Iraqi Journal of Oil & Gas Research, Vol. 05, No. 2 (2025)

Iraqi Journal of Oil & Gas Research

Journal homepage:https://ijogr.uotechnology.edu.iq/

Advances in the Field of Ultrasound-assisted Water-Oil Emulsion Separation: a Comprehensive Review

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Article information

Article history:
Received: Apirl, 14, 2025
Revised: September, 26, 2025
Accepted: September, 27, 2025
Available online: October, 04, 2025

Keywords:
W/O Emulsion, ultrasonic waves, crude oil, chemical demulsifiers, pretreatment.

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Abstract

Crude oil is typically produced as a complex mixture containing saline water, leading to the formation of water-in-oil emulsions during fluid transport through pipelines and valves. These emulsions are further stabilized by natural components in crude oil, such as asphaltenes, resins, waxes, and suspended solids. The presence of water negatively affects crude oil production by increasing transportation costs and accelerating pipeline corrosion. To reduce reliance on chemical demulsifiers in oil processing, this study provides a comprehensive review of low-frequency ultrasound as an environmentally friendly alternative technique. The review discusses emulsion stabilization and destabilization mechanisms, with a focus on chemical, biological, membrane, electro-radiation, and microwave methods, in comparison with ultrasound-assisted separation. The findings highlight that low-frequency ultrasound has the potential to significantly improve emulsion breakdown efficiency while minimizing the environmental impact of conventional chemical treatments. This approach offers a promising pathway toward sustainable crude oil processing and enhanced operational efficiency.

DOI: http://doi.org/10.55699/ijogr.2025.0502.1086 , College of Oil and Gas Engineering, University of Technology-Iraq

1. Introduction

In order to create stable emulsions, salty water is usually combined with the complex mixture known as crude oil. Emulsions of water and oil are created when the coproduced water flows through pipelines and choke valves. These emulsions can be stabilized by components found naturally in crude oil, such as particles, asphaltenes, and resins [1]. The major reasons why water should not be present during the production of crude oil are transportation costs and pipeline corrosion. In this respect, pipeline flow and particularly refining activities require crude oil that is almost entirely devoid of water [2]. Prior to being used in refining operations, crude oil needs to be treated in order to facilitate the removal of water and, therefore, salt. Demulsification removes a lot of water from crude oil, and most refineries require that the oil's water content be below 0.5% before refining [3]. Some disadvantages of traditional extraction techniques include lesser extraction efficiency, lower yield, and the need for large amounts of materials or solvents. These techniques include solvent extraction, distillation, and pressing. Moreover, high temperatures are required for some extraction techniques, which may negatively impact some bioactive ingredients [4]. Numerous demulsification techniques, including membrane filtration, centrifugation, and microwave radiation, have been created for the laboratory scale or the petroleum industry. Even while these processes are fairly effective for light crude oils, they take a lot of time, and adding chemical demulsifiers is practically always necessary (particularly for heavy crude oils), which raises the cost of treatment [5]. The aim of the current work is to conduct a thorough investigation into the development of an environmentally acceptable technique that uses low frequency ultrasonic waves to suppress the emulsion. This method is inexpensive, locally produced, and involves the addition of natural or chemical ingredients. The study also examines the effects of sonication time and power in addition to adding natural or chemical substances on W/O emulsion separation, since the impact of operational parameters is a critical issue in ultrasonication demulsification.

Definitions of emulsions:

Since the contact area between the oil and water components of an emulsion diminishes with time, these systems are thermodynamically unstable. The presence of solid particles, amphiphilic polymers, or surfactant molecules typically results in the formation of emulsions, which are metastable systems [6]. The main element that dictates the emulsion's shape is the balance between the emulsifiers' hydrophilic and lipophilic properties: The presence of hydrophobic molecules causes the formation of water-in-oil (W/O) emulsions, while the presence of relatively hydrophilic molecules causes the formation of oil-in-water (O/W) emulsions [7]. An emulsion is a finely suspended suspension of one liquid in another that is almost stable. A system where one of the two liquid phases is dispersed throughout the other as globules, is referred to as an emulsion. The emulsifying agent that stabilizes an emulsion, which is defined as a mixture of two mutually immiscible liquids, one of which is dispersed as extremely minute droplets in the other [8]. Roberts et al., defined emulsions by arguing that there are two types of oilfield emulsions: extremely unstable ones (which are actually more appropriately named suspensions) and extremely stable ones. Based on their behavior in a hand centrifuge, he utilized that knowledge to categorize emulsions into three groups. These are the following:

a) A better name for emulsions that only show oil is a suspension; as a result, if left to stand untreated, they will typically split into their several phases. Nonetheless, there are some unstable emulsions that can resolve in a centrifuge, particularly when diluted with gasoline, although they need treatment in order to settle to water and oil.
b) Emulsions exhibiting both a transparent oil phase and the emulsion phase, with or without water. Since these are actual emulsions, the emulsified oil needs to be recovered through treatment.
c) Those that, following centrifuging, display oil with a haze, whereas emulsion and water phases could be present or absent [9].

Several of the definitions given in this review and many others not mentioned here have one thing in common: these emulsions are thermodynamically unstable and split into two phases if permitted to settle for an extended period of time. Because of the unfavorable interaction between the water and oil molecules, these emulsions, with scattered phase sizes larger than 0.1 μm, which are categorized as macro-emulsions and are thought to be thermodynamically unstable systems that will eventually break up. Oil-in-water emulsions have undergone more extensive investigation and are better understood in terms of their production and stability than the type of water-in-oil emulsions [7]. Surfluh et al., divided emulsions into two categories: long-term and short-term. compared to a transient emulsion, which settles and separates into water and oil, a permanent emulsion will remain stable until it is properly treated. Eliminating agitation or using chemicals to cause physicochemical changes is the only certain way to stop water and oil mixes from creating emulsions. Becker et al., classifying emulsions according on dispersion phase size. The scattered droplets in an emulsion are considered macro-emulsions if they are bigger than 0.1 μm. Because of the emulsion's tendency to coalesce and split, the interfacial energy decreases, and the two phases finally separate; this makes the emulsion thermodynamically unstable. We call it a micro-emulsion if the diameters of the dispersed phase droplets in an emulsion are less than 0.1 μm. Fig. (1) shows that transparent micro emulsions can be oil-in-water or water-in-oil mixtures [10].

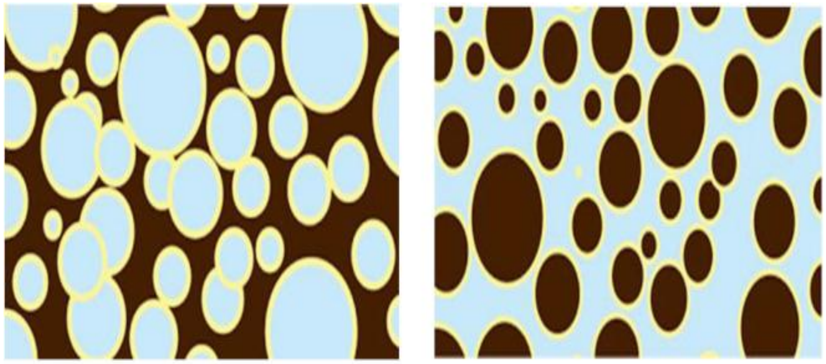

Fig. (1): Examples of oil-water emulsions: (a) water-in-oil (W/O) and (b) oil-in-water (O/W), showing the dispersed and continuous phases [10].

During the EOR technique, Mandal et al. tested the efficacy of o/w emulsions as a displacement fluid. The research employed gear oil to create synthetic emulsions, which were then evaluated for their displacing fluid performance by sand pack flooding. More than 20% of the original oil was recovered, which is far more than what would have been achieved with conventional water flooding [11].

The emulsification process:

When oil and brine come into contact, enough mixing occurs, and an emulsifying agent or emulsifier is present, crude oil emulsions are created. For an emulsion to form, there must be sufficient mixing and an emulsifier present [12]. Throughout the process of producing crude oil, there are multiple causes of mixing, It is a component that's often called the shear. These include, as shown by the letters A through F on Fig. (2), flow through reservoir rock, bottom-hole perforations/pump, flow via tubing, flow lines, production headers, valves, fittings, chokes, surface equipment, gas bubbles released due to phase change, etc [13].

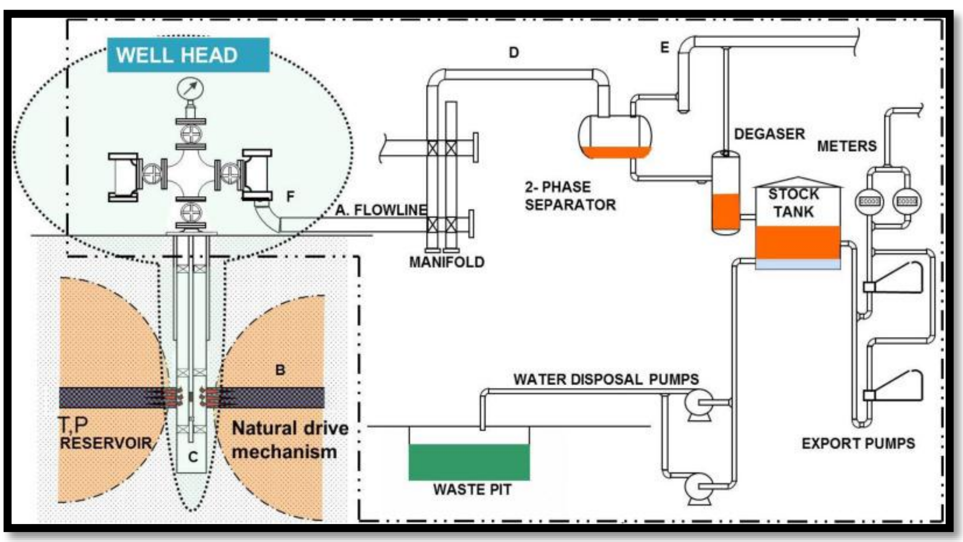

Fig. (2): Flow of crude oil from the reservoir to the storage containers [7].

Chemical demulsification:

Given the limitations of chemical demulsification, researchers have explored alternative methods, among which ultrasound has emerged as a promising environmentally friendly approach. It is widely acknowledged that the most popular technique for pretreating crude oil is chemical demulsification. Chemical demulsifiers have a high interfacial activity, which causes them to adsorb or displace native species found in crude oil, weakening the interfacial layer in the process [13]. Yet, it has been demonstrated that chemical demulsifiers have real-world drawbacks. After injection, the material is expensive and non-recyclable. Additionally, a part of the material is combined with the water used to extract the crude oil and added to the effluent. Most demulsifiers are made of synthetic chemicals that leak into effluents and damage the environment [12]. Thus, new methods are being investigated for processing crude oil due to the limits of thermal and chemical demulsification. Emulsion demulsification in an ultrasonic field result in a variety of separation events [14]. The material vibrates in the direction of the wave's propagation due to the passage of pressure pulses across molecules [7].

A number of previous studies have investigated various demulsification methods. For clarity, these works are summarized separately to highlight their methodologies and key findings. This research summarizes a set of previous techniques related to separating water from oil, which is divided into three sections: the first section deals with studies that used ultrasound, the second section deals with studies that used an emulsifier, and the third section summarizes some of the reviewed studies.

Mechanism of Demulsification:

The emulsions must go through a number of stages in the demulsification process in order to be divided into phases for water and oil. This process involves the following mechanisms: flocculation, coalescence, creaming and sedimentation, and Ostwald ripening. Fig. 3 shows a schematic of the destabilizing mechanisms [15].

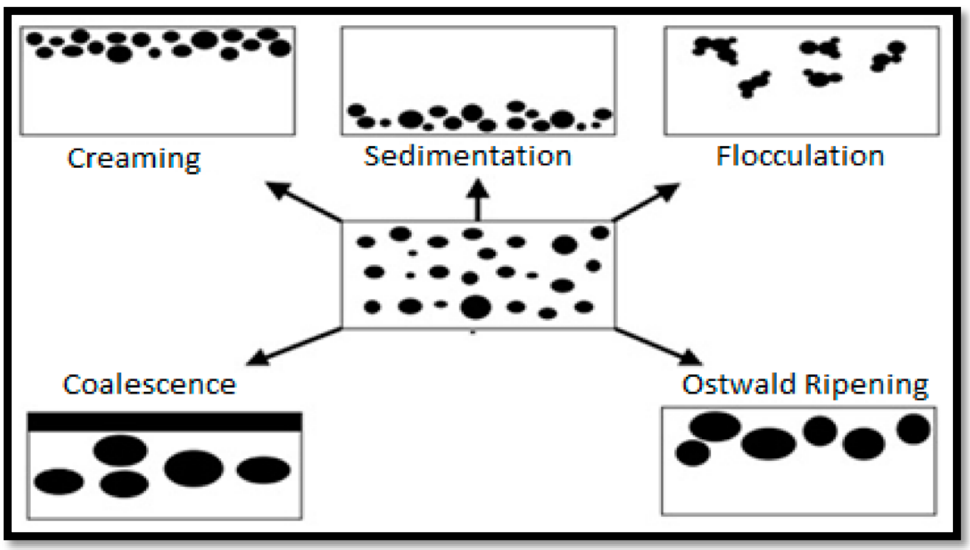

Fig. 3: Schematic illustration of the main mechanisms involved in demulsification, including flocculation, coalescence, creaming/sedimentation, and Ostwald ripening [16].

1. Sedimentation and Creaming under Ultrasound:

US alters density-driven separation by reducing droplet size distribution and disrupting stabilizing films, which allows heavier water droplets to settle faster (sedimentation) and lighter oil droplets to rise (creaming). Acoustic streaming also promotes directional movement, accelerating phase disengagement.

2. Flocculation under Ultrasound:

Flocculation refers to the reversible aggregation of dispersed water droplets into loose clusters (flocs) driven by inter-droplet interactions without rupture of the interfacial film. In contrast, coalescence is the irreversible merging of droplets after interfacial film drainage and rupture, forming larger droplets. The flocculation rate is affected by a number of factors, including the following: electrostatic field, temperature, emulsion water content, oil and water densities, and water viscosity.

3. Ostwald Ripening under Ultrasound:

Acoustic cavitation enhances mass transfer between droplets of different sizes, intensifying Ostwald ripening. Larger droplets grow at the expense of smaller ones, which accelerates phase separation compared to natural aging in static systems.

4. Coalescence under Ultrasound:

The collapse of cavitation bubbles near droplet interfaces generates localized shear and turbulence that drain thin liquid films between droplets. This facilitates irreversible coalescence into larger droplets, significantly improving water–oil separation efficiency [16].

2. Ultrasound-Based Demulsification:

Ultrasound (US) has emerged as a promising non-chemical technique for separating water-in-oil emulsions. Unlike traditional demulsifiers, US relies on acoustic cavitation and microstreaming effects, which promote droplet collision, flocculation, and eventual coalescence [17]. This process weakens the interfacial film formed by natural surfactants such as asphaltenes and resins, thereby enhancing water-oil separation. Several studies have reported that US treatment can significantly reduce water content in crude oil while minimizing the environmental concerns associated with chemical additives [18]. Fig. (4) illustrates the ultrasonic apparatus.

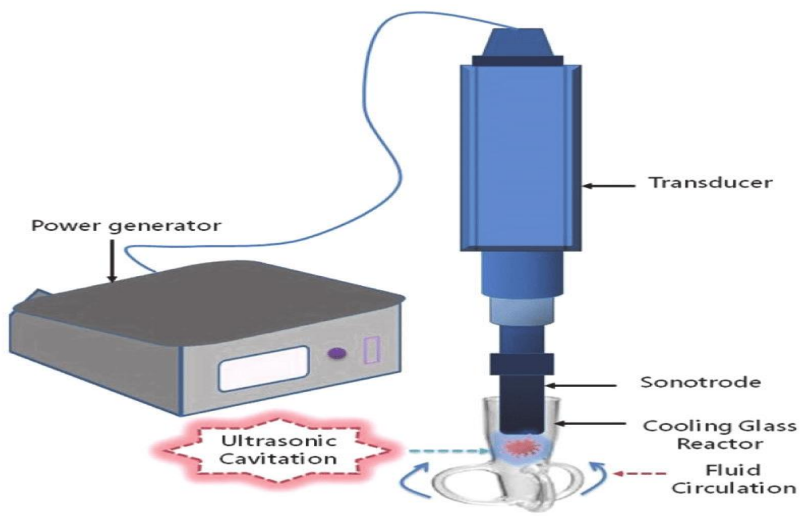

Fig. (4): Basic elements of the ultrasonic device [19].

3. Ultrasonic Application in pretreatment of Oils:

Guoxiang et al. [20] investigated the use of ultrasound and electricity in the desalination and dewatering of crude oil. The standing wave field created by the ultrasonic setup is better suited for the aggregation of water molecules. Additionally, contrasted the outcomes of the electrical process with those of the combined electro-ultrasonic process for desalination and dewatering, as illustrated in fig. (5) that illustrate the solid line represents the electric process, while the dashed line represents the combined ultrasonic-electric process. Handling high-salinity oil has never been easier than with the standardized electro-ultrasonic process. According to the results, the combined ultrasonic approach outperforms the electric method for desalting oil that has a high salt concentration.

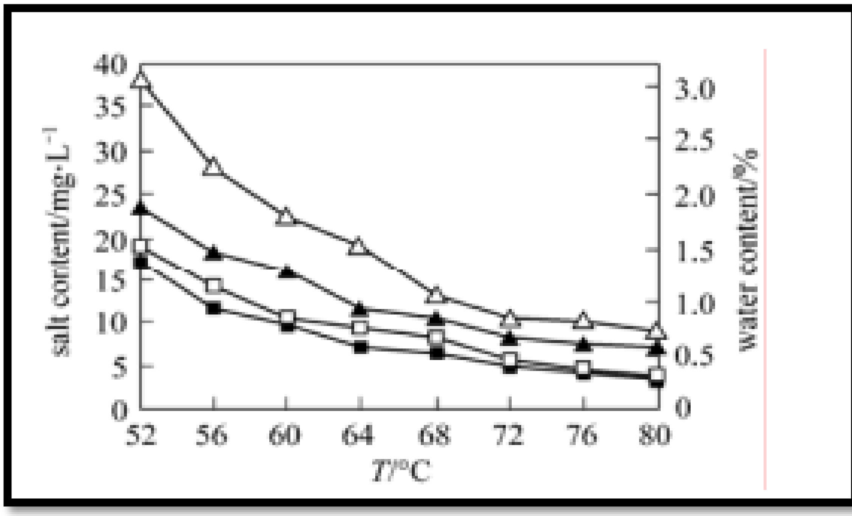

Fig. (5): Comparison between the electric process and the ultrasonic-electric combined process for crude oil desalting and dewatering. The solid line represents the electric process, while the dashed line represents the combined process [20].

Azubike et al. [21] conducted an assessment of the efficacy of demulsifiers derived from tobacco seed oil, leaf extracts, and stem ash in breaking crude oil emulsions. Hydrophilic and hydrophobic demulsifier constituents were discerned in the physicochemical characteristics of Nicotiana tabacum seed oil, the phytochemical evaluation of Nicotiana tabacum leaf extracts, and the potash levels in Nicotiana tabacum stalk ash extract. The characteristics of the developed demulsifier are comparable to those of commercial demulsifiers. The results of the bottle tests suggested that the demulsifier's formulation might destabilize medium- and high-density crude oil emulsions. The efficacy of the formulated demulsifier was comparable to that of the commercial alternatives. Check [22] conducted a theoretical and experimental study on the desalting and drying of crude oil utilizing a novel standing wave resonator reactor with ultrasonic irradiation. Investigated the significance of components, including ultrasonic irradiation parameters (radiation input intensity and irradiation duration) and operational parameters (temperature and water injection), on the efficacy of salt and water removal. As a result, the crude oil underwent optimal ultrasonic irradiation for 6.2 minutes at 100 °C and an input power of 57.7 W. A 7 vol% water injection was utilized to dissolve the salt from crude oil. The dosage of the chemical demulsifier was 2 ppm, and the application time was 60 minutes. Xie et al. [23] examined how to improve oil separation and gather water droplets using resonant cavity ultrasonic standing waves. Their research concentrated on analyzing the impact of ultrasonic irradiation on the properties of the water-in-oil emulsion, namely the dimensions of the water droplets, the size of asphaltene flocculation, and the shear strength of the oil-water interfacial layer. They also talked on how the dewatering of W/O emulsion is affected by ultrasonic parameters as acoustic intensity, frequency, irradiation period, and kind of ultrasonic field. Mohsin et al. [24] devised an experimental apparatus, illustrated in fig. (6), to assess the efficacy of demulsifying water-in-oil emulsions with varying water concentrations utilizing a 20 kHz ultrasonic wave. Their investigations proved sufficient repeatability and that the emulsion layer that contained between 10% and 40% less water broke faster. Additionally, they used COMSOL Multiphysics software to do a finite-element based simulation in order to ascertain the rate of flocculation and analyze the distribution of ultrasonic waves within the treater.

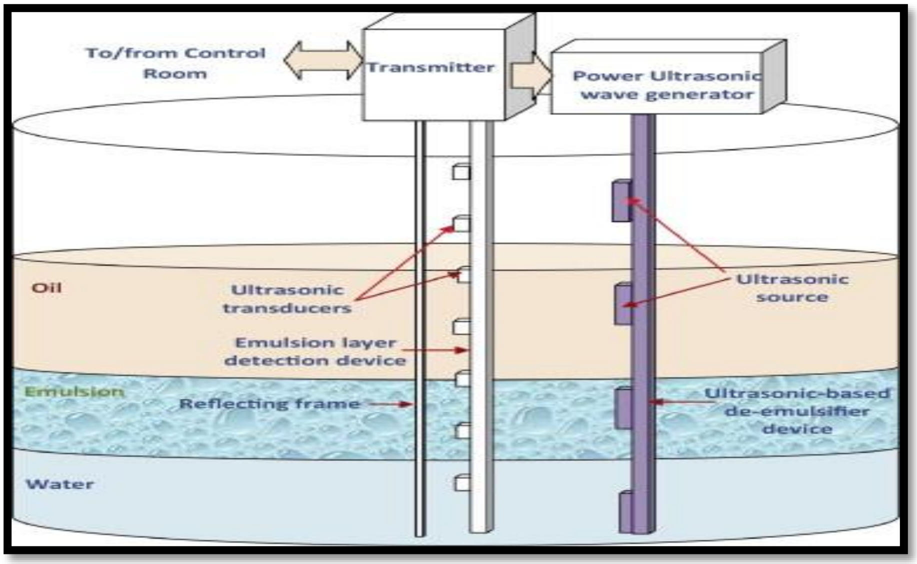

Fig. (6): The de-emulsifying device [24].

Romanova et al. [25] established the viability of unstable stable water-in-oil (W/O) emulsions, ranging from 30 to 45 μm in diameter, including those with "gel," with the use of ultrasonic treatment alongside a nanosized additive. The influence of sonication parameters, including power and exposure duration, on the separation efficiency of emulsions in batch mode has been analyzed. The research concentrated on submerged and reactor-type ultrasonic apparatuses. Ultrasonic treatment at 1.0 kW, in conjunction with nanopowder AlN suspension in acetone, successfully eradicates more than 99% of the emulsions analyzed. The additive content varied between 4% and 8% by volume, with an exposure length of 0.5 to 3 minutes, depending on the composition and characteristics of the emulsion. The devised demulsification technology may create an oil phase with a maximum water content of 0.5 weight percent and an aqueous phase with a maximum oil concentration of 46 mg L^{1-}. Atehortúa et al. [26] delineated the design and implementation of an ultrasonic demulsifier system operating at a frequency of 1 MHz, as seen in fig. (7). The control system, power electronics for the piezoelectric transducers, and ultrasonic resonant chamber are all included in the design. By monitoring the working frequency, the control adjusts for variations in temperature. The system's evaluation in a lab pipeline demonstrated that, in every situation, using ultrasound lowers the ultimate water content.

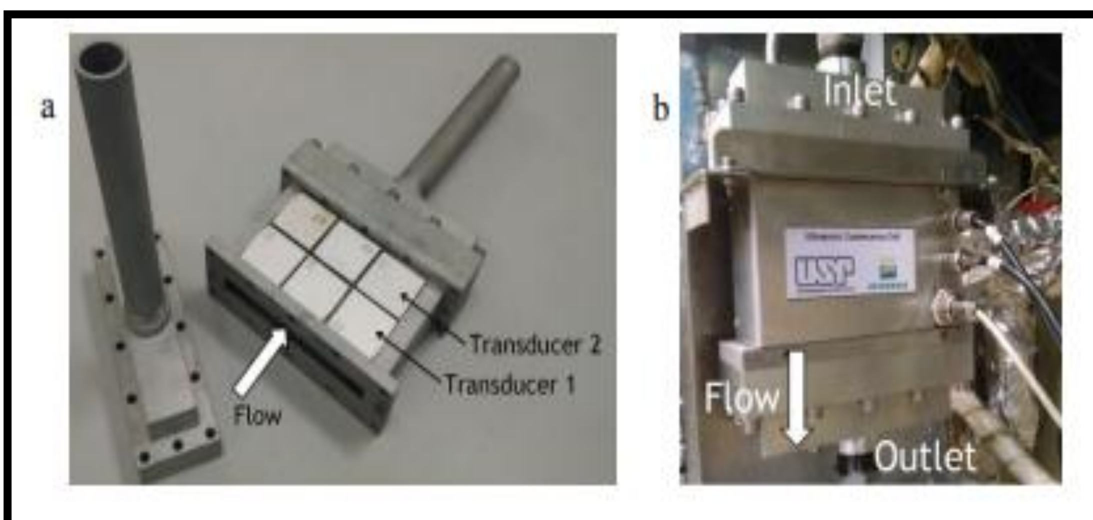

Fig. (7): Ultrasonic rupture chamber for water-in-oil emulsion [26].

Yi et al. [27] investigated the demulsification of crude oil using ultrasonic treatment, a chemical agent alone, and a combination of ultrasonic and chemical demulsification methods at three distinct temperatures (40°C, 60°C, and 70°C). The findings indicate that the amalgamation of chemical demulsifier and ultrasound yields the most effective demulsification, followed by the combination of chemical demulsifier and ultrasonic treatment in second place. Additionally, it was shown that the demulsification of heavy crude oil could be accomplished with a combination of ultrasonic waves and chemical demulsifiers, which might also shorten the demulsification and drying times. Additionally, pictures of the distribution of water droplets in crude oil are shown in fig. (8). Using the combined chemical demulsifier and ultrasonic treatment described earlier, a microscopic imaging system was employed to capture images of water droplet distribution in crude oil before and after demulsification. Antes et al. [4] carried out a thorough investigation to assess the effect of ultrasonic frequency on the demulsification of crude oil emulsions. After 15 minutes of US application, at a frequency of 45 kHz, a demulsification efficiency of around 65% was achieved (emulsions with 50% initial water content and a median droplet diameter, D(0.5), of 10 μm). It's noteworthy that no chemical demulsifiers were employed and that the demulsification effectiveness was judged high considering that unconventional crude oil was utilized to obtain the outcomes. Luo et al. [28] Using high-speed photography, the coalescence process of binary droplets in oil under ultrasonic standing waves was examined. Three motion models of binary droplets during the coalescence process are shown in Fig. (9): (1) translational oscillation with a small amplitude; (2) translational oscillation with a sinusoidal waveform; and (3) migration accompanied by acoustic streaming. The findings indicated that a reduction in drop size, oil viscosity, and interfacial tension leads to an increase in droplet oscillation frequency and a decrease in coalescence duration. The maximum oscillation frequency (3.5 Hz) and the minimum coalescence duration (35 ms) are achieved at an interfacial tension of 13.62 mN/m.

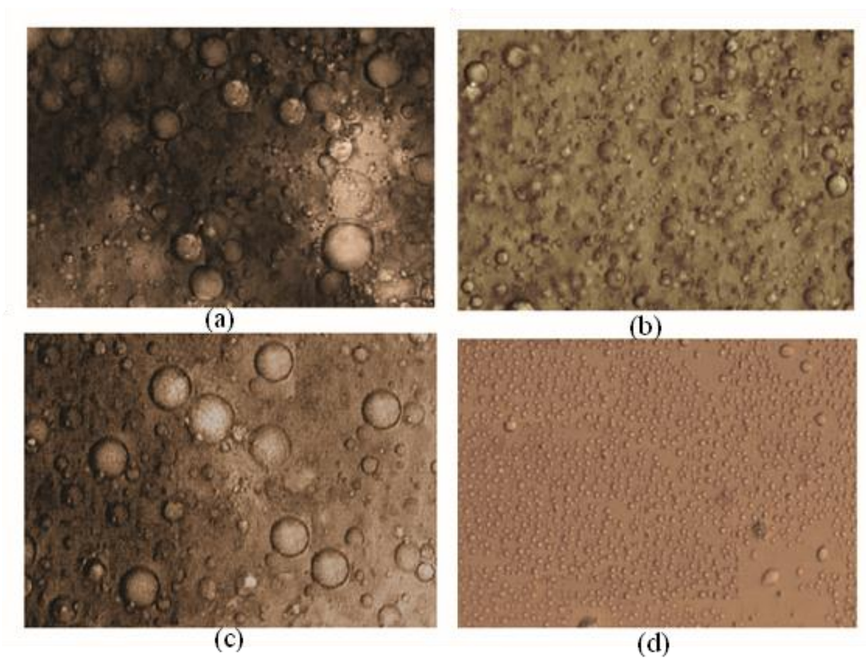

Fig. 8: Results of demulsifying crude oil utilizing various processes. The research investigates four distinct methodologies for demulsification: (a) prior to demulsification; (b) using a chemical demulsifier; (c) using ultrasonic therapy; and (d) combining chemical demulsifier with ultrasound [27].

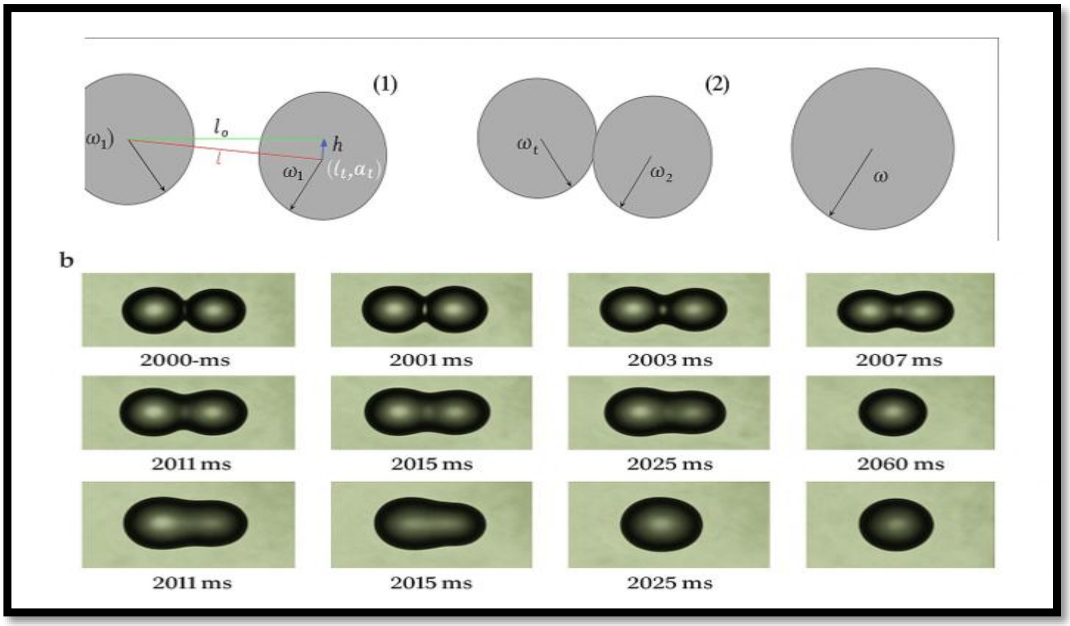

Fig. (9): Binary droplet coalescence process: (a) schematic illustration showing the binary droplet coalescence process. (1) Binary droplets' initial location (2) Binary droplets' first coalescence time (3) Binary droplet termination time fusion; (b) The process of real binary droplet coalescence in No. 1 white oil under ultrasonic light. (D2 = 400 µm (right), D1 = 450 µm (left)) [28].

Luo et al. [29] studied interruption qualities of water droplet in oil under ultrasonic standing waves are investigated with fast-moving photos. Analyze the quantitative impacts on droplet suspension positioning at different frequencies concerning droplet size, acoustic pressure, and density ratio. The experimental findings showed that the density ratio and acoustic pressure at 39.4 kHz had no effect on the suspension position of the droplet. This would be advantageous in order to keep the banding stable and reduce its width. Additionally, it was demonstrated that, at various frequencies, the droplet's suspension location showed a roughly linear relationship with the density ratio. Wang et al. [30] summed up the process of demulsifying extremely heavy crude oil and drying it at high temperatures with ultrasonic waves. The rate of dehydration increases as sound intensity increases, but it also decreases as sound intensity reaches a specific point, according to research findings. As the ultrasonic frequency increases, the rate of dehydration reduces. The study's data offer significant proof that ultrasonic demulsification and dehydration technology is widely used in China. Luo et al. [31] centered on the many uses of ultrasonic separation technology, particularly in the petrochemical sector. Wastewater-based phase separation is a commonly employed technique for emulsion dissolution, sludge extraction, and wastewater disposal. Comprehensive discussions are also held regarding the kinetic mechanism of ultrasound, active element design, separation principles, and associated applications. It has been demonstrated that ultrasound's mechanical and thermal effects can significantly improve oil-water separation. Three key categories comprise the elements influencing the effectiveness of oil-water separation: two-phase physical and chemical features, acoustic parameters, and experimental operating conditions (including temperature). Khajehesamedini et al. [32] created an experimental ultrasound setup to look at the possibility of replacing chemical demulsifiers in the processing of crude oil with low-frequency ultrasonic waves. The experiments' findings demonstrated that it is impossible to entirely avoid consuming chemically demulsified food. However, it might be possible to lower the injection of demulsified by 50% for a W/O emulsion with the appropriate duration and intensity of ultrasonic wave irradiation. When the acoustic cavitation is delayed, increasing the irradiation time increases the dehydration rate more effectively than increasing the acoustic intensity. Luo et al. [33] examined the influence of radiation length, frequency, acoustic intensity, oil viscosity, and oil-water interfacial tension on the separation parameters of the emulsion. They demonstrated the existence of an optimal oil-water interfacial tension, an optimum irradiation duration, and a perfect acoustic intensity for achieving maximum separation efficiency. Attempts have been undertaken to model the phenomenon in order to gain a better understanding of the coalescence of dispersed particles under the influence of ultrasonic vibrations. Pedrotti et al. [34] created an automated system employing open-source hardware to map the distribution of sound field in ultrasonic bath using a hydrophone operating at 35 kHz. This system's data collection allowed for the evaluation of the demulsification efficiency at various points along the American bath and its correlation with the distribution of acoustic intensity. Higher sound intensity (approximately 0.6 W cm −2) was found in the locations directly above the transducers using the automated 3D mapping technique, while other places showed significantly lower intensity (around 0.1 W cm −2). Using a little amount of chemical demulsifier, 15 minutes of 100% capacity sonication resulted in a demulsification efficiency of up to 93%. Luo et al. [35] centered on the range of applications and ideal settings for employing standing ultrasounds (USWs) to separate water-in-oil (W/O) emulsions. The theoretical investigation of the influence of droplet bandings on the demulsification process is conducted. The efficiency of separation is enhanced when droplet bandings and droplet sedimentation occur simultaneously under horizontal irradiation. Based on this, a detailed analysis is conducted on the impacts of oil water characteristics and acoustic parameters on demulsification. Additionally, it has been demonstrated that ultrasonic therapy is a successful demulsification technique and that the acoustic intensity and treatment time may be optimized to increase demulsification effectiveness. Sadatshojaie et al. [36] evaluated the efficacy of utilizing advanced tubular apparatus and ultrasonic fields to extract water from crude oil emulsions. The transducer had a 20 kHz frequency and an 80–1000 W power range. It was a piezoelectric ultrasonic transducer in the form of a horn. It was demonstrated that the application of ultrasonic fields caused water to separate efficiently and swiftly even in the absence of a chemical demulsifier. The more water was extracted from the crude oil, the stronger the ultrasonic field that was applied. Prolonged ultrasonic irradiation durations and elevated initial water separation (up to 15% or greater) in crude oil samples resulted in improved water-crude oil separation percentages under constant field intensity exposure. Parvasi et al. [37] showed how low-frequency ultrasonography affected the demulsification of wastewater with a low crude oil content (500 mg/L). subsequently conducted studies using a laboratory ultrasonic bath at frequencies of 25 kHz and 45 kHz without the use of chemical demulsifiers. Create experiments to assess how wastewater temperature, ultrasound power, ultrasound frequency, and ultrasound irradiation duration affect separation efficiency. The findings showed that the efficiency of crude oil emulsion separation rose by 72% when ideal circumstances were met.

Table (1) shows a summary comparison of the experimental studies in the section “Applications of Ultrasound”.

Table 1: A summary comparison of the experimental studies.

Author	Method	Material/Emulsion	Operating Conditions	Key Findings
Guoxiang et al. (2008)	Ultrasound + Electricity	Crude oil desalting	Standing wave field, combined with electric process	Combined process more efficient than electricity alone
Check et al. (2013)	Ultrasound + Chemical (Break 6500)	Crude oil	Ultrasonic irradiation, chemical demulsifier	Removal efficiencies: 84% desalting, 99.8% dehydration
Xie et al. (2015)	Resonant cavity ultrasound	Crude oil emulsion	Standing waves	Reduced water content from 40% to 3.8%
Mohsin et al. (2015)	Ultrasound only	W/O emulsions (10–40% water cut)	20 kHz ultrasonic wave	Faster separation than natural settling
Romanova et al. (2022)	Ultrasound + Nano-additives	Stable W/O emulsions	1.0 kW, 0.5–3 min, AlN suspension	>99% removal efficiency

4. Pretreatment of oils by adding material:

Hamidi et al. [38] compiled many methodologies and research findings for enhanced oil recovery with high-power ultrasonic waves. Mitigate formation damage next to the wellbore, since it leads to scale deposition, mud infiltration, and other complications that impede hydrocarbon production. Laboratory tests and mathematical models produced results consistent with field study, including reduced oil viscosity, lower residual oil saturation, and improved oil recovery under ultrasonic radiation. Gandomkar et al. [39] investigated the use of silica nanoparticles in chemical demulsifiers to increase their performance. Polyvinyl alcohol (PVA) and polyethylene glycol (PEG) were used as surfactants during the sol-gel method to create silica nanoparticles, which were subsequently added to the demulsifier. Particle size analyzers (PSAs) and SEM were used to characterize silica nanoparticles. According to the findings, silica nanoparticles raised the demulsifier's effectiveness by almost 40%. Hassan et al. [40] examined how various chemical removal techniques affected samples of heavy crude oil. The best demulsifier (KT-1903) was supplemented with a silica nanoparticle suspension. The greatest results, with a 53% increase in separation, were obtained from the chemical particle-to-nanosica removal procedure using silica nanoparticles with a diameter of 25 nm at a concentration of 60 ppm and a dosage of 1:0.5. Furthermore, it was amply demonstrated that the demulsifier's effectiveness was impacted by the aging of crude oil samples. Saat et al. [41] explored the potential of employing coconut oil and its byproduct, coconut betaine, as green demulsifiers for the water-to-crude-oil separation process. The findings of every trial examining the effect indicated that coconut betaine outperformed coconut oil in terms of effectiveness. Without adding xylene, 3 mL of coconut betaine to 10 mL of crude oil emulsion produced the maximum water separation of about 35% at 70 °C. Yu et al. [42] created a range of cutting-edge filtration and adsorption materials, including self-cleaning filtration membranes and oil adsorption materials with in situ heat generation, to enhance the performance of crude oil/water separation. For the first time, he also included a background on crude oil and mixes of crude oil and water. Additionally, a summary of the most recent materials for viscous crude oil/water separation based on filtration and adsorption techniques, respectively, is provided. This includes information on manufacturing procedures, strategies, mechanisms, and separation performance. Hassan et al. [43] examined the application of silica nanoparticles to improve the demulsification process in crude oil, both technically and economically. For the Central Processing Facility (CPF) in Balila, Sudan, which processes heavy crude oil from Fula, a software model was created in Microsoft Excel. A sensitivity analysis of the major production cost and net present value (NPV) variables was conducted for multiple flow schedule selection options. When flow tables are compared using equal plant capacity, production costs are reduced by 19%; however, production costs are reduced by just 3.7% when flow tables are compared using constant yearly crude oil processing. Pal et al. [44] focuses on employing an environmentally friendly demulsifier to break up the emulsion in order to increase water separation. It was determined from the data that the produced demulsifier functions optimally at 2000 ppm. It removes up to 88% of the water and effectively separates oil and water in a day. DEMLOCS is used to treat the emulsion, and at 45°C, the maximum water volume is separated. The application of biodemulsifier in heavy crude oil and water emulsion has shown a lot of encouraging results. Nadirov et al. [45] evaluated the demulsifying efficacy of original and fresh ground quartz (FMQ) particles extracted from river sand in the absence of an emulsifier. Using standard solid-liquid characterisation techniques together with rheological, surface tension, and demulsification studies, observe how quartz with a 75-micron mesh size affects emulsion stability. After 100 minutes of deposition, 3 weight percent FMQ was added, resulting in a 97% demulsification efficiency as opposed to 140 minutes for immaculate quartz. The purpose of grinding quartz is to make water more soluble, which raises the pH level locally and reduces the stability of the emulsion, ultimately leading to its disintegration. Okereke et al. [10]intends to use locally produced raw ingredients to design and formulate an inexpensive, ecologically friendly demulsifier. To find out how well it broke up the crude oil emulsion, an experimental examination was conducted. Locally produced liquid soap, starch, alum, camphor, castor oil, and distilled water were among the ingredients. Two distinct demulsifier compositions were created, evaluated, and heated to 60°F using an emulsion sample of crude oil from a Niger Delta field. Using a specially designed demulsifier, the process successfully separated the oil from the water.

5. Reviewed studies for Pretreatment:

Issaka [46] introduced a wide range of techniques, such as air flotation, ultrasonic, microwave, bacteriological, membrane, chemical, and electrical methods. This helps allay worries about the environment and financial instability while treating petroleum emulsions, as water is undesired because it could lead to serious problems. Demulsifiers are chemical additives that were used to treat petroleum emulsion. As a result, it has been said that silicone-based demulsifiers are very efficient, eco-friendly, and pricy. Future options for treating petroleum emulsions include microwaves and ultrasonography, both of which have demonstrated remarkable efficacy in treating petroleum emulsions. Zolfaghari et al. [47] designed to take into account the effects of emulsion composition and stabilization and destabilization with respect to prevailing parameters, and to give an overview of some of the most commonly used demulsification techniques (such as chemical, biological, membrane, electrical, and microwave irradiation) for both synthetic and oilfield emulsions. Additionally, talk about how the demulsification process affects the interfacial characteristics of emulsions. Next, describe the mechanism or mechanisms that each approach uses to analyze the emulsions. Umar et al. [7] provided a comprehensive overview of the progress in petroleum emulsions, emphasizing the function of particles combined with asphalt and resin in stabilizing emulsions in their absence. Developing demulsifiers based on the features of these emulsions, it also demonstrates a methodology for emulsion analysis that can provide effective demulsification through comprehensive assessment of substances believed to enhance emulsion stability. Table (2) shows summary of studies.

Table 2: Summary of previous works on water-oil separation using ultrasonic techniques.

Researchers	Method	Material used	Results
Guoxiang et al. (2008) [20]	The use of ultrasound and electricity in the desalination and dewatering of crude oil.	Without any material	The salt content decreased from 67.5 mg·L−1 to 3.97 mg·L−1 at lower temperature (80°C) in one stage treatment.
Ye et al. (2010) [48]	Use of ultrasound in water desalination and water drying processes	Without any material	The final findings for the water and salt contents were 0.37% and 3.851 mg/L.
Check et al. (2013) [22]	using ultrasonic radiation to help desalt and dehydrate crude oil	The chemical used as a demulsifier “break 6500”.	The desalting and dehydration processes have removal efficiencies of 84% and 99.8%, respectively.
Xie et al. (2015) [23]	Resonant cavity ultrasonic standing waves to collect water droplets and enhance oil separation.	Without any material	cutting the crude oil emulsion's water content from 40% to 3.8%.
Mohsin et al. (2015) [24]	De-emulsification of oil and water using ultrasonic technology	Without any material	The corresponding separation rate for emulsions with a 10–40% water cut is significantly quicker than natural separation, hence justifying the application of ultrasonic waves.
Antes et al. (2015) [49]	low frequency ultrasound for water	without using chemical demulsifiers.	Demulsification efficiency is 65% after 15 minutes at 45 °C and 160 W of ultrasonic power.
Atehortúa et al. (2015) [26]	ultrasonic standing waves.	Without using chemical demulsifiers.	The application of standing waves was discovered to improve the disruption of the water-in-oil emulsion in a laboratory processing facility.

Antes et al. (2017) [4]	the assessment of ultrasonic (US) frequency for demulsifying emulsions made from crude oil.	Without using chemical demulsifiers.	Following 15 minutes of US application, demulsification efficiencies of around 65% were achieved at a frequency of 45 kHz, utilizing emulsions with 50% initial water content and D (0.5) = 10 µm.
Luo et al. (2017) [28]	The formation of binary droplets in oil under ultrasonic standing waves and their coalescence process.	Surfactant (SDBS, Aladdin Industrial Inc.)	When the interfacial tension is 13.62 mN/m, the maximum oscillation frequency (3.5 Hz) and the shortest coalescence period (35 ms) are reached.
Luo et al. (2017) [29]	Water droplet suspension properties in oil under ultrasonic standing waves	the silicone oil	The density ratio and acoustic pressure at 39.4 kHz had no effect on the suspension position of the droplet.
Wang et al. (2018) [30]	Ultrasonic wave demulsification and dehydration of super heavy crude oil	Without any material	Dehydration rate increases with the increase of sound intensity, but dehydration rate will decrease when sound intensity reach a certain level; dehydration rate decreases with the increase of ultrasonic frequency.
Khajehesamedini et al. (2018) [32]	The preliminary treatment of crude oil with low-frequency ultrasonic waves	The RP-6348 and V-4654 demulsifiers	• With AW/O emulsion, it is feasible to reduce the injection of demulsifier by 50% by employing the proper irradiation period and ultrasonic wave strength. • It is impractical to completely eliminate the use of chemical demulsifiers. • There were fewer than 5% experimental mistakes.
Luo et al. (2018) [33]	water in oil (W/O) emulsion separation using an ultrasonic standing wave field	Surfactant (SDBS, Aladdin Industrial Inc.)	After irradiating the emulsion for 20 minutes at 5.87 W cm−2, the maximal dehydration rates were 78.43%, 62%, and 58.13% at 20.9 kHz, 28.2 kHz, and 39.4 kHz, respectively.
Pedrotti et al. (2018) [34]	Intensification of ultrasonic-assisted crude oil demulsification	Sodium chloride solution	Using a little amount of chemical demulsifier, 15 minutes of 100% capacity sonication resulted in a demulsification efficiency of up to 93%
Luo et al. (2019) [35]	Improved water-in-oil emulsion	The silicone oils	The optimal acoustic intensity of I_o = 2.03 W cm^2 occurs at a frequency

	separation by the use of ultrasonic standing waves		of 18.96 kHz. In this case, gravity sedimentation is 2.2 times less efficient at demulsifying the substance compared to ultrasonic treatment.
Sadatshojaie et al (2021) [36]	Ultrasonic fields for the separation of water in medium-gravity crude oil emulsions.	mineral salts	The more salty the crude oil, the more likely it is that the ultrasonic fields will be able to separate the water droplets from the oil and desalt the samples of crude oil.
Parvasi et al. (2022) [37]	low-frequency ultrasonography on low-grade crude oil demulsification	did not use chemical demulsifiers	The efficiency of crude oil emulsion separation rose by 72% when ideal circumstances were met.

Conclusion:

This review has demonstrated that ultrasound (US), particularly in the low-frequency range, offers a promising alternative or complementary method for demulsification of crude oil emulsions. Its key benefits include significant reduction in chemical demulsifier dosage, accelerated phase separation through enhanced droplet flocculation and coalescence, and the potential to integrate seamlessly with existing separation units. These advantages make ultrasound an environmentally friendly and operationally efficient option compared to conventional chemical or thermal approaches. However, several limitations remain. The high energy demand of ultrasonic irradiation raises concerns about cost-effectiveness at industrial scale, and the lack of standardized scaling laws limits the direct translation of laboratory results to field operations. Moreover, excessive sonication can lead to re-emulsification, highlighting the importance of precise control of acoustic parameters. Future research should focus on establishing clear energy–efficiency benchmarks, developing reliable scale-up models, and investigating the interaction between ultrasonic fields and interfacial film rheology in heavy crude systems. Integration with real-time monitoring tools and hybrid configurations (US combined with reduced chemical or electrostatic methods) may provide practical pathways for large-scale adoption. By addressing these gaps, ultrasound can move from being an experimental laboratory technique to a robust, sustainable solution for crude oil processing.

Acknowledgment:

The authors would like to thank the Electromechanical Department and the oil/Mid land Refineries Company of the Ministry of Oil for assistance in providing materials and testing.

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