.org/10.1016/j.petrol.2017.11.010

[4] U. Chaudhuri, *Fundamentals of petroleum and petrochemical engineering*. Boca Raton: CRC Press, 2011. [Online]. Available: https://doi.org/10.1201/b10486

[5] M. Hussain, M. Fares, and M. Taher, "Optimization and design of a new column sequencing for crude oil distillation at basrah refinery," *Open Engineering*, vol. 14, no. 1, p. 20220571, 2024. [Online]. Available: http://dx.doi.org/10.1515/eng-2022-0571

[6] H. Jasima, A. Ala'aa, and A. Al-Hilfi, "Development of a new type of epoxy coating for crude oil storage tanks," *American International Journal of Research in Science*, pp. 13–143, 2013.

[7] F. Souas, A. Safri, and A. Benmounah, "A review on the rheology of heavy crude oil for pipeline transportation," *Petroleum Research*, vol. 6, no. 2, pp. 116–136, 2021. [Online]. Available: http://dx.doi.org/10.1016/j.ptlrs.2020.11.001

[8] R. Ibrahim, M. Odah, and A. Al-Mufti, "An overview on the recent techniques for improving the flowability of crude oil in pipelines," in *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, 2019. [Online]. Available: http://dx.doi.org/10.1088/1757-899X/579/1/012054

[9] S. Hasan, M. Ghannam, and N. Esmail, "Heavy crude oil viscosity reduction and rheology for pipeline transportation," *Fuel*, vol. 89, no. 5, pp. 1095–1100, 2010. [Online]. Available: http://dx.doi.org/10.1016/j.fuel.2009.12.021

[10] M. Meriem-Benziane *et al.*, "Investigating the rheological properties of light crude oil and the characteristics of its emulsions in order to improve pipeline flow," *Fuel*, vol. 95, pp. 97–107, 2012. [Online]. Available: https://doi.org/10.1016/j.fuel.2011.10.007

[11] J. Bassane *et al.*, "Study of the effect of temperature and gas condensate addition on the viscosity of heavy oils," *Journal of Petroleum Science and Engineering*, vol. 142, pp. 163–169, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.petrol.2016.02.006

[12] J. Navas Guzman, "Chemical enhanced oil recovery simulation in highly stratified heterogeneous reservoir: a field case study," Master's thesis, 2020. [Online]. Available: http://dx.doi.org/10.26153/tsw/8331

[13] M. Hasan, "Various techniques for enhanced oil recovery: A review," *Iraqi Journal of Oil and Gas Research (IJOGR)*, vol. 2, no. 1, pp. 83–97, 2022. [Online]. Available: http://dx.doi.org/10.55699/ijogr.2022.0201.1018

[14] M. Agista, "A literature review and transport modelling of nanoparticles for enhanced oil recovery," Tech. Rep., 2017. [Online]. Available: http://dx.doi.org/10.13140/RG.2.2.15515.57124

[15] A. Sircar *et al.*, "Applications of nanoparticles in enhanced oil recovery," *Petroleum Research*, vol. 7, no. 1, pp. 77–90, 2022. [Online]. Available: https://doi.org/10.1016/j.ptlrs.2021.08.004

[16] D. Montes *et al.*, "Effect of the nio/sio2 nanoparticles-assisted ultrasound cavitation process on the rheological properties of heavy crude oil: steady state rheometry and oscillatory tests," *Energy & Fuels*, vol. 33, no. 10, pp. 9671–9680, 2019. [Online]. Available: http://dx.doi.org/10.1021/acs.energyfuels.9b02288

[17] H. Patel *et al.*, "Effects of nanoparticles and temperature on heavy oil viscosity," *Journal of Petroleum Science and Engineering*, vol. 167, pp. 819–828, 2018. [Online]. Available: https://doi.org/10.1016/j.petrol.2018.04.069

[18] S. Afzal *et al.*, "Reduction of heavy oil viscosity using nanoparticles in enhanced oil recovery process," in *Enhanced Oil Recovery Methods: Economic Benefits, Impacts on Environment*, 2015, pp. 169–185. [Online]. Available: https://doi.org/10.1016/j.colsurfa.2021.126863

[19] R. de la Cruz Parejas *et al.*, "Effects of al2o3-nio, tio2 and (mg, ni)o particles on the viscosity of heavy oil during aquathermolysis," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 625, p. 126863, 2021. [Online]. Available: https://doi.org/10.1016/j.colsurfa.2021.126863

[20] S. Shakir *et al.*, "Effect of titanium oxide (tio2) nanoparticles on reduced crude oil residue," in *IOP Conference Series: Materials Science and Engineering*. IOP Publishing, 2020. [Online]. Available: http://dx.doi.org/10.1088/1757-899X/870/1/012058

[21] A. Garmroudi *et al.*, "Effects of graphene oxide/tio2 nanocomposite, graphene oxide nanosheets and cedr extraction solution on ift reduction and ultimate oil recovery from a carbonate rock," *Petroleum*, vol. 8, no. 4, pp. 476–482, 2022. [Online]. Available: http://dx.doi.org/10.1016/j.petlm.2020.10.002

[22] I. Nowrouzi, A. Manshad, and A. Mohammadi, "Effects of tio2, mgo and γ-al2o3 nano-particles on wettability alteration and oil production under carbonated nano-fluid imbibition in carbonate oil reservoirs," *Fuel*, vol. 259, p. 116110, 2020. [Online]. Available: https://doi.org/10.1016/j.fuel.2019.116110

[23] J. Ali *et al.*, "Emerging applications of tio2/sio2/poly(acrylamide) nanocomposites within the engineered water eor in carbonate reservoirs," *Journal of Molecular Liquids*, vol. 322, p. 114943, 2021. [Online]. Available: http://dx.doi.org/10.1016/j.molliq.2020.114943

[24] D. Bavykin and F. Walsh, "Kinetics of alkali metal ion exchange into nanotubular and nanofibrous titanates," *The Journal of Physical Chemistry C*, vol. 111, no. 40, pp. 14 644–14 651, 2007. [Online]. Available: http://dx.doi.org/10.1021/jp073799a

[25] Q. Chen *et al.*, "Active anatase (001)-like surface of hydrothermally synthesized titania nanotubes," *Chemical Physics Letters*, vol. 482, no. 1-3, pp. 134–138, 2009. [Online]. Available: https://doi.org/10.1016/j.cplett.2009.10.003

[26] M. Uddin *et al.*, "Hydrothermal synthesis of mesoporous tio2 nanoparticles for enhanced photocatalytic degradation of organic dye," *Indian Journal of Chemical Technology (IJCT)*, vol. 30, no. 3, pp. 320–330, 2023. [Online]. Available: https://doi.org/10.56042/ijct.v30i3.61561

[27] S. Kawasaki *et al.*, "Continuous supercritical hydrothermal synthesis of controlled size and highly crystalline anatase tio2 nanoparticles," *The Journal of Supercritical Fluids*, vol. 50, no. 3, pp. 276–282, 2009. [Online]. Available: http://dx.doi.org/10.1016/j.supflu.2009.06.009

[28] G. Mersal, N. Mostafa, and A. Omar, "Hydrothermal synthesis and processing of hydrogen titanate nanotubes for nicotine electrochemical sensing," *Materials Research Express*, vol. 4, no. 8, p. 085031, 2017. [Online]. Available: http://dx.doi.org/10.1088/2053-1591/aa83de

[29] S. Muniyappan *et al.*, "Conventional hydrothermal synthesis of titanate nanotubes: Systematic discussions on structural, optical, thermal and morphological properties," *Modern Electronic Materials*, vol. 3, no. 4, pp. 174–178, 2017. [Online]. Available: https://doi.org/10.1016/j.moem.2017.10.002

[30] K. Alkanad *et al.*, "One-step hydrothermal synthesis of anatase tio2 nanotubes for efficient photocatalytic co2 reduction," *ACS Omega*, vol. 7, no. 43, pp. 38 686–38 699, 2022. [Online]. Available: https://doi.org/10.1021/acsomega.2c04211

[31] S. Zhou *et al.*, "Titania nanotubes-bonded sulfamic acid as an efficient heterogeneous catalyst for the synthesis of n-butyl levulinate," *Frontiers in Chemistry*, vol. 10, p. 894965, 2022. [Online]. Available: https://doi.org/10.3389/fchem.2022.894965

[32] H. Zare, M. Bosaghzadeh, and F. Farahbod, "Investigation of physical properties of nano crude petroleum: Increasing oil flow rate in reservoirs," *Advances in Nanoparticles*, vol. 12, no. 01, pp. 1–10, 2023. [Online]. Available: http://dx.doi.org/10.4236/anp.2023.121001

[33] N. Ogolo and M. Onyekonwu, "Potential application of aluminum oxide nanoparticles in the oil and gas industry," *Journal of Oil, Gas and Petrochemical Technology*, vol. 9, no. 1, pp. 8–20, 2022. [Online]. Available: http://dx.doi.org/10.22034/JOGPT.2022.325676.1102

[34] E. Majeed and T. Naife, "Enhancement viscosity reduction and api of iraqi heavy crude oil by nanoparticles," in *AIP Conference Proceedings*. AIP Publishing, 2023. [Online]. Available: http://dx.doi.org/10.1063/5.0107261

[35] C. Jothi Prakash and R. Prasanth, "Approaches to design a surface with tunable wettability: a review on surface properties," *Journal of Material Science*, vol. 56, pp. 108–135, 2021. [Online]. Available: https://doi.org/10.1007/s10853-020-05116-1

[36] N. Hadi and D. Mohamed, "The effect of nanoparticles on the flow and physical behavior of engine lubricant oil," Master's thesis, College of Materials Engineering, Polymer and Petrochemical Industry, 2015.

[37] H. Zaid, N. Ahmad Latiff, and N. Yahya, "The effect of zinc oxide and aluminum oxide nanoparticles on interfacial tension and viscosity of nanofluids for enhanced oil recovery," *Advanced Materials Research*, vol. 1024, pp. 56–59, 2014. [Online]. Available: https://doi.org/10.4028/www.scientific.net/AMR.1024.56

[38] S. Gomaa, "Investigating the effect of different nanoparticles on the interfacial tension reduction," *Petroleum & Petrochemical Engineering Journal*, 2018. [Online]. Available: http://dx.doi.org/10.23880/ppej-16000176

How to cite this article:

Zainab M. Mahdy, Abdulwahid A. Al-Hajjaj, and Shaima Albazzaz (2026). 'Performance evaluation of titanate nano structures on enhancement of oil recovery', Al-Qadisiyah Journal for Engineering Sciences, 19 (2), pp. 211- 218. https://doi.org/10.30772/qjes.2024.151866.1311