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Conventional and Unconventional Enhanced Oil Recovery Methods: A Review Study of Ultrasound Application in EOR

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Abstract

Only a small portion of the oil can be recovered during the primary and secondary stages of oil production, leaving considerable amounts in reservoirs. Enhanced oil recovery (EOR) procedures are utilized to remove stranded high-viscosity oil from reservoirs and increase production efficiency. To address this problem, enhanced oil recovery techniques are applied. These techniques aim to increase production efficiency and remove the remaining oil from reservoirs. One promising technology that researchers are currently studying is ultrasonic-based oil recovery. This technology involves using ultrasonic waves to break down the high viscosity of the trapped oil and facilitate its removal. The ultrasonic-based improved oil recovery method is a cheap and environmentally friendly approach that can be used in any type of reservoir. It protects the well from damage, prevents heat loss, and allows for stimulation. This study provides an overview of both traditional and unconventional enhanced oil recovery methods. The traditional methods include chemical, gas, and thermal procedures, while the unconventional methods include electromagnetic, microwave heating, and ultrasonic methods. The study gives a comprehensive assessment of the literature on ultrasonic wave application and advancements in improved oil recovery. It highlights the potential benefits of ultrasonic-based improved oil recovery technology and its role in addressing the challenges facing the oil industry.

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1. Introduction

Despite advances in renewable energy, oil and gas remain the world's primary energy sources, with growing worldwide demand over the last decade. Over the last two decades, its output has climbed to 84 million barrels per day. It is regarded as a key source of economic activity in many nations, particularly in Iraq, which has traditionally provided around 95% of foreign currency revenues [1] [2]. Crude oil is a complex combination of hydrocarbons, including carbon, hydrogen, sulfur, nitrogen, oxygen, metals, and salts. Natural gas consists of tiny hydrocarbon molecules (e.g., methane, propane, butane) [3]. Petroleum products are generated by bigger hydrocarbons such as hexane and octane [4]. About 2 billion years ago, marine life and macroscopic flora and fauna went extinct and settled on the ocean floor. These fossils became kerogens as oxygen was lost beneath the seafloor silt. The heat and pressure present gradually convert the kerogen into oil or gas. In general, the formation of the two major forms of crude oil, light oil and heavy oil, takes at least one million years. Light crudes that are easily extracted have low viscosity, low density, and a high API-specific gravity. Heavy crude oil, on the other hand, has high viscosity, density, acidity, and sulfur concentration as its key qualities. Heavy crudes have viscosities ranging from 50 to 50,000 mPa, limiting their mobility and making them difficult to flow at reservoir pressure and temperature [4] [5]. As a result, crude oil is classified into four types depending on its relative density: light, medium, heavy, and extra-heavy. The final two are referred to as "heavy oil" internationally [6] [7]. Carbonate reservoirs are particularly interesting since they hold more than 60% of the world's remaining conventional oil reserves and contribute to more than 30% of daily oil production [8].

There are three stages to the production of oil: primary, secondary, and tertiary. The process of recovering oil using the reservoir's natural pressure or energy is the first stage. The first stage lasts until either the reservoir's available pressure is noticeably low or there is a large volume of gas or water in the recovery stream. Between 5 and 20% of the of the original oil in place (*OOIP*) is typically extracted at the primary stage The primary stage of oil extraction's influencing factors includes the rock's and oil's qualities and the drive mechanism [5] [9]. The secondary stage of oil recovery increases pressure inside reservoirs or by oil displacement directly into production wells and pushes oil to the surface using various methods to prolong the field's useful life [10].

Depending on the oil's characteristics, geology and reservoir characteristics, well structure and rate of oil extraction after using the secondary recovery technique can be enhanced by up to 40% [11]. Then the interfacial tension between oil and water (capillary forces), high mobility ratio, and heterogeneities in the reservoir rock are the main causes of the poor oil recovery rate in the primary and secondary phases. The tertiary recovery, or enhanced oil recovery (*EOR*), is a technique used to displace the residual oil contained in the reservoir by injecting ingredients that are not typically found in the reservoir. It is applied after the primary and secondary recovery phases, enhanced oil recovery (*EOR*) is used to recover the residual oil by increasing oil displacement and sweep efficiency. By lowering the interfacial tension or oil viscosity, the oil displacement efficiency may be increased. On the other hand, by creating a good mobility ratio between the displacing fluid and the residual oil, the sweep efficiency might be increased [12] [13] [14]. It can be represented by many techniques divided into two type conventional and unconventional as shown in **Fig. 1** [15].

Our contribution is to give a general overview of both conventional and unconventional enhanced oil recovery (*EOR*) techniques, with a focus on the advancement of ultrasonic stimulation technology for better oil recovery. The section that follows the introduction discusses traditional *EOR* techniques. The consequences of ultrasonic waves in EOR are covered in the following part of performed study. Our conclusions are presented in the final part.

2. Conventional Techniques for Recovering Heavy Oil

Following oil discovery, a primary recovery proceeds through a phase of oil production dependent on the energy or pressure of the natural reservoir. When oil cannot be retrieved if the extraction depends just on the natural reservoir pressure, EOR is utilized as a secondary recovery technique. As a result, an energy injection into the reservoir is typically necessary at this point in the recovery process. Water flooding is the most often employed secondary recovery method in traditional oil recovery. Hence, the reservoir is flooded with water to force the remaining oil toward the producing well. Yet, this approach may also result in some significant restrictions.

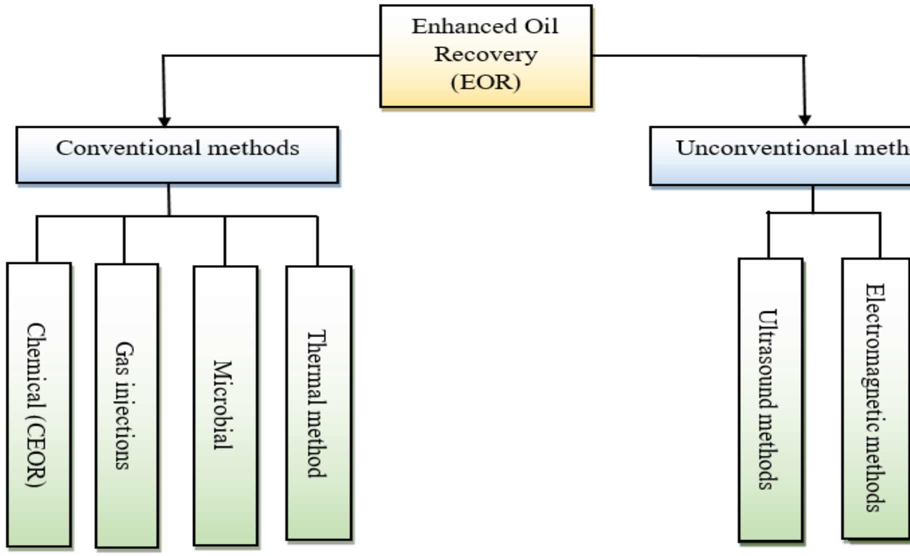

Figure 1: Methods of Enhanced Oil Recovery (EOR).

For instance, the interaction between the injected water and the formation water may result in formation damage [16] Moreover, this method can cause the subsurface electromechanical equipment to corrode (e.g. pumps, valves, and sensors). Moreover, the heterogeneous reservoir rocks might occasionally make it difficult for water to pressurize oil. This necessitates the adoption of a more potent recovery strategy, namely the tertiary recovery technique, also known as *EOR* in this work [16] [17].

The oil sector frequently uses the following EOR techniques:
- Thermal method
- Microbial
- Gas injections
- Chemical (*CEOR*)

Thermal technology is a method of producing heavy oil in which heat transfer materials are burned locally or injected into the oil layer to produce heat. The heating process reduces the viscosity of the crude oil and increases its fluidity [18]. The cost of thermal oil recovery techniques varies depending on, cyclic steam stimulation (CSS), steam-assisted gravity drainage (*SAGD*), and steam flooding (*SF*), and in situ combustion (*ISC*) [19] [20]. Microbial-enhanced oil recovery (*MEOR*) is a popular treatment approach in energy research since it is low-cost and ecologically friendly. It might thus be seen as a viable alternative to typical *EOR* techniques. The *MEOR* technique has been shown to significantly improve oil recovery in both sandstone and carbonate reservoirs with varying flow characteristics and types (microbial flooding recovery (*MFR*), cycle microbial recovery (*CMR*), micrthe type of medium used and the techniques used to generate heat, including hot water injectable selective plugging recovery (*MSPR*), and others). Unfortunately, due to a lack of data, *MEOR* is currently underfunded despite its numerous benefits [3] [16]. Chemical enhanced oil recovery, also known as alkaline flooding, polymer flooding, surfactant flooding, micellar flooding, and alkaline-surfactant-polymer (*ASP*) flooding, is a process where one or more pre-selected chemicals are combined with water and then injected into the reservoir to raise the oil recovery factor above water flooding levels. Acids, solvents, and foaming agents Flooding from low-salinity water (*LSW*) [17] [21].

The objective of *EOR* screening is to prioritize options based on reservoir characteristics and oil attribute criteria and choose an optimum approach from among them. Table 1 provides a summary of the specifics of some investigations using conventional techniques and their conclusions.

Mirosław Wojnicki et al. used the water alternating gas injection (*WAG*) method with a range of gases, such as *CO2*, acid gas (a mixture of *CO2* and *H2S* at a 70/30% vol/vol ratio), and high-nitrogen natural gases prevalent in the Polish Lowlands. The results indicate that the WAG procedure is superior to continuous gas injection (*CGI*) and continuous water injection (*CWI*), and that the use of *CO2 WAG* injection resulted in a recovery factor (RF) of up to 82%, while the use of high-nitrogen natural gas WAG injection was less successful and had a higher recovery of only 70% [22]. Qiuxia Wang et al. utilized combined profile control and thermal recovery technologies to improve heavy oil recovery. Observe the outcomes. From 10.8% at 55 °C to 42.9% at 200 °C, the oil recovery correlated with thermal recovery in the heterogeneous core increased. From 8.9% to 13.2%, more oil was recovered using thermal recovery with profile control. Three slugs of oil with various viscosities were used to maximize the regions that the thermal fluid swept at a distance of 3/10 of the injector-producer [23]. Bright Bariakpoa Kinate et al. also used the Water Alternate Gas (*WAG*) Injection Method to EOR Technique, which combines the benefits of gas injection with water flooding, to increase sweep efficiency, mobility control, and total recovery from the given reservoir. The results show that the WAG ratio was shown to have an effect on total oil recovery, with the ideal ratio falling between 1:2 and 1:3, and the oil recovery factor and cumulative production are also impacted by the longer cycle duration of water compared to gas [24]. Liang Xue et al. in this work, four fundamental technological forms—steam huff and puff, steam-driven, *SAGD*, and fire-driven—have been created. The findings show that polymer flooding at 200 MPa has issues with difficult injection and expensive chemical agents, and it is still necessary to do more research and keep an eye on how microbial oil recovery works and how chemical viscosity reduction develops [1]. Rana Abbas Azeez et al. study is concerned with the use of toluene, dimethyl ketone (*DMK*), and a mixture of toluene and dimethyl ketone (50/50 vol.%) as diluted solvents with different weight fractions (0, 5, 10, and 15 wt.%) at 298.15 K. The heavy oil needed came from the Amara oil field in southern Iraq. The findings indicated that dilution of heavy oil samples with toluene, *DMK*, or a combination of (50/50 vol.%) toluene and *DMK* is a practical method for reducing viscosity. In the presence of the diluents, there is a considerable reduction in viscosity [25]. Raheek I. Ibrahim et al. the current work focuses on contrasting the effects of polymethyl methacrylate (*PMMA*) alone and PMMA with carbon nanotubes (*CNT*) on the drag reduction of crude oil viscosity. With varying concentrations of 1000, 2000, 3000, and 4000 mg/L, the outcome demonstrates that *PMMA* is a methacrylate. Since it achieves a 65% reduction in drag, it has been proven that 3000 ppm is the best. PMMA, a polymer consisting of polymethyl methacrylate, is offered in concentrations of 1000, 2000, 3000, and 4000 mg/L. It has been established that 3000 ppm is ideal since it causes a 65% reduction in drag [26]. M. M. Hasan et al. Toe-to-heel air injection (*THAI*), a cutting-edge technique, improves the recovery and upgrading of heavy oil and bitumen. This method combines the principles of a horizontal well's with high-temperature oxidation processes to possibly achieve a high recovery ratio. It was found that the locations of the well injections and well output significantly affected the amount of oil production [27]. Changhong Gao Sinopec the results of this study, which used microbial technology for enhanced oil recovery *MEOR*, demonstrate that for the *MEOR* operations carried out in China, we saw increased injection pressure, decreased IFT, and decreased oil viscosity. In China, the bulk of MEOR initiatives were highly successful. Good outcomes were found in more than 70% of the microbe-treated wells. In China, every *MEOR* project was successful. The experiences in China show *MEOR* is efficient for difficult reservoir conditions, such as high temperature 80°C, high salinity 46,000 mg/L, and heavy oil [28]. Raheek I. Ibrahim et al. utilized the electrical field by creating and utilizing an original capacitor to lower viscosity. The results showed that as treatment time, voltage, and electrode spacing were increased, viscosity drastically decreased. The lowest viscosity was reached after 32 seconds of treatment at 188 volts and with capacitor electrodes spaced 6.11 cm apart. With a minimum viscosity of 20.479 cSt, the ideal conditions were present in this case. The results of the tests indicated that the newly created capacitor provided a good 37% power savings under optimum circumstances at 10 2°C as well as a great viscosity reduction. With a drop percentage and power savings of 60.6%, nanosilica had the lowest viscosity at its ideal concentration of 100 mg/L, which was 12.8 cSt. The 11-hour viscosity reduction is finally finished [29]. H. Yousefvand et al. the effects of nanosilica (*NS*) in the polymer flooding in the presence of salt on the oil recovery factor were investigated in a heavily oil-wet five-spot glass micromodel saturated with heavy oil. Each flooding test's efficiency was calculated using an image processing approach, which was also utilized to investigate the displacement processes. According to the results, the viscosity augmentation of the injected fluid can increase the ultimate oil recovery by around 10% when *NS* is present. Nanoparticles have the capacity to change the wettability of some regions of the micromodel to water-wet [30].

3. Unconventional Techniques for Recovering Heavy Oil

In addition to traditional enhanced oil recovery methods, there are many unconventional methods to improve the extraction of heavy oil, which represents 70% of global oil reserves. These methods are considered more effective, less expensive, and less time-consuming and they use a variety of techniques, the most important of which is electromagnetic heating, ultrasound stimulation, etc. This will reduce oil viscosity, enhance oil mobilization, and ultimately increase oil production [31]. The electromagnetic heating (*EM*) process technique is particularly advantageous for heavy oil recovery, as shown in **Fig.2**, employing the *EOR* approach that produces heat volumes, known as the eddy current loss. Eddy current is the induction of an electromagnetic field caused by an *AC* current being passed through an inductor cable [32] [33]. Depending on the frequency of the electrical current being utilized, *EM* techniques may be categorized into three groups: inductive heating (*IH*), low-frequency (resistive), and high-frequency [5]. The needed current may be generated using solar and wind energy, making this one of the most environmentally friendly solutions. The highest temperature we can get using this approach is 250˚C [18].

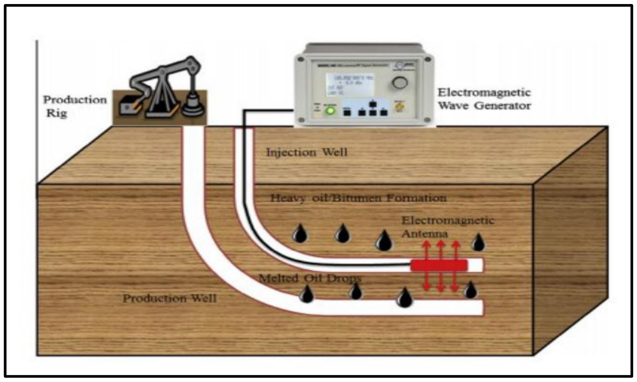

Figure 2: Electromagnetic Heating [33].

Another method for improving oil extraction and/or repairing formation damage around the wellbore is ultrasonic-based *EOR*, which uses mechanical vibration in elastic material as shown in **Fig.3** [5]. Ultrasonic waves have frequencies of 20 kHz above the human audible range. By causing vibrations around the reservoir and contributing to oil coalescence, ultrasonic waves will boost capillary strength and, as a result, the adhesion between rocks and liquids [34].

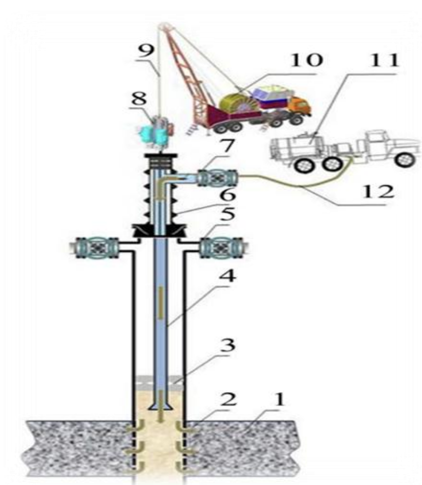

Figure 3: Hardware elements arrangement during ultrasonic treatment: 1) oil reservoir; 2) ultrasonic downhole equipment; 3) packer; 4) tubing; 5) casing valve; 6) lubricator; 7) flow out line; 8) cable feed; 9) cable; 10) wire line truck ПКС-5; 11) pump unit СИН-32, 12-house [35].

The studies that dealt with unconventional oil extraction methods and their most important findings are summarized in **Table 2**.

Jinbiao Gao et al. study looked at the connection between the electric power supplied to the *US* transducer and the viscosity of heavy oil. The outcome demonstrates that the oil sample's viscosity decreased for the majority of temperature points under ultrasonic 50 W, whether the *US* irradiation period was 6 or 12 min, and increased when the input electric power was 100 W or 200 W [8]. Augustine Agi et al. In this work, thermally treated empty fruit bunch *SiO2* nanofluid (*EFBSNF*) was produced by wet milling with the aid of ultrasound, and its effectiveness in enhancing the cavitation effect of ultrasound to improve heavy oil recovery was evaluated. According to this investigation, it was discovered that the treatment process showed a noticeable decrease in trace element concentration with increasing temperature and an equivalent increase in *SiO2* content. Ultrasound-assisted *EFBSNF* flooding enhanced oil recovery by 44.33% in comparison to *EFBSNF* flooding without ultrasound, which increased oil recovery by 26.33% utilizing Bjerknes forces and peristaltic motion [36]. Ephraim Otumudia et al. here several transparent porous micromodels were designed, built, and tested to quantitatively assess the impact of reservoir rock pore geometry and ultrasonic parameters on asphaltene deposition during ultrasonic stimulation. It was shown that the effectiveness of ultrasonic treatment at various sonication periods affected the pore geometries of the different micromodels. The percentage of eliminated asphaltene deposition after two hours increased from 12.6 to 14.7, 11.5 to 14.63, and 5.8 to 7.1 percent, respectively, when the ultrasonic power was increased from 400 to 1000 W for micromodels with throat diameters of 300 m and pore forms of circle, square, and triangle [37]. Razavifar, Mehdi et al. this study's main objective is to carry out experimental research into the interactions between solvents and ultrasonic waves in order to better understand how these factors affect oil viscosity, asphaltene precipitation behavior, and the recovery of heavy asphaltene crude oil. Results showed that ultrasonic treatment decreased the size of asphaltene aggregate, which in turn decreased the viscosity of the crude oil. The results revealed that the solvent and ultrasound combination had the strongest effect on lowering oil viscosity when compared to crude oil that had not been treated with either solvent or ultrasonic waves [38]. Hengli Wang et al. this study reveals the CO2-miscible EOR processes that are assisted by ultrasound in the generation of tight oils. It was discovered that the oil's properties were dramatically changed by the ultrasonic treatment (40 KHz and 200 W for 8 h), with viscosity (at 60 °C) reducing from 4.1 to 2.8 mPa.s. From 27.94% and 6.03% and 14.2% and 3.79%, respectively, asphaltene and resin content decreased. The ultrasonic induced the unsaturated C-H bond, C-O bond, and C≡C bond in macromolecules to rupture, which led the macromolecules to break down into smaller carbon-number molecules, as seen by the FTIR spectrum. It was determined that the slim-tube test caused the MMP to drop from 15.8 to 14.9 MPa and the oil recovery factor to rise by 11.7% [39]. Liu, Jing et al. this study examines the physical-chemical processes that cause different heavy oils to become less viscous when they are subjected to ultrasonic vibrations. The study demonstrates: An experiment on ultrasonic viscosity reduction demonstrates: The ultrasonic wave has the best effect on lowering the viscosity of heavy oil, resulting in a viscosity of up to 32.8% when the temperature is 40 °C, the ultrasonic frequency is 15 kHz, the power is more than 500 W/h, the treatment period is more than 20 min, and the amount of water is more than 30%. The ultrasonic wave has the greatest viscosity reduction effect on heavy oil with a higher viscosity up to 47.8% when the temperature is 80 °C, the ultrasonic frequency is 15 kHz, the power is more than 500 W/h, the treatment duration is longer than 30 min, and the volume of water is larger than 40% [40]. Yeh, Hsiang Lan et al. this article examines the potential application of ultrasonic fields to enhance colloidal particle mobility in porous media. We found that the diffusion and average velocity peaked at a frequency of roughly 40 kHz for porosities of 0.62, 0.76, and 0.9. This discovery raises the possibility of a natural frequency. A second natural frequency with a value similar to 90 kHz was discovered in experiments conducted at 0.62 and 0.76 [41]. Razavifar, Mehdi et al. this investigation examined the effects of ultrasonic waves on the viscosity and thermal behavior of a crude oil with a high asphaltene content at varied irradiation times, powers, and frequencies. It was found that the oil's viscosity was significantly reduced by the ultrasonic radiation before the fluid cooled. A second test was performed on the viscosity after the irradiation oil had reached room temperature to see how rapidly it would change. For each ultrasonic frequency at which the cooled-down, irradiated oil attained a minimal viscosity, an optimal time for irradiation was found. It was found that after cooling down, the oil was exposed to radiation for the optimal time of 8 minutes, during which it lost 10% of its permanent viscosity [42]. Vahdanikia, Nabi ey al. the purpose of this study was to investigate how microorganisms and ultrasonic waves both affect the stability of water-in-oil emulsions. Compared to similar samples combined for 5 minutes, emulsions that have been mixed for 20 minutes are 5–10% more stable. Under the ideal circumstances of this study, ultrasonic radiation reduces emulsion stability by roughly 6%, lowers surface tension by 15%, and increases stability by roughly 20% [43]. Louhenapessy et al. by varying the physical properties of the rock, the fluid's viscosity, the composition of the oil, and the amount of oil that is saturated in the oil, this laboratory study seeks to understand how to employ circular and longitudinal wave patterns to boost oil output. The study's results show that circular waves perform 3% better at boosting oil recovery than intermittent longitudinal waves. According to laboratory tests and SEM digitization analysis results, circular waves have differences in porosity and permeability of 10% to 34% when compared to longitudinal waves. The composition of oil may be changed by longitudinal and circular waves to make it more liquefiable by reducing the amount of alkane molecules and aromatic compounds [44]. Taheri-Shakib, Jaber et al. the purpose of this study was to examine the effects of *MW* and *US* waves on a sample of heavy crude oil extracted from a reservoir in southwest Iran. The search results shown here are representative. *MW* at 2 and 4 min reduced the viscosity of the material by generating hot zones. The viscosity dropped by 16% as a result of the heavier components, such as asphaltenes, which have a greater capacity to absorb *MW*, breaking at 2 minutes [45]. Keshavarzi, B et al. in this study, ultrasonic waves were used to enhance the permeability of reservoir rocks through an experimental examination. According to the experiment's findings, paraffin (heavy oil) recovered 70% of *OOIP* when vibration was intermittent but only 55% when vibration was constant at the same 40 kHz frequency, 500 W power level, and 15 cm from the source. Additionally, 42% of *OOIP* was recovered from kerosene (light oil) when vibration was applied intermittently as opposed to 32% when vibration was applied continuously. After 4 minutes, light components started escaping from the sample, causing the viscosity to rise and the radiation time to lengthen [46]. Agi, Augustine et al. the use of intermittent vibration as a productive and long-lasting way to enhance oil recovery (*EOR*) is discussed in this paper. The experiment's findings reveal that paraffin (heavy oil) recovered 70% of *OOIP* with intermittent vibration but only 55% with continuous vibration at the same 40 kHz frequency, 500 W power level, and 15 cm from the source. Additionally, 42% of *OOIP* was recovered when vibration was applied intermittently to kerosene (light oil), as opposed to 32% when vibration was applied continuously [47]. Bera, Achinta et al. in this research, we provide an experimental study for the electromagnetic recovery of heavy oil from oilsands in a conceptual sandbox. At 1200 W, which also attained the greatest equilibrium temperature of 125 °C, the most oil was produced. *Ni* and *Fe* nanoparticles produced 32% and 13% of *OOIP*, respectively. Ni nanoparticles are therefore more effective than Fe nanoparticles during *EM* heating. According to *GC* analysis, the mass fraction of the heavy and light components of the original oil decreased after heating under microwave exposure [48]. Zemenkov, Y. D. et al. this study's objective is to conduct experimental research to determine any connections between the combined use of viscous oil depressor additives and ultrasonic therapy. Oil dynamic viscosity increased following treatment in the experimental process in comparison to the baseline values [49]. Doust, Akbar Mohammadi et al. in this study, the effects of temperature, solvent concentration, and ultrasonic irradiation time are examined in relation to the decrease in residual fuel oil (*RFO*) viscosity. The findings showed an improved viscosity decrease and promoted API gravity due to the solvent and ultrasonic irradiation combination. The combination of 5% by volume acetonitrile loading, 50 °C temperature, and 5-minute ultrasonic treatment resulted in the largest viscosity reduction [50]. Hamidi, H. et al. this paper develops a technique for directly measuring the influence of ultrasonic waves on the viscosity of paraffin, synthetic oil, and kerosene. When paraffin and synthetic oils were tested using ultrasonic at 68 kHz and 500 W, their respective viscosities dropped by almost 16% (31.7 to 26.65 cP) and 13% (68.2 to 59.3 cP) [51]. Abramova, Anna et al. this research included an overview of ultrasonic technology for improved oil recovery. *EOR* monitoring of more than 100 wells after ultrasonic treatment in two different locations led to the following discovery: The method is 90% effective, and it is feasible to enhance oil output by 40% to 100%. The main advantages of ultrasonic *EOR* technology are its low energy consumption, capacity to treat the reservoir selectively, lack of damage to the well or its casing, and lack of negative impacts on either humans or the environment [35].

4. Discussion

This study reviewed the application of conventional *EOR* techniques as well as unconventional *EOR* methods, with an emphasis on ultrasound-assisted oil recovery. The studies discussed the most suitable and efficient techniques for ultrasound-based enhanced oil recovery. Ultrasonic stimulation can greatly assist in the water immersion method by increasing the recovery rate. The use of low-viscosity, high-API fluids such as kerosene results in a low mobility ratio and high sweep efficiency; therefore, the recovery rate of ultrasonicstimulated water flooding will be high. Likewise, *CO2* flooding under controlled and uncontrolled temperature conditions can be assisted by ultrasonic stimulation. In fact, the use of ultrasound-assisted *CO2* immersion technology will reduce parameters such as viscosity, capillary pressure, and surface tension to improve oil recovery. Oil wells that are losing production can be revived and their production increased by downhole ultrasonic stimulation. Wells with permeabilities greater than 20 mD and porosities greater than 15% respond favorably to ultrasonic treatment. Wells with low permeability and porosity should use ultrasound with chemicals to increase their production rate. The efficiency of ultrasonic radiation is affected by the moisture of the rocks. Both wet oil and water situations can benefit from the use of ultrasound to increase oil recovery. However, oil-wet cases experience a high rate of ultimate recovery, while water-wet cases show only a slight increase in ultimate recovery. Therefore, oil-wet cases are more suitable for ultrasonic applications than water-wet cases. The effect of ultrasound waves on the interface between immiscible liquids. Surface tension decreases with increasing ultrasound intensity.

5. Conclusions

The use of ultrasound to improve oil recovery was examined in the review. In the past few decades, many experimental studies and related field applications have been conducted in different environments to examine the effects of ultrasound on key parameters of enhanced oil recovery. Using ultrasound to increase oil recovery is beneficial for a number of reasons. It is a cost-effective and sustainable solution, as the tools and mechanisms used to generate ultrasound are less expensive than other traditional methods, in addition to the fact that this method reduces environmental pollution resulting from the use of chemicals used in traditional methods. Secondly, it can be used in any type of reservoir and significantly increases oil production rates. Third, it will prevent damage to formations near the wellbore and keep the well and its casing safe. Additionally, it prevents heat loss and allows stimulation for any length of time of interest. In conclusion, the use of ultrasound for *EOR* has recently shown promising results and presents *EOR* experts with a fascinating and demanding topic of study.

Table 1: Summary of previous work for conventional methods of *EOR*.

References	Method used in EOR	Experiment	Method used to analyze results	Finding
Mirosław Wojnicki et al.	employed the water alternating gas injection (WAG) technique with a variety of gases, including as CO2, acid gas (a combination of CO_2 and H_2S at a 70/30% vol/vol ratio), and high-nitrogen natural gases found in the Polish Lowlands.	Using composite carbonate cores made up of four dolomite core plugs, a series of 17 core flooding tests were carried out at 126 °C and 270 and 170 bar of pressure. Rock and fluids from the original reservoir were utilised. To ascertain the miscibility conditions of the injected fluids with reservoir oil, a series of slim tube experiments were carried out.	• Laboratory application • Based on the experimentally determined RF and additional factors such as the gas composition, WAG ratio, and injection pressure.	• The WAG procedure was shown to be superior than continuous gas injection (CGI) and continuous water injection (CWI). • CO2 WAG injection resulted in a recovery factor (RF) of up to 82%. • the high nitrogen natural gas WAG injection was less effective with the highest recovery of 70%
Qiuxia Wang et al.	Used integrated technology of profile control and thermal recovery to enhance heavy oil recovery.	The thermal recovery process was implemented in the laboratory by suturing the core with crude oil with different viscosities	• Laboratory application • Diagram showing the	• The oil recovery associated with the thermal recovery in the hetero-

References	Method used in EOR	Experiment	Method used to analyze results	Finding
		to simulate the oil in areas swept by the thermal fluid.	distributions of oil viscosity in the cores.	generous core increased from 10.8% at 55 °C to 42.9% at 200 °C. • the oil recovery associated with thermal recovery assisted by profile control increased from 8.9% to 13.2%. • The areas swept by the thermal fluid were optimized at 3/10 of the injector–producer distance with three slugs of oils with different viscosities.
Liang Xue et al.	In this study four basic technical forms have been developed: steam huff and puff, steam-driven, SAGD, and fire-driven	Polymer flooding, chemical viscosity reduction development, and microbial oil recovery have been tested in the field and have achieved certain results.	• Laboratory application • Diagram showing the distributions of oil viscosity in the cores	• polymer flooding above 200MPa s has the problems of difficult injection and high chemical agent costs. • The mechanisms and development effects of chemical viscosity reduction development and microbial oil recovery still need to be studied further and observed
Raheek I. Ibrahim et al.	The present work focuses on comparing between the effect of Polymethyl methacrylate PMMA only and PMMA with carbon nanotube CNT on drag reduction 0n viscosity of crude oil	• an experimental rig has been designed and implemented • the ring consists of: a crude oil Perspex pipe, oil pump, pressure sensors. • Two additive materials including PMMA and CNT with different concentrations have been used to reduce the drag inside the oil pipe.	• Laboratory application • Pressure drop reading can be calculated by: $DR = \frac{\Delta p_b - \Delta p_a}{\Delta p_b}$	• PMMA is a methacrylate with varying concentrations of 1000, 2000, 3000, and 4000 mg/L. It has been demonstrated that 3000ppm is the best since it achieves a 65% drag reduction. • PMMA, a polymer made of

References	Method used in EOR	Experiment	Method used to analyze results	Finding
				polymethyl methacrylate, is available in 1000, 2000, 3000, and 4000 mg/L concentrations. It has been proven that 3000ppm is the best since it results in a 65% reduction in drag.
M M asanH et al.	used Enhancing heavy oil and bitumen recovery and upgrading by toe-to-heel air injection (THAI) is a revolutionary method. To reach a potentially high recovery ratio, this technology combines the ideas of a horizontal well with the reactions of high-temperature oxidation.	• The THAI and THAI-CAPRI processes have been simulated using 3D models using CMG-STARS to examine the effects of various parameters on the effectiveness of the method. • The THAI approach has been examined to see how different well designs with two horizontal injectors and producers affect certain factors.	• Simulations method. • For this technique, a 3D dimensional model using the CMG-STARS simulator was used.	• It was discovered that the positions of the well injections and well output had a substantial impact on the oil production.
Changhong Gao Sinopec	Used the Microbial technique for enhanced oil recovery (MEOR)	• Injections of nutrients or live microorganisms are made into the reservoir. Oil in reservoirs can be mobilized by bacteria and the metabolic byproducts they produce, such as biosurfactants and biopolymers.	• Laboratory application	• For the MEOR projects conducted in China, we observed increase injection pressure, decrease in IFT, and decrease in oil viscosity. • The majority of MEOR projects in China saw high success rates. More than 70% of the microbe-treated wells had favorable results. • All MEOR projects in China were profitable. (4) The experiences in China prove MEOR is effective

References	Method used in EOR	Experiment	Method used to analyze results	Finding
				for challenging reservoir conditions, i.e. high temperature (80 ?C), high salinity (46,000 mg/L) and heavy oil
H.Yousefvand et al.	• In a strongly oil wet five-spot glass micromodel saturated with heavy oil, the impact of nanosilica (NS) in the polymer flooding in the presence of salt on the oil recovery factor has been examined. • Image processing technique was used to analyze the displacement mechanisms as well as to calculate the efficiency in each flooding test.	• The micromodel setup consists of a low rate syringe pump that is precise, a micromodel holder, a light source, a vacuum pump, and a professional camera with a recording system that takes pictures of the EOR procedure every two minutes.	• Laboratory application • Photoshop program was used to evaluate the data and determine the recovery factor by Equation: $R=\frac{S_{oi}-S_{or}}{S_{oi}}$	• Results show that the viscosity augmentation of the injected fluid can result in an improvement of roughly 10% in the final oil recovery when NS is present. • In some areas of the micromodel, nanoparticles can convert the wettability to water-wet.

Table 2: Summary of previous work for unconventional methods of *EOR*.

References	Method used in EOR	Experiment	Method used to analyze results	Finding
Jinbiao Gao et al.	Examine the relationship between the US transducer's electric power input and the heavy oil viscosity.	the experimental including reduce the viscosity of heavy oil with deferent temperature by using ultrasonic irradiation with variety electrical power(50 W, 100 W, or 200 W) and with center frequency 18KH and ultrasonic irradiation time of 6 or 12 min.	• Laboratory application • used the viscosity reduction rate (VRR) to indicate the $\mathrm{VRR}=\frac{\mu_0-\mu}{\mu_0}\times 100\%$ degree of change in viscosity: • The chromatography (GC) is	• Under ultrasonic 50 W, whether US irradiation time was 6 or 12 min, the viscosity of the oil sample reduced for the majority of temperature points, and rose when the input electric power was 100 W and 200 W.

References	Method used in EOR	Experiment	Method used to analyze results	Finding
			used to explain the differences in various functional groups, heavy components, and carbon chains before and after ultrasonic irradiation, gas.	
Augustine Agi et al.	In this study, wet milling with ultrasound assistance was used to create thermally treated empty fruit bunch SiO_2 nanofluid (EFBSNF), and their efficiency in boosting the cavitation impact of ultrasound to enhance heavy oil recovery was assessed.	• 100 mL of deionized water was ultrasonicated and the temperature was measured every 30 s. using a thermometer. • The temperature was measured after ultrasonically processing various concentrations of EFBSNF (0.05–0.2 wt%) and 0.2 wt% of EFBA.	• Laboratory application. • Using Fourier-transform infrared spectroscopy, the active group was identified, and differential scanning calorimetry was used to determine the thermal stability.	• The treatment procedure demonstrated a considerable drop in the trace element concentration with rising temperature and an equal rise in SiO^2 content. • By using Bjerknes forces and peristaltic motion, ultrasound-assisted EFBSNF flooding boosted oil recovery by 44.33% compared to EFBSNF flooding without ultrasound, which increased oil recovery by 26.33%.
Ephraim Otumudia et al.	Different transparent porous micromodels were created, constructed, and tested in this work to quantitatively evaluate the effect of reservoir rock pore geometry and ultrasonic parameters on asphaltene deposition during	• To evaluate the effect of pore geometries on the ultrasonic removal of asphaltene deposition, five two-dimensional glass micromodels with various pore sizes were created. • An ultrasonic bath was used for the experiments, which were run at a fixed frequency of 20	• Laboratory application. • The effect of pore geometry and a change in ultrasonic parameter on the removal of asphaltene deposition was evaluated	• It was discovered that the pore geometries of the individual micromodels were dependent on the efficacy of ultrasonic therapy at different sonication times. When the ultrasonic power

References	Method used in EOR	Experiment	Method used to analyze results	Finding
	ultrasonic stimulation.	kHz and variable powers of 100–1000 W.	using direct image analysis before to, during, and following sonication.	was increased from 400 to 1000 W for micromodels with throat diameters of 300 m and pore forms of circle, square, and triangle, the percentage of eliminated asphaltene deposition after two hours increased from 12.6 to 14.7, 11.5 to 14.63, and 5.8 to 7.1 percent, respectively.
Razavifar, Mehdi et al.	The primary goal of this study is to conduct experimental investigations into the effects of solvent and ultrasonic waves on oil viscosity, asphaltene precipitation behavior, and recovery of a heavy asphaltenic crude oil.	• Crude oil samples were exposed to ultrasonic radiation at a frequency of 20 kHz and for diverse amounts of time with different output powers (30, 60, and 100 W). Each oil sample's viscosity was assessed both immediately following the cessation of ultrasonic radiation and 24 hours later. The minimal viscosity of the radiated oil after cooling down was used to calculate the optimal time for ultrasonic radiation. • In order to determine the synergistic impact of ultrasonic radiation and solvation on the oil viscosity, the viscosity of the ultrasonically treated oil samples mixed with a solvent (i.e., n-heptane) was determined.	• Laboratory application	• The outcomes demonstrated that ultrasonic treatment reduced asphaltene aggregate size, which in turn lowered the viscosity of the crude oil. • In comparison to crude oil that had not been treated with solvent or ultrasonic waves, the results showed that the combination of ultrasound and solvent had the highest effect on reducing oil viscosity.
Liu, Jing et al.	This study investigates the physical-chemical mechanisms that	• The ideal ultrasonic parameters, ultrasonic physical disturbance, and cavitation viscosity	• Laboratory application • The influence of ultrasonic	• An ultrasonic viscosity reduction experiment shows that:

References	Method used in EOR	Experiment	Method used to analyze results	Finding
	reduce the viscosity of various heavy oils when they are exposed to ultrasonic waves.	reduction extent of various oil samples were identified by experiments on the viscosity reduction and recovery of various heavy oils under ultrasonic excitation. • The instruments used in the experiment are ultrasonic generator (the experimental frequencies are 15, 18, 20, 25, and 28 kHz) with power (300, 500, and 1000 W/h), viscometer, gas chromatograph, elemental variety EL cube element analyzer, pH measuring instrument, high temperature and high pressure oil storage cylinder, water bath, and crude oil four-component analyzer.	wave on the structure of the oil sample and the change in the structure of the formation water is studied through experiments involving element analysis, four-component analysis, gas chromatography analysis, and a pH test of the formation water. The chemical mechanism and range of action of ultrasonic wave in reducing heavy oil viscosity are also explored.	- When the temperature is 40 °C, the ultrasonic frequency is 15 kHz, the power is more than 500 W/h, the treatment period is more than 20 min, and the amount of water is more than 30%, the ultrasonic wave has the best impact on reducing the viscosity of heavy oil, resulting in a viscosity of up to 32.8%. - When the temperature is 80 °C, the ultrasonic frequency is 15 kHz, the power is more than 500 W/h, the treatment period is greater than 30 min, and the volume of water is greater than 40%, the ultrasonic wave has the best viscosity reduction impact on heavy oil with a higher viscosity up to 47.8%.
Razavifar, Mehdi et al.	This study looked at the effects of ultrasonic waves at various irradiation periods, powers, and frequencies on the viscosity and thermal behavior of a crude oil with a high asphaltene concentration.	• The ultrasonic used radiation with a frequency of 46 kHz and an output power of 50 W and optimum time of 8 min.	• Laboratory application • The relationship between changes in viscosity and thermal characteristics of the oil was evaluated by analyzing the impact of ultrasonic irradiation on the oil's	• It was discovered that before the oil cooled down, the ultrasonic radiation greatly decreased the viscosity of the oil. After the irradiation oil cooled to room temperature, the viscosity was once again tested in order to assess how quickly the viscosity may change. An ideal

References	Method used in EOR	Experiment	Method used to analyze results	Finding
			thermal behavior using thermogravimetric and differential thermal (TGA/DTA) techniques.	period for irradiation was discovered for each ultrasonic frequency at which the cooled-down, irradiated oil attained a minimal viscosity. • It was discovered that the cooled-down oil exposed to radiation for an ideal duration of 8 min lost 10% of its permanent viscosity.
Louhenapessy et al.	This laboratory study's goal is to determine how to best use circular and longitudinal wave types to increase oil production by adjusting the rock's physical characteristics, the fluid's viscosity, the composition of the oil, and the amount of oil that is saturated in the oil.	• Rayleigh waves are a pair of wave phenomena that include longitudinal waves (P) and transverse waves (S), or even both P and SV waves. To get the best results in altering rock structure, fluid viscosity, and impacting the composition of petroleum in terms of results from gas chromatography, frequency variations are also used in addition to variations of the two waves. • According to the findings of laboratory experiments, the optimal frequency that can improve the maximum oil recovery is 35 Hz in longitudinal waves and 20 Hz in circular waves.	• Laboratory application • reviewing the oil composition using the GC-MS technique and assessing the vibroseismic effect using SEM photos in comparison to lab data, which have an error rate of less than 2%.	• According to the study's findings, circular waves outperform intermittent longitudinal waves in terms of improving oil recovery by 3%. • In comparison to longitudinal waves, circular waves exhibit variations in porosity and permeability of 10% to 34%, according to laboratory testing and SEM digitization analysis results. • By creating fewer alkane molecules and less aromatic compounds, longitudinal and circular waves can alter the composition of oil and make it more liquefiable.
Keshavarzi, B et al.	This work was an experimental	• In this study, a unique core holding apparatus	• Laboratory application	• The results of the experiment

References	Method used in EOR	Experiment	Method used to analyze results	Finding
	investigation of the use of ultrasonic waves to increase the permeability of reservoir rocks.	was created and used throughout the experimentation. • An ultrasonic wave generator with a power output of up to 1000 watts and a frequency of 20 kHz was used to apply the ultrasound exposure. Altering the probe-plug distance can also be done by repositioning the probe within the core holder. A range of 0.6 to 4 cm is possible for this distance. • A carbonate sample had a permeability of 140 md and 11.1% porosity, whereas a sandstone sample had an absolute permeability of 115 md and 15.6% porosity. These two different core plugs were used for the studies. • The crude oil sample with an API gravity of 21 and an asphaltene concentration of 8.91% was employed. • The experiment was performed three times on the sandstone plug at three different ultrasound exposure intervals(10, 20, and 30 minutes),three different ultrasound powers(100, 200, and 300 watts) and three different distances between the ultrasound probe and plug(0.6, 1.6, and 3.6 cm).	• The permeability recovery parameter, is used to measure the degree of permeability stimulation in several cases .	show that paraffin (heavy oil) recovered 70% of OOIP with intermittent vibration but only 55% with continuous vibration using the same frequency of 40 kHz, an intensity of 500 W, and a distance of 15 cm from the source. Additionally, when vibration was intermittently applied to kerosene (light oil), 42% of OOIP was recovered as opposed to 32% with continuous vibration.
Bera, Achinta et al.	In this paper, we introduce an experimental investigation in a conceptual sandbox for the electromagnetic	• The EM waves were captured using a microwave antenna operating at Different powers (500, 800, 1000, and 1200 W) were used in a 2.45 GHz	• Laboratory application • The produced gases and oil collected were analyzed	• The most oil was produced at 1200 W, which also reached the highest equilibrium temperature of

References	Method used in EOR	Experiment	Method used to analyze results	Finding
	recovery of heavy oil from oilsands.	microwave generator. • Heavy oil with viscosity of 67,424 cP (at 23 °C) was used in the experiments. • Thermometers made of fiber optics were used to measure temperatures at various distances from the antenna. • By positioning samples of oil-soaked sand at various distances from the antenna in Buchner funnels, oil recovery tests were carried out. • Through the use of oil samples in the model's Buchner funnels, the impact of temperature on the viscosity of crude oil both before and after exposure to EM radiation was also investigated. • The experiment was replicated using a combination of oil and silica beads and Ni and Fe nanoparticles, which can absorb EM radiation.	through GC to ensure the loss of component from the original oil and upgradation study.	125 °C. • 32% and 13% of OOIP were generated by Ni and Fe nanoparticles, respectively. Therefore, during EM heating, Ni nanoparticles are more efficient than Fe nanoparticles. • The mass fraction of the original oil's heavy and light components was reduced following heating under microwave exposure, according to GC analysis.
Doust, Akbar Mohammadi et al.	In this research, the effects of temperature, solvent concentration, and ultrasonic irradiation time on residual fuel oil (RFO) viscosity reduction are investigated.	• Used ultrasonic irradiation at low frequency of 24 kHz and power of 280 W, irradiation for 5 min at initial temperature of 20 C°. • A probe with a 20 mm diameter and a 30 cm height was also utilized in the trials, and cycle and amplitude were set.	• Laboratory application. • Artificial neural network (ANN) feed-forward back propagation was used to assess the observed findings, which included 336 data points from 84 samples. Any $y_j = F_t(\sum_{i=1}^{n} w_{ji} x_i b_j)$	• The combination of solvent and ultrasonic irradiation resulted in an enhanced viscosity drop and promoted API gravity, according to the results. The 5-minute ultrasonic exposure, 50 °C temperature, and 5% by volume acetonitrile loading produced the greatest viscosity decrease.

References	Method used in EOR	Experiment	Method used to analyze results	Finding
			connection's output is determined by the following equation:	
Hamidi, H. et al.	In this work, a method for directly examining how ultrasonic waves affect the viscosity of paraffin, synthetic oil, and kerosene is developed.	•	• Laboratory application.	• When oil viscosity was tested using ultrasonic at 68 kHz and 500 W, it decreased for paraffin and synthetic oils, respectively, by around 16% (31.7 to 26.65 cP) and 13% (68.2 to 59.3 cP).
Abramova, Anna et al.	In this study, ultrasonic technology for enhanced oil recovery (EOR) was described.	• Used an ultrasonic generator with a frequency range of 13 to 26 kHz and a power of 10 kW.	• Laboratory application. • Used The finite element method to analyzed the results.	• The following finding may be obtained from the monitoring of more than 100 wells after ultrasonic therapy in two separate areas: The technique has a 90% success rate, and an increase in oil output of 40% to 100% is possible.

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