Petroleum 11 (2025) 391–409

Contents lists available at ScienceDirect

Petroleum

journal homepage: www.keaipublishing.com/en/journals/petlm

Review Article

The role of resins in crude oil rheology and flow assurance: A comprehensive review

H.A. El Nagy[a], Elsayed H. Eltamany[a], Mostafa A.A. Mahmoud[a], Ahmed Z. Ibrahim[a,b,*], Sherin A.M. Ali[c]

[a] Chemistry Department, Faculty of Science, Suez Canal University, Ismailia, 41522, Egypt
[b] Egyptian General Petroleum Company, Research and Development Department, Gharib Quality Control Lab, Egypt
[c] Department of Mechanics, Faculty of Engineering, Suez Canal University, Ismailia, 41522, Egypt

ARTICLE INFO

Article history:
Received 22 December 2024
Received in revised form
7 June 2025
Accepted 14 July 2025

Keywords:
Resins
Crude oil
Flow assurance
Asphaltene stabilization
Rheology
Pipeline transportation

ABSTRACT

Resins are a significant component of crude oil, distinct from asphaltenes, and play a crucial role in influencing both rheological properties and flow characteristics. Understanding resin behavior is particularly important in crude oil operations and offshore operations, where flow assurance challenges can arise. This review article focuses on the impact of resins on the flow and rheological properties of crude oil. It examines the various compositions of resins and the molecular interactions between resins and asphaltenes that determine the viscosity and stability of crude oil. The presence of high concentrations of resins in certain crude oils can complicate flow assurance and pipeline transportation. Recent advancements in chemical treatments and additive technologies have addressed these challenges. This review highlights emerging research areas and technologies aimed at improving the understanding of resin behavior under extreme conditions, such as high-pressure and high-temperature reservoirs. Through this comprehensive analysis, the review aims to provide valuable insights into the role of resins in crude oil flow, guiding future research and innovations in petroleum engineering.

© 2025 Southwest Petroleum University. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Crude oil is a complex mixture of hydrocarbons, such as cycloalkanes, isoalkanes, n-alkanes, and aromatic compounds, with trace amounts of metals like nickel and vanadium and heteroatoms like nitrogen (N), sulfur (S), and oxygen (O). These non-hydrocarbon elements are frequently linked to resins and asphaltenes, which adds to the variation in the characteristics of crude oil.

Resins, as one series of molecules in crude oil, have gained much attention in recent years. Their importance cannot be overly assessed in chemistry because of their wide industrial applications, such as oil production, refining, petrochemicals, and composites. Resins are a kind of compound and they are classified into natural resins and synthetic resins. From the chemical point of view, resins are amorphous organic macromolecules with long carbon chains and they have no fixed melting point [1,2].

Crude oil can be separated by utilizing the varying volatilities of the chemicals comprising petroleum or by exploiting their unique solubility. Crude oil can be divided into four categories based on solubility: saturates (including waxes), aromatics, resins, and asphaltenes [3], or into eight categories: saturates, light aromatics, medium aromatics, heavy aromatics, light resins, middle resins, heavy resins, and asphaltenes [4]. The volatility fractionation process segregates crude oil into gas, naphtha, kerosene, diesel, vacuum gas oil, and vacuum residue [5].

Waxes exist as dissolved molecules in crude oil above the wax appearance temperature and do not directly mix with resins [6]. Despite their low volatility, research demonstrates considerable molecular weight diversity in resins, spanning from 775 to 2780 g/mol. This diversity affects their conduct in crude oil stabilization·

1.1. Background on crude oil composition and flow assurance

The composition of crude oil varies significantly based on its geographical origin and the geological conditions of its reservoir. The SARA analysis is commonly used to categorize crude oil into its primary components:

---

[*] Corresponding author.
E-mail address: a.zaki_89@yahoo.com (A.Z. Ibrahim).
Peer review under the responsibility of Southwest Petroleum University.

https://doi.org/10.1016/j.petlm.2025.07.009
2405-6561/© 2025 Southwest Petroleum University. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

(1) Saturates: these are straight or branched-chain alkanes and cycloalkanes, which are non-polar and exhibit low viscosity [7]. However, wax crystallization can severely hinder crude oil flowability, leading to pipeline challenges.
(2) Aromatics: compounds containing one or more aromatic rings that contribute to the intermediate polarity and viscosity of crude oil [8,9].
(3) Resins: polar, heavy compounds containing heteroatoms such as nitrogen, sulfur, and oxygen (NSO compounds). Resins play a crucial role in stabilizing asphaltenes and preventing their aggregation [10].
(4) Asphaltenes: the heaviest, most polar fraction of crude oil, composed of polyaromatic hydrocarbons with attached heteroatoms and metals [11].

Flow assurance, the ability to ensure the continuous flow of crude oil from the reservoir to the surface, is a major challenge in the oil and gas industry. One of the critical issues in flow assurance is the precipitation and deposition of heavy fractions like asphaltenes, which can clog pipelines and processing equipment [12,13]. The interaction between resins and asphaltenes is central to these flow assurance problems. When the resin content in crude oil is high enough to stabilize asphaltenes, the risk of precipitation is minimized. However, when the resin content is insufficient or the environmental conditions change (e.g., pressure drops or temperature fluctuations), asphaltenes begin to precipitate, leading to flow issues [14,15].

However, resins are also problematic in certain cases. While they prevent asphaltene precipitation, their polar nature can lead to the formation of viscous, gel-like structures in heavy crude oils, increasing resistance to flow and complicating transportation [16–18]. This dual role makes understanding resin behavior a crucial element in flow assurance strategies, especially in offshore production environments, where temperature and pressure variations can exacerbate the precipitation and aggregation of heavy fractions [19,20].

1.2. *Significance of resins in crude oil*

Resins are a distinctive element of crude oil owing to their amphiphilic properties, enabling interaction with both non-polar and polar components of crude oil. Their capacity to stabilize asphaltenes via peptization is extensively reported in the literature. The peptization process entails resins encasing asphaltene molecules, inhibiting their aggregation into bigger clusters that may precipitate from the solution [21,22].

As illustrated in Fig. 1, resins perform several critical functions across the heavy oil production and handling chain. These include aiding extraction, facilitating transport, and stabilizing asphaltenes, thereby playing a key role in flow assurance strategies.

Initially, research on resins was conducted within the context of understanding asphaltenes; however, resins have since been acknowledged for their independent and vital influence on the flow dynamics of crude oil. Resins impact the viscosity, stability, emulsification tendencies, and overall flow characteristics of crude oil. In heavy and extra-heavy crude oils, the resin-to-asphaltene ratio is critical, as resins inhibit the formation of solid deposits in pipelines and production facilities [23,24].

Nonetheless, the function of resins is accompanied by difficulties. Their polar characteristics might result in increased viscosity in some crude oils, complicating transportation through pipelines. Moreover, resins promote fouling and deposition in downstream processes due to their elevated molecular weight and polar functional groups, which render them susceptible to heat breakdown and the generation of coke-like compounds in refining units [25].

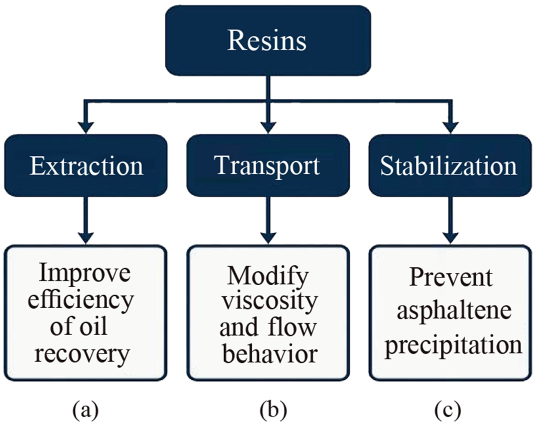

Fig. 1. Schematic flowchart summarizing the multifaceted roles of resins in heavy oil systems. Resins contribute to (a) enhancing extraction efficiency by modifying interfacial properties, (b) improving flow behavior during transport by reducing viscosity, and (c) stabilizing asphaltenes to prevent flocculation and deposition during processing and flow.

Table 1 highlights the principal distinctions between resins and asphaltenes, contrasting their molecular weight, solubility, polarity, chemical makeup, and industrial significance. The interactions between resins and asphaltenes significantly influence the rheological behavior and stability of crude oil. wherein resins stabilize asphaltenes to avert aggregation and precipitation. Comprehending these distinctions is essential for alleviating operational concerns, including fouling and flow assurance problems.

1.3. *Objectives of the review*

This review aims to deliver a thorough analysis of the function of resins in crude oil flow, emphasizing their interactions with asphaltenes, their influence on viscosity, and the issues they pose in flow assurance and transportation. The review will specifically consider the following critical topics:

(1) The molecular structure and composition of resins and how these properties influence their role in crude oil systems.
(2) The interactions between resins and asphaltenes, with a focus on how these interactions impact crude oil stability and viscosity.
(3) The challenges posed by resin-rich crude oils in pipeline transportation and flow assurance, particularly in deepwater and offshore operations.
(4) Current and emerging technologies designed to mitigate resin-related flow issues, including chemical treatments and nanotechnology.
(5) Future research directions aimed at improving the understanding of resin behavior in extreme production environments, such as high-pressure, high-temperature reservoirs.

2. Definition of resins

Crude oil or petroleum is a complex mixture of hydrocarbons with some heteroatoms, metallo-organic compounds, minerals [26]. It is known as the “mother of chemical feedstocks” because of its considerable economic importance and various applications in several industries. The hydrocarbon content in crude oils generally ranges from 83.2% to 87.1% and consists of n-alkanes, isoalkanes, cycloalkanes, and aromatic classes of molecules which differ from

Table 1
Key differences between resins and asphaltenes.

Property	Resins	Asphaltenes
Molecular weight	775–2780 Da	Lower than 1000 to 10,000 Da (or higher)[a]
Solubility	Soluble in most organic solvents	Insoluble in light alkanes (e.g., n-heptane), soluble in toluene
Polarity	Intermediate polarity	Highly polar
Role in crude oil	Stabilizes asphaltenes, prevents aggregation	Can aggregate and precipitate without stabilization by resins
Chemical composition	Contains heteroatoms (N, S, O), aromatic and aliphatic structures	Contains polycyclic aromatic hydrocarbons with heteroatoms and metals
Industrial impact	Contributes to crude oil viscosity and emulsion formation	Major cause of fouling, asphaltene precipitation leads to flow issues

[a] Molecular weight typically ranges from <1000 Da for individual molecules to aggregates of 10,000 Da or more, depending on the analytical technique used (e.g., GPC, MALDI-TOF, vapor pressure osmometry) [27].

source to source [28]. The determination of hydrocarbon content is generally performed using methods such as gas chromatography (GC).

Resins, a significant component of crude oil, have been characterized in numerous methods in the literature, illustrating the intricacy of their chemical structure and their crucial function in petroleum systems. Tissot and Welte [29] characterized resins as high-molecular-weight molecules soluble in aromatic hydrocarbons yet insoluble in mild paraffinic solvents. They designated resins as intermediary compounds between lighter oils and asphaltenes, significantly influencing the viscosity and emulsification characteristics of crude oil. Similarly, Speight [30] provided a functional definition, highlighting that resins work as surface-active agents. Their polar characteristics are crucial for preserving the colloidal stability of crude oil, particularly by stabilizing asphaltenes and inhibiting their aggregation and precipitation. According to foundational studies, including Andersen & Speight [31] and Koots & Speight [32], resins are amphiphilic molecules containing both aromatic and aliphatic structures, along with heteroatoms such as nitrogen (N), sulfur (S), and oxygen (O). Often linked with porphyrins, resins also contain trace metals, including vanadium and nickel. These structural properties help to explain their function in preventing asphaltene precipitation and modifying crude oil's rheological behavior. Mullins et al. [33] elaborated on this perspective by characterizing resins as intermediate polar molecules that facilitate the solubilization of asphaltenes and maintain the stability of crude oil. The notion of the “asphaltene-resin complex” was established, highlighting the crucial function of resins in preserving the dispersive state of asphaltenes. Yen and Mullins [34] elaborated on this concept, characterizing resins as polyaromatic frameworks that incorporate heteroatoms including oxygen, nitrogen, and sulfur. These substances affect the solubility of asphaltenes and enhance the overall stability of crude oil in various settings.

Speight re-examined the subject, providing a more technical viewpoint, wherein resins are characterized as aromatic and heteroatomic molecules that display considerable polar functionality. These chemicals are essential in refining processes, as they affect the viscosity and phase behavior of crude oils.

Goual et al. [35] reports that resins separated by liquid propane are part of the total resins. So, the question of what resins are is very difficult to answer.

Anderson et al. [36], in their investigation of heavy oils, characterized resins as polymers possessing varying molecular weights and functional groups that engage with various components of crude oil. They contended that these interactions are essential in ascertaining the oil's composition and quality, particularly in refining processes. Marshall and Rodgers [37] underscored the molecular intricacy of resins, characterizing them as amalgamations featuring aromatic centers and polar side chains. They emphasized their contribution to crude oil stability by inhibiting asphaltene precipitation and improving colloidal system stability. Burgess et al. [38] recently emphasized the significance of resins in improved oil recovery (EOR) techniques. Resins are characterized as chemicals with intermediate solubility that enhance the emulsion stability of crude oil and substantially influence the efficacy of recovery methods in conjunction with surfactants.

Alongside these academic definitions, industrial standards, including those from the American Society for Testing and Materials (ASTM), offer insights into resin characterisation. ASTM D2007-06 [39] defines resins polar aromatic molecules with intermediate molecular weights and heteroatom concentration. ASTM D 2007 states that although resins are precipitated by lesser alkanes like propane and butane, they are soluble in organic solvents including toluene. These molecules stabilize asphaltenes through peptization, so bridging the characteristics of saturates, aromatics, and asphaltenes.

The varied classifications, encompassing both functional and structural viewpoints, highlight the complexity of resins and their essential significance in the behavior of crude oil. As the petroleum industry progresses, a comprehensive understanding of resins will be essential for optimizing crude oil usage and refining processes.

Understanding these foundational structural traits of resins is essential for interpreting their behavior in complex petroleum systems. In light of the literature reviewed above, Resins are structurally complex molecules situated chemically and functionally between saturates and asphaltenes. Their amphiphilic character, driven by polar functional groups (e.g., OH, $S{=}O$, NH_2) attached to aromatic or alkyl frameworks, gives them a unique ability to interface between polar and nonpolar phases. The literature supports that this interfacial activity plays a fundamental role in crude oil stability. However, the precise contribution of resin substructures varies with origin and processing history, making compositional profiling critical. This section establishes that any serious attempt to understand or control the rheological behavior of heavy oils must begin with a chemically nuanced understanding of resin molecular architecture.

3. Molecular structure and composition of resins in crude oil

Resins are complicated polar compounds that constitute an essential portion of crude oil. Their distinct molecular structure, featuring heteroatoms and aromatic rings, plays a crucial role in stabilizing asphaltenes and affecting the overall flow characteristics of crude oil [40]. Grasping the chemical makeup and composition of resins is essential for formulating effective strategies for flow assurance, as their molecular structure directly influences their interactions with other crude oil components.

3.1. Chemical composition and heteroatom content

Resins represent the heavier fraction of crude oil and exhibit distinct chemical characteristics compared to lighter components, such as saturates and aromatics. They primarily comprise polycyclic aromatic hydrocarbons (PAHs) with alkyl side chains, which may include functional groups containing nitrogen (N), sulfur (S), and oxygen (O) heteroatoms, collectively referred to as NSO compounds. The inclusion of heteroatoms imparts a polar nature to resins, granting them amphiphilic properties that enhance their interaction with both polar and non-polar molecules within the crude oil matrix [41,42].

The molecular weight of resins is less than that of asphaltenes but considerably greater than that of the lighter components of crude oil. Recent studies indicate that the molecular weight of single asphaltenes is generally less than 1000 g/mol, and the molecular weight of resins is often lower than that of asphaltenes. The polarity of resins is chiefly attributed to the presence of heteroatoms, and the extent of polarity may fluctuate depending on the concentration of these heteroatoms [43,44].

Besides NSO compounds, resins may include trace metals like vanadium and nickel, frequently linked to porphyrin structures inside the resin molecules. These metals often exist in lesser quantities than asphaltenes, however they nonetheless enhance the overall molecular complexity of resins. The presence of this metal concentration might complicate refining, as the metals often accelerate undesirable reactions, including coke formation during thermal cracking stages [45,46].

The polar characteristics of resins are essential for their role in stabilizing asphaltenes. Resins, owing to their amphiphilic characteristics, can engage with the aromatic, polar cores of asphaltenes while concurrently engaging with the non-polar components of crude oil, so producing a stabilizing effect that inhibits asphaltene aggregation and precipitation [47,48].

Fig. 2 illustrates a hypothetical molecular structure of resins, showcasing their polycyclic aromatic core with alkyl and heteroatomic functional groups. The presence of sulfur, oxygen, and alkyl side chains suggests their role in crude oil stabilization by interacting with asphaltenes. These functional groups contribute to solubility, polarity, and dispersion properties, preventing asphaltene precipitation and ensuring crude oil flow stability [49–51]. The depicted structure represents a generalized model, as actual resin compositions vary depending on crude oil origin and composition.

In 2017, Imanbayev et al. contributed to the literature by investigating the structural features of resin-asphaltene molecules during cracking processes [52]. They claim that resins, which persist after asphaltene precipitation, exhibit unique properties that affect the total viscosity and density of bitumen. This underscores the dual function of resins as stabilizers and enhancers of the physical qualities of crude oil.

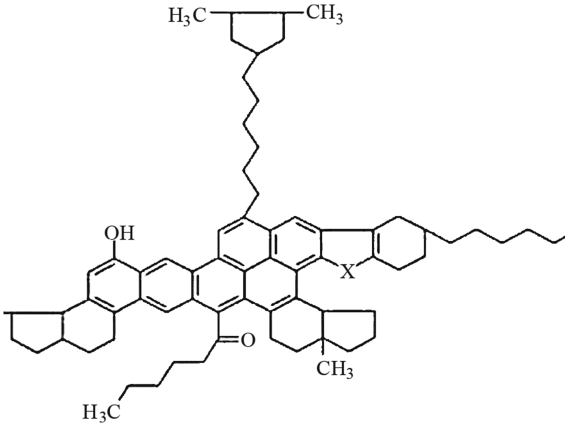

Fig. 2. Hypothetical structure of resins. X is heteroatom (N,O,S).

M. Iwase et al. in 2018 presents molecular modeling and simulations, highlighting the significance of chemical compositions in enhancing models for asphalt systems. Their discovery indicates a transition towards a more sophisticated knowledge of resin-asphaltene interactions, which is essential for grasping the molecular dynamics involved in heavy crude oil [53].

In 2019, G. Singh et al. examined the combustion properties of crude oil droplets, highlighting the impact of resin content on the combustion characteristics of different crude oil types [54]. This study demonstrates the practical effects of resin composition on energy generation and environmental consequences, thereby connecting chemical composition to tangible uses [55]. Their research highlights the necessity for sophisticated analytical methods to accurately define the intricate interactions among crude oil constituents.

A. Abou-Dib et al. article discusses the difficulties in attaining thorough molecular characterization in intricate organic mixtures, such as bio-oils [56]. Their focus on the imperative for fractionation and separation techniques before mass spectrometry examinations corresponds with the continuous pursuit of a more profound comprehension of crude oil's chemical composition, especially regarding resin interactions.

Recent breakthroughs by S. F. Alkafeef et al. [57] elucidate the interactions between asphaltene and resin molecules in solvent deasphalting technology. Their studies demonstrate how the chemical composition of resins impacts asphaltene stability, thereby influencing oil recovery methods [58]. Expand on this understanding by examining the stability of crude oil systems concerning resin content, positing that an ideal equilibrium of resin and asphaltene is crucial for sustaining system stability.

These papers collectively enhance the understanding of the chemical composition of resins in crude oil, demonstrating their essential significance in the stability, recovery, and exploitation of petroleum resources. The development of this literature indicates an increasing awareness of the intricacies associated with resin-asphaltene interactions and their consequences for industrial applications and environmental factors.

Building on the molecular characteristics discussed, it becomes clear that variations in resin structure strongly influence their role in oil stabilization. The literature suggests several key trends and implications: Studies consistently show that resin molecules comprise polyaromatic cores with varying degrees of alkylation, branching, and heteroatom substitution. However, the ratio between light and heavy resins significantly influences their role in flow behavior. Lighter resins, often rich in short alkyl chains and oxygen groups, behave more like surface-active agents, while heavier resins—with multiple fused rings and sulfur or nitrogen groups—tend to form stronger intermolecular networks. This structural variation governs how resins associate with asphaltenes and how they respond to stress, temperature, or diluents. The data implies that optimizing heavy oil processing requires not only resin concentration control but selective targeting of resin fractions by structure.

4. Techniques for measuring resins in crude oil

Characterizing the molecular structure of resins poses numerous challenges owing to their intricate and heterogeneous composition. Resins constitute a heterogeneous combination of substances characterized by diverse molecular weights, functional groups, and heteroatom content, rather than being a singular, well-defined chemical entity. Advanced analytical techniques are necessary to isolate and analyze resins, and many ways have been developed to do this [59,60].

Table 2 outlines the methodologies employed for the separation of resins from petroleum, encompassing ASTM D2007, SAR-AD, and propane precipitation. It offers insights into the principles, benefits, and constraints of each method, aiding in the selection of suitable analytical techniques for resin characterization.

Fig. 3 shows the spatial structure of resins in heavy oil from the Zuunbayan field (Mongolia) highlights their complex molecular architecture, consisting of polycyclic aromatic cores with alkyl, oxygen, and sulfur-containing functional groups.

4.1. Recent analytical techniques for resin characterization

The following instrumental techniques are commonly used for resin characterization:

4.1.1. Mass spectrometry (MS)

It is a highly effective method for determining the molecular weight distribution of resins. Advanced mass spectrometry techniques, such as electrospray ionization (ESI) and matrix-assisted laser desorption/ionization (MALDI), allow for the analysis of complex resin mixtures and the identification of heteroatoms and trace metals [61–64]. Fourier-transform ion cyclotron resonance mass spectrometry (FT-ICR MS) offers ultrahigh resolution, which is particularly valuable for studying the molecular diversity of resin fractions [65].

4.1.2. Nuclear magnetic resonance (NMR) spectroscopy

It serves as an effective method for elucidating hydrogen and carbon environments within resin molecules. Despite ongoing difficulty in interpreting general signals from structurally varied species, ^{1}H NMR effectively distinguishes hydrogen atoms bonded to aromatic, aliphatic, hydroxyl, and heteroatom-substituted carbons. Aromatic protons generally resonate between δ 6.0–8.5 ppm, whereas aliphatic chain protons appear between δ 0.8–2.0 ppm. Functional groups such as –OH, –SH, and $-NH_2$ manifest in the δ 1–6 ppm range, but with broadening attributed to exchange processes.

^{13}C NMR enhances this investigation by facilitating the identification of quaternary carbons, carbonyls, and aromatic core structures. Carbon atoms neighboring oxygen (e.g., phenolic or ether linkages) generally reverberate in the δ 150–160 ppm region, whereas aliphatic carbons resonate between δ 10–50 ppm.

The categorization of hydrogens according to their bonding environments, as outlined in the study on hydrothermal lignite treatment, serves as a valuable reference for analyzing resin spectra in intricate systems [66]. Their application of isotope tracing alongside NMR underscores the significance of integrating experimental design with spectral analysis in resin-dense samples.

4.1.3. Fourier-transform infrared (FTIR) spectroscopy

It is widely used to identify functional groups in resin molecules, including hydroxyl, carbonyl, and sulfur-containing groups. These functional groups are critical for understanding the amphiphilic characteristics of resins and their interactions with other crude oil components [67,68].

4.1.4. Chromatographic techniques, including gas chromatography-mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC)

They are frequently employed to isolate and examine resin subfractions. These methods, when combined with spectroscopic techniques, offer comprehensive insights into resin heterogeneity and composition [69].

4.1.5. Solvent precipitation (ASTM D2007-06)

It is a widely utilized method for quantifying resins, particularly in industry. This approach involves categorizing resins based on their solubility in aromatic hydrocarbons and their insolubility in non-polar solvents, providing a simple, reliable technique for bulk resin quantification. However, this method has limitations in terms of the structural detail it can provide, as it focuses mainly on bulk quantities and lacks the ability to resolve finer compositional differences (ASTM D2007-06) [39].

Notwithstanding these sophisticated techniques, the comprehensive molecular characterisation of resins continues to pose challenges. Their intricate and fluctuating makeup, along with interactions among other crude oil constituents, necessitates continuous enhancement of analytical techniques to achieve a more profound comprehension of their structure [70,71].

4.2. Advances in resin characterization

In recent years, there has been a strong focus on integrating multiple analytical techniques to gain a more comprehensive understanding of resin composition and structure. This multi-modal approach allows for a more detailed analysis of resin heterogeneity and functional properties.

Multi-modal techniques: integrating methods like HPLC with FTIR or MS enhances the characterization of resin mixtures. Such integration allows for a deeper analysis of resin composition, functional groups, and molecular diversity [72].

Environmental and functional studies: Recent research has highlighted the role of resins in environmental processes such as photooxidation, where exposure to light induces significant chemical changes in resin fractions. These changes are important for understanding the environmental degradation of crude oil and the implications for oil spill management [73]. Additionally, the resin-to-asphaltene ratio plays a vital role in stabilizing crude oil emulsions. Resins help to prevent flocculation and promote emulsion stability by enhancing the solvency of asphaltenes [74].

Table 2
Different methods employed to separate resins from petroleum.

Method	Principle	Advantages	Limitations
ASTM D2007	Solubility in solvents	Widely accepted and standardized	Limited differentiation of subtypes
Sar-ad method	Sequential adsorption and desorption	Detailed fractionation into SARA subgroups	Time-consuming and complex process
Propane precipitation	Solubility in propane and butane	Simple and effective for isolating resins and asphaltenes	Overlapping boundaries between resins and asphaltenes
Liquid chromatography	Adsorption and separation based on polarity	High-resolution separation	Requires specialized equipment
Mass spectrometry-based	Molecular weight and compositional analysis	Provides detailed molecular insights	Expensive and requires skilled interpretation

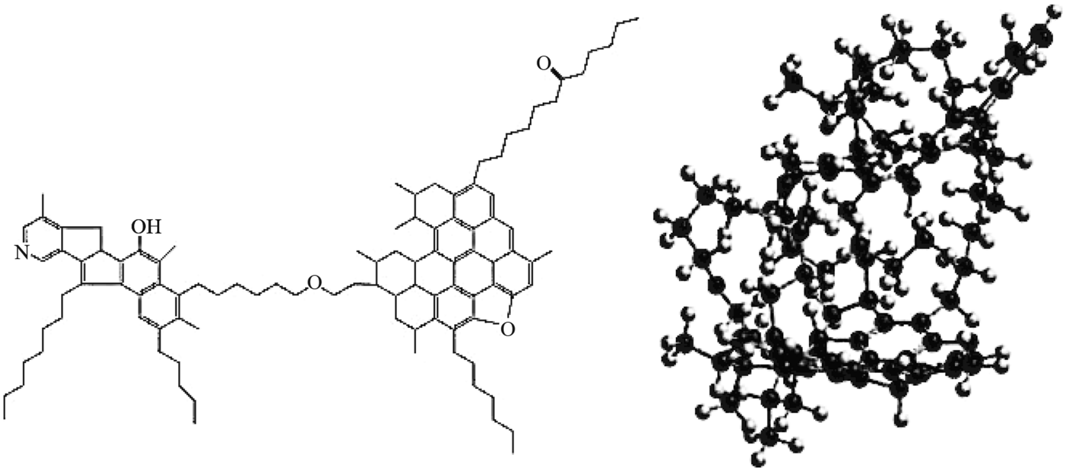

Fig. 3. Spatial resins structure of heavy oil of Zuunbayan field (Mongolia) [39].

Elemental analysis: The Inductively coupled plasma optical emission spectrometry (ICP-OES) technique is used to quantify trace metals, such as vanadium and nickel, in resins. These elements are of particular concern in industrial processes, as they contribute to catalyst poisoning and equipment fouling [75].

4.3. Thermal and molecular dynamics simulations

Alongside spectroscopic and chromatographic methods, thermal analysis techniques such as Thermogravimetric analysis (TGA) and Differential scanning calorimetry (DSC) provide insights into the thermal stability and decomposition behavior of resins. These methods are particularly useful for understanding resin interactions with other crude oil components during refining processes [76].

Molecular dynamics simulations are another advanced approach used to study the aggregation behavior of resins and their interactions with asphaltenes. These simulations help predict the behavior of emulsions and the flow characteristics of crude oil, which are important factors in refining and enhanced oil recovery techniques [77].

Given the wide range of analytical tools and challenges in resin characterization, the collective findings point to the following integrated perspective: Modern characterization of resins requires a multifaceted approach due to their structural complexity and high heteroatom variability. Techniques like FTIR and GC-MS reveal the broad functional diversity of resins, but their resolution is often insufficient to distinguish subtle polar features. NMR spectroscopy, particularly ^{1}H and ^{13}C NMR, provides a clearer window into the local environment of hydrogen and carbon atoms, revealing degrees of aromaticity, alkyl substitution, and functional group clustering. However, many studies highlight the challenges of overlapping signals due to resin heterogeneity. The referenced work by Liu et al. demonstrates how isotope tracing combined with NMR can resolve dynamic hydrogen migration during thermal processing — a method particularly suited for studying resin reactivity. These findings collectively indicate that the most reliable understanding of resin function emerges not from a single technique but from integrated spectroscopic profiling, ideally applied under reservoir-simulated conditions.

5. Resin types in different crude oils

The content and properties of resins can differ markedly based on the geographic origin and reservoir conditions of the crude oil. Resins derived from light, medium, heavy, and extra-heavy crude oils have distinctions in molecular structure, heteroatom composition, and molecular weight distribution, resulting in variances in flow behavior and interaction with asphaltenes.

5.1. Light and medium crude oils

They often possess reduced resin content in comparison to heavier crude kinds. These resins are defined by their very low molecular weights, reduced heteroatom content (including sulfur, nitrogen, and oxygen), and mostly aliphatic molecular structures [33]. Consequently, they demonstrate a significant capacity to stabilize asphaltenes. Resins in these oils frequently establish temporary contacts with asphaltenes, inhibiting their aggregation and precipitation, thus enhancing the stability of crude oil [78,79].

The lighter hydrocarbons in light and medium oils predominantly dictate the rheological properties, eclipsing the influence of resins on flow behavior [80].

Although less abundant, the interaction between resins and lighter hydrocarbons facilitates the effective dispersion of asphaltenes, reducing fouling in refining operations and transportation systems [81].

5.2. Heavy and extra-heavy crude oils

They have markedly elevated resin concentrations, characterized by larger molecular weights, enhanced heteroatom content, and heightened aromaticity [82].These molecular attributes facilitate more robust polar contacts between resins and asphaltenes, leading to improved stability of asphaltenes within the crude oil matrix. Nonetheless, these interactions also result in problems, including heightened viscosity and the development of organized networks that display gel-like properties under certain conditions [83,84].

The elevated resin concentration in heavy oils serves a twofold purpose. Resins inhibit asphaltene precipitation, hence diminishing the probability of operational complications such as pipeline obstructions [85]. Conversely, the enhanced interactions between resin and asphaltene elevate flow resistance, hence hindering the extraction and transfer of these oils [35].

Reservoir factors, including temperature, pressure, and the presence of water or gas, can affect the composition of resins in crude oil. Thermal maturity influences the molecular composition of resins; oils from more mature reservoirs typically possess resins with increased aromaticity and condensed ring structures, whereas oils from less mature reservoirs are likely to contain resins characterized by elongated aliphatic chains and reduced aromaticity [86]. Geochemical variables, including sulfur-rich environments, can elevate the sulfur concentration in resins, hence augmenting their polarity and affecting their interactions with other crude oil constituents [28]. These sulfur-rich resins exhibit a strong interaction with asphaltenes and other polar constituents, perhaps resulting in the creation of more stable yet viscous crude oil mixes [87]. The presence of water and gas in the reservoir might modify the phase behavior of crude oil, affecting the solubility and distribution of resins and their interactions with other oil fractions [88].

6. Resin-asphaltene interactions

Interactions between resin and asphaltene are crucial in influencing the flow characteristics and stability of crude oil, particularly in heavy and extra-heavy grades. These interactions are pivotal to flow assurance, since they influence the precipitation, aggregation, and stabilization of asphaltenes, the heaviest and most polar part of crude oil. Comprehending the mechanics of resin-asphaltene interactions can aid in alleviating flow assurance challenges, including heightened viscosity, pipeline obstructions, and sedimentation in wells and processing apparatus.

Asphaltenes exist in crude oil as colloidal micelles, stabilized by the adsorption of resins and other aromatic maltenes. Pfeiffer and Saal [89] proposed that these structures are formed with an asphaltene-rich core and layers of adsorbed resins that prevent aggregation. When sufficient resin is present, micelles are fully peptized and dispersed; when deficient, they flocculate and form gel networks due to intermicellar attractions.

Fig. 4 illustrates the distinctive changes in appearance that can be seen between asphaltenes and resins.

The range of studies explored here presents a consistent narrative regarding resin–asphaltene interaction mechanisms. The authors' synthesis and interpretation are summarized below:

The literature consistently describes resins as key agents in the stabilization of asphaltenes via adsorption mechanisms, preventing their aggregation and precipitation. While classical micellar models (e.g., Pfeiffer and Saal) propose physical encapsulation by resins, more recent spectroscopic and computational studies reveal that polarity, heteroatom content, and aromatic ring stacking significantly affect adsorption affinity and steric hindrance. Several cited works highlight that resin efficiency in peptizing asphaltenes depends not only on concentration but also on molecular architecture — with light resins favoring dispersibility and heavy resins offering more persistent anchoring under thermal stress. This suggests that resin–asphaltene interactions are not static but evolve with temperature, pressure, and chemical environment. Therefore, optimizing resin profiles could offer a tunable strategy for preventing flocculation in heavy oil pipelines, especially under variable flow conditions.

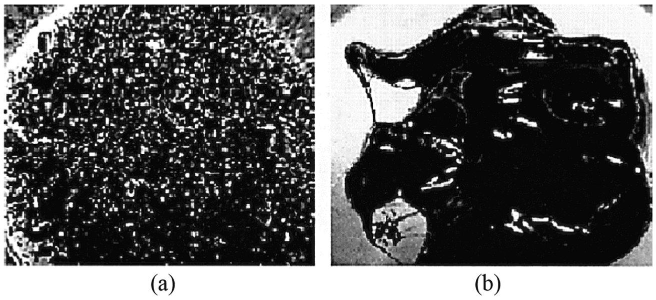
(a) (b)

Fig. 4. (a) Asphaltenes and (b) resins separated from crude oils [34].

6.1. Asphaltenes and their precipitation in crude oil

Asphaltenes are high-molecular-weight polyaromatic hydrocarbons that include heteroatoms such as nitrogen, sulfur, and oxygen, along with trace metals like vanadium and nickel. Their intricate and inflexible structure renders them susceptible to aggregation and precipitation under specific conditions, including pressure reductions, temperature variations, and alterations in crude oil composition (e.g., the incorporation of lighter hydrocarbons such as n-alkanes) [90].

Asphaltenes in solution exist as scattered particles, stabilized by resins and other polar constituents. When destabilized, asphaltenes tend to create colloidal suspensions that can aggregate into bigger particles, ultimately resulting in phase separation and precipitation [91]. This precipitation poses a significant challenge in flow assurance, as it may lead to deposit development in pipelines, wells, and other infrastructure, resulting in blockages, elevated operational expenses, and production interruptions [92].

Asphaltene precipitation is influenced by several factors:

1. Pressure and temperature: asphaltenes are more likely to precipitate as the pressure decreases, particularly in offshore and deepwater production environments where the temperature difference between the reservoir and surface conditions is significant [93].
2. Composition of crude oil: the addition of lighter hydrocarbons, such as n-alkanes, can destabilize asphaltenes, causing them to precipitate out of solution [94].
3. Resin-to-asphaltene ratio: the ratio of resins to asphaltenes in crude oil is a critical factor in determining asphaltene stability. A higher resin concentration is associated with more stabilization of asphaltenes, while a lower resin concentration can lead to asphaltene precipitation [95].

As shown in Fig. 5, the presence or absence of sufficient resins significantly alters the colloidal stability of asphaltenes in crude oil. In well-stabilized systems, asphaltenes remain dispersed, whereas resin-deficient systems promote flocculation and the formation of gel-like structures.

6.2. The role of resins in asphaltene stabilization

Resins are essential in inhibiting the precipitation and aggregation of asphaltenes. Resins, owing to their amphiphilic characteristics, can engage with both the polar and non-polar constituents of crude oil. They function as peptizing agents by adsorbing onto the surfaces of asphaltene particles, inhibiting their aggregation and the formation of bigger clusters. This stabilizing technique is essential for preserving the fluidity of crude oil and averting flow assurance issues [96].

The stabilization of asphaltenes by resins transpires via a synthesis of polar and non-polar interactions. Polar groups in resins, including hydroxyl, carbonyl, and sulfur-containing functional groups, engage with the polar surfaces of asphaltenes. The non-polar portions of resins interact with neighboring hydrocarbons, forming a barrier that inhibits asphaltenes from contacting one another [97,98].

The effectiveness of resins in stabilizing asphaltenes depends on several factors:

1. Resin concentration: a higher concentration of resins relative to asphaltenes increases the stability of the colloidal

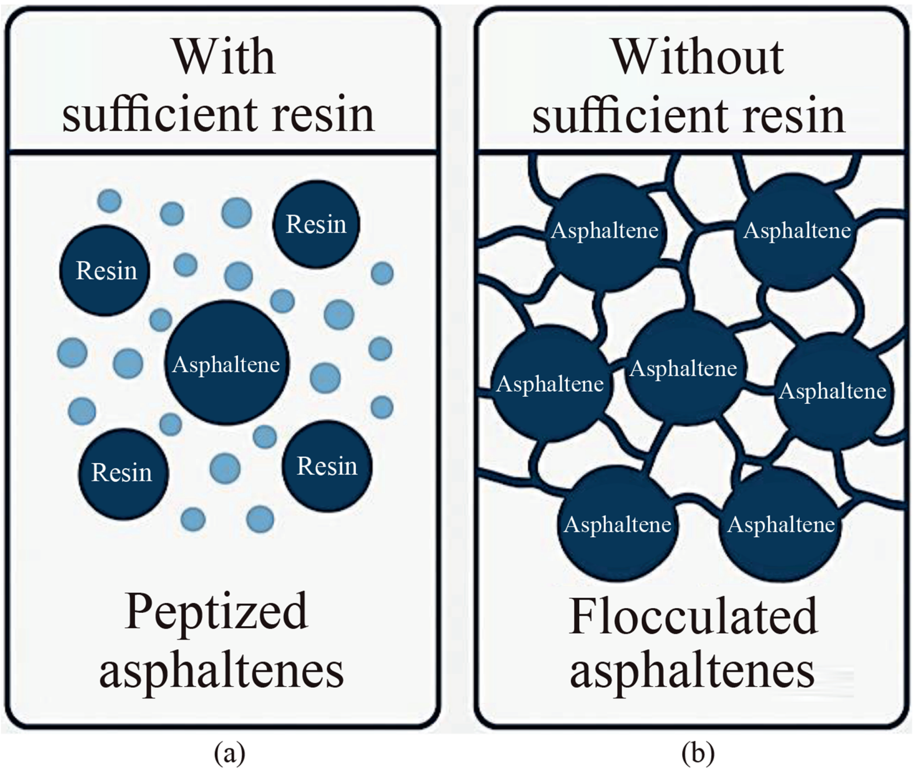

Fig. 5. Comparison of crude oil behavior with and without sufficient resin content. (a) In resin-rich systems, resins adsorb onto asphaltenes, maintaining their dispersion as peptized micelles. (b) In resin-deficient conditions, asphaltenes aggregate and flocculate, forming network structures that negatively affect flow properties.

suspension. When the resin concentration is sufficient, asphaltenes remain dispersed and do not precipitate, even under adverse conditions [99,100].

(2) Molecular structure of resins: the molecular weight, aromaticity, and heteroatom content of resins influence their ability to stabilize asphaltenes. Resins with higher aromaticity and a greater number of polar functional groups are generally more effective at stabilizing asphaltenes [101,102].
(3) Environmental conditions: temperature and pressure can impact the ability of resins to stabilize asphaltenes. At lower temperatures, resins may lose their effectiveness, leading to the formation of gel-like structures or solid deposits [103,104].

The resin-asphaltene interaction is not a static process; it is highly dynamic and influenced by changes in crude oil composition and environmental conditions. This dynamic nature makes predicting asphaltene stability a complex challenge, particularly in reservoirs with fluctuating pressure and temperature profiles [105].

Fig. 6. Schematic diagram showing the stabilization of asphaltenes by resin adsorption in crude oil. Left: isolated, resin-coated asphaltene micelles; Right: flocculated micelles forming gel networks due to resin deficiency. Adapted based on the model proposed by [89].

6.3. Resin influence on viscosity and rheology

The interaction between resins and asphaltenes significantly influences the viscosity and rheology of crude oil. The presence of asphaltenes and resins in heavy and extra-heavy oils leads to the production of complex, structured fluids that display non-Newtonian characteristics. The viscosity of these oils is variable, influenced by the applied shear rate, temperature, and pressure [106,107].

When resins effectively stabilize asphaltenes, the crude oil has reduced viscosity and enhanced flow properties. The asphaltene particles remain dispersed, preventing the formation of big aggregates that would enhance the oil's flow resistance. Nevertheless, if the resin concentration is inadequate or if the resin-asphaltene interactions are compromised by alterations in environmental conditions, asphaltenes commence aggregation, resulting in a significant rise in viscosity and diminished flowability [108].

The correlation between resin-asphaltene interactions and crude oil viscosity can be elucidated by rheological models that incorporate the presence of suspended colloidal particles. These models generally encompass parameters for particle size, concentration, and the extent of interaction among particles. In resin-laden crude oils, these interactions lead to the development of network architectures that influence the overall flow characteristics of the oil [109].

Multiple factors affect the rheological properties of crude oil in the presence of resins and asphaltenes.:

(1) Temperature: as the temperature decreases, the viscosity of crude oil increases. In resin-rich oils, this effect is more pronounced, as the resins become less effective at stabilizing asphaltenes, leading to the formation of larger aggregates [110].
(2) Pressure: high-pressure environments, such as those encountered in deepwater reservoirs, can affect the

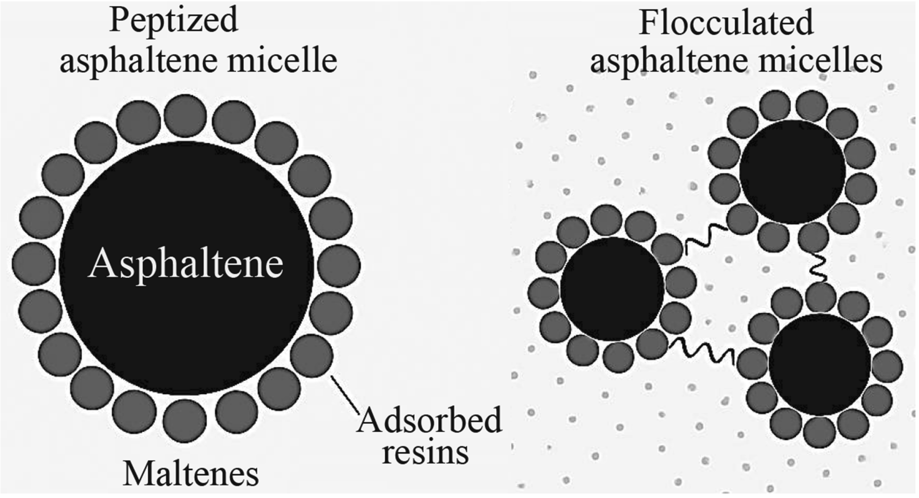

Fig. 6. Resin-mediated stabilization of asphaltenes: peptized micelles form when resins adsorb onto asphaltene cores, while resin deficiency leads to micelle flocculation and network gelation.

dispersion of asphaltenes and the ability of resins to stabilize them. Pressure drops during production can trigger asphaltene precipitation, further increasing viscosity [111].

(3) Shear rate: non-Newtonian behavior is common in resin-asphaltene systems, with viscosity decreasing under high shear conditions. This shear-thinning behavior is beneficial in pipeline transportation, as it allows crude oil to flow more easily at high pumping rates [112].

Resin-asphaltene interactions not only influence viscosity but also impact the yield stress of crude oil. Yield stress is the minimal tension necessary to commence flow in a structured fluid. The yield stress in resin-rich oils may be elevated due to the establishment of robust network structures between resins and asphaltenes, which must be disrupted for the oil to flow. This behavior presents difficulties for oil transportation and processing, as elevated pumping pressures are necessary to surpass the yield stress and sustain flow [113].

From these studies, a clearer picture of the rheological significance of resins in flow systems can be drawn. The key implications are outlined as follows:

A wide range of rheological behaviors observed in heavy oils can be traced back to the presence and concentration of resins and their interaction with asphaltenes. Studies show that when resin concentrations fall below critical values, flow resistance increases due to asphaltene aggregation and network formation. However, at optimal concentrations, resins can reduce yield stress and maintain Newtonian-like behavior, especially in the presence of external modifiers like solvents or nanoparticles. Interestingly, the literature indicates that heavy oils with resins rich in aromatic heterocycles display better resistance to shear thickening — likely due to stable π–π interactions maintaining colloidal dispersion under stress. From an operational standpoint, this insight implies that controlling resin composition and distribution in real time could allow operators to dynamically adjust flow conditions or additive dosing strategies to prevent blockage and reduce pumping costs.

7. Challenges in flow assurance due to resins

Resins are essential for stabilizing asphaltenes and preventing precipitation, although they provide multiple issues with crude oil flow assurance. These issues are most pronounced in heavy and extra-heavy crude oils, characterized by elevated resin concentrations, where the interaction between resins and asphaltenes affects the oil's rheology and stability. Comprehending and alleviating these issues is essential for effective crude oil production, transportation, and processing [114,115].

7.1. Increased viscosity and gel-like behavior

One of the principal issues related to resins in crude oil is their role in elevating viscosity, especially in heavy and extra-heavy oils. The amphiphilic characteristics of resins enable interaction with both polar and non-polar constituents of oil, resulting in the creation of organized networks with asphaltenes. These networks can produce a gel-like consistency in the oil, markedly enhancing its viscosity and diminishing its flowability [116,117].

The increased viscosity caused by resins presents several operational challenges:

(1) Pumping and transportation: high-viscosity crude oils require more energy to pump through pipelines, leading to increased operational costs. In extreme cases, the viscosity can become so high that it exceeds the capabilities of standard pumps, necessitating the use of specialized equipment or the addition of diluents to reduce viscosity [118,119].
(2) Pipeline blockages: the gel-like behavior of resin-rich oils can result in the formation of blockages in pipelines, especially in cold environments where the viscosity of the oil increases further. These blockages can disrupt production and lead to costly shutdowns for maintenance and cleaning [120,121].
(3) Rheological complexity: the non-Newtonian behavior of resin-rich oils, where viscosity decreases with increasing shear rate, complicates the design of pumping and transportation systems. While the shear-thinning behavior of these oils can be advantageous under high-flow conditions, the yield stress required to initiate flow in static conditions can be a significant challenge [122].

7.2. Precipitation and deposition in pipelines and wells

Although resins typically stabilize asphaltenes, variations in environmental circumstances, including temperature and pressure changes, can compromise this stabilization and result in asphaltene precipitation. This precipitation poses a significant flow assurance challenge, as solid asphaltene particles may accumulate in pipelines, wells, and processing equipment, resulting in obstructions and diminished production efficiency [115,123].

Several factors contribute to the precipitation and deposition of asphaltenes in resin-rich crude oils:

(1) Temperature fluctuations: as the temperature decreases, the solubility of asphaltenes decreases, leading to the formation of solid particles. This is particularly problematic in offshore production environments, where crude oil is transported from high-temperature reservoirs to colder surface conditions. Resins lose their effectiveness as stabilizers at lower temperatures, increasing the risk of asphaltene precipitation [124,125].

(2) Pressure drops: pressure reductions during oil production, particularly in deepwater and ultra-deepwater operations, can trigger asphaltene precipitation. The resin-asphaltene interactions are highly sensitive to pressure changes, and even small pressure drops can disrupt the stability of the colloidal suspension, leading to the formation of solid deposits [126,127].

(3) Incompatible crude oil mixtures: mixing crude oils with different resin-to-asphaltene ratios can destabilize asphaltenes and lead to precipitation. When a resin-poor crude oil is mixed with a resin-rich crude, the overall resin concentration may be insufficient to stabilize the asphaltenes, causing them to precipitate [21].

The accumulation of asphaltenes in pipelines and wells can lead to considerable production difficulties. These deposits diminish the effective diameter of pipes, augmenting flow resistance and resulting in elevated pumping pressures. In severe instances, asphaltene accumulations can entirely obstruct pipes, requiring expensive measures such as pigging, chemical remediation, or even pipeline replacement [128].

7.3. Impact on emulsion stability

Resins also facilitate the creation and stability of water-in-oil emulsions, which can present difficulties in crude oil processing. The polar characteristics of resins enable their adsorption at the oil-water interface, thereby stabilizing emulsions and complicating the separation of water from oil during production and refining processes [13].

Emulsions stabilized by resins pose significant challenges in heavy oil production, because the water concentration frequently exceeds that of lighter oils. These stable emulsions augment the viscosity of crude oil and complicate the separation process, resulting in elevated processing costs and probable output delays [129].

The impact of resins on emulsion stability is influenced by several factors:

(1) Water content: higher water content in the crude oil increases the likelihood of emulsion formation. Resins, along with asphaltenes, adsorb at the oil-water interface, creating a stable emulsion that is resistant to separation [130].

(2) Surface activity of resins: the amphiphilic nature of resins makes them effective emulsifiers. Their ability to interact with both polar and non-polar components allows them to stabilize the interface between oil and water, making it difficult to break the emulsion [131].

(3) Temperature and pressure: temperature and pressure fluctuations can affect the stability of emulsions. In high-pressure environments, the emulsifying properties of resins are enhanced, leading to more stable emulsions. Conversely, temperature increases can reduce emulsion stability by disrupting the resin-asphaltene interactions at the oil-water interface [132].

The existence of stable emulsions in crude oil complicates processing, necessitating supplementary demulsification processes to extract water from the oil. Chemical demulsifiers, thermal treatment, and mechanical separation techniques are frequently employed to disrupt emulsions; nevertheless, these approaches increase the total cost and energy expenditure of oil [133].

7.4. Fouling in downstream processes

Besides their influence on flow assurance, resins also exacerbate fouling in downstream processes, including refining. The polar characteristics of resins render them susceptible to thermal deterioration and the development of coke-like residues during high-temperature refining processes. This fouling can diminish the effectiveness of heat exchangers, distillation columns, and other processing apparatus, resulting in increased maintenance expenses and decreased throughput [134].

During distillation, resins may build and generate sludge in the bottoms of distillation columns, resulting in equipment fouling and operational interruptions. Furthermore, during hydrotreating and catalytic cracking, resins facilitate coke deposition on catalysts, hence diminishing their longevity and necessitating more frequent regeneration. This resin-induced coking diminishes the overall production of valued products and incurs expensive maintenance and equipment downtime [135,136].

Resins and asphaltenes are significant contributors to fouling in refinery operations. Their elevated molecular weight and heteroatom presence increase the likelihood of degradation under thermal stress, resulting in solid deposits that stick to processing equipment surfaces. These deposits diminish heat transfer efficiency, elevate energy consumption, and necessitate regular cleaning to sustain operating performance [137].

Refineries processing high-resin-content crude oils, such as those from Venezuela or Canada, must implement more rigorous maintenance schedules or employ alternate upgrading procedures to address resin-induced fouling. Technologies including delayed coking, fluid catalytic cracking (FCC), and hydrocracking are frequently utilized to transform resins into lighter products; nevertheless, these processes present problems, including elevated hydrogen consumption and increased capital expenditures [138].

The fouling behavior of resins in downstream processes is influenced by several factors:

(1) Temperature: higher refining temperatures increase the likelihood of resin degradation and the formation of solid deposits. Resins with a high aromatic content are more resistant to thermal degradation, but those with a higher concentration of heteroatoms are more prone to fouling [139].

(2) Composition of crude oil: resin-rich crude oils are more likely to cause fouling in downstream processes. The higher the resin content, the greater the potential for coke formation during thermal cracking or distillation [140].

(3) Residence time: the longer the crude oil remains in high-temperature refining units, the greater the likelihood of resin degradation and fouling. This is particularly

problematic in processes such as delayed coking, where the oil is subjected to high temperatures for extended periods [141].

Fouling caused by resins not only reduces the efficiency of refining operations but also increases the frequency of equipment shutdowns for cleaning and maintenance. This adds to the operational costs of refining resin-rich crude oils and reduces overall profitability [142].

The evidence presented across different operating conditions highlights the complex role of resins in flow assurance. The following conclusions can be drawn from this synthesis: resins contribute to both mitigating and exacerbating flow assurance challenges, depending on their concentration, chemical structure, and interaction with asphaltenes. Multiple studies cited in this section confirm that resin-deficient systems exhibit increased flocculation, viscosity spikes, and yield stress thresholds, particularly during shut-in and restart cycles. However, the presence of structurally optimized resins—especially those with polar side chains and high aromatic content—appears to stabilize flow by preserving micellar dispersion under fluctuating temperature and pressure. The dualistic role of resins makes their behavior difficult to generalize, yet essential to model. The complexity of resin–asphaltene networks underlines the need for predictive tools that factor in resin speciation, molecular weight distribution, and phase behavior. Thus, flow assurance in resin-rich crude oils cannot rely solely on empirical adjustment but requires chemically informed strategies tailored to specific operational regimes.

8. Current technologies for managing resin-related flow issues

Prompt defeat of flow problems caused by the presence of resin in crude oil production and transport is central to ensuring operational continuity, reduced outages, and bottom-line costs. Various technologies and approaches have been developed to reduce resin-related problems such as increasing viscosity, asphaltene precipitation, emulsion stability, and fouling. These technologies are designed to improve crude oil flow properties, reduce blockages from resins, and enhance production and refining efficiency [143].

8.1. Chemical additives for viscosity reduction

One of the more common approaches to lower the high viscosity introduced by resins in crude oil is adding chemical additives. These additives work by breaking the resin-asphaltene networks, reducing the oil's overall viscosity, and improving its flowability. Different chemical additions are used depending on the unique properties of the crude oil and the operational conditions [144].

(1) Flow improvers (drag reducing agents): these long-chain polymers help eliminate turbulence and drag inside crude oil pipelines. By reducing drag, they lower the pressure drop across the pipeline and improve the oil flow rate. DRAs are particularly effective for heavy crude oils with high resin content, where viscosity is a major challenge [145,146].

(2) Pour point depressants: these are used to lower the temperature at which crude oil begins to solidify. PPDs alter the crystal structure of wax and other solidifying components in the oil, preventing the formation of gel-like structures that can block flow. Although primarily used for waxy crude oils, PPDs can also assist with resin-rich oils that display similar gelling behavior at low temperatures [147,148].

(3) Viscosity reducers: chemical compounds, such as solvents and surfactants, are applied directly to reduce crude oil viscosity by disaggregating resin-asphaltene clusters and enhancing particle dispersion. Surfactants, in particular, reduce surface tension between asphaltene molecules, preventing the formation of large aggregates that increase viscosity [149].

8.2. Dilution with lighter hydrocarbons

Dilution with lighter hydrocarbons is a widely used technique to reduce the viscosity of heavy and extra-heavy crude oils. By mixing the crude oil with lighter hydrocarbon solvents, such as naphtha or condensates, the overall viscosity is reduced, and the oil becomes easier to transport through pipelines. The lighter hydrocarbons disrupt the interactions between resins and asphaltenes, reducing the likelihood of precipitation and aggregation [150,151].

The effectiveness of dilution depends on several factors:

(1) Diluent-to-oil ratio: the proportion of diluent to crude oil must be meticulously regulated to attain the intended viscosity decrease. Insufficient diluent may fail to adequately reduce viscosity, whilst excessive diluent might elevate operational expenses and diminish the overall profitability of oil production [152].

(2) Compatibility of the diluent: the selection of diluent is crucial, as incompatible diluents can destabilize asphaltenes and result in precipitation. Light hydrocarbons with minimal aromaticity are typically more efficient in decreasing viscosity without inducing asphaltene precipitation [153].

While dilution is effective for viscosity reduction, it also increases the cost of crude oil production, as additional steps are required to separate the diluent from the oil during refining. Moreover, the availability of suitable diluents may be limited in certain production environments, making this approach less viable in some cases [154].

8.3. Thermal methods for flow improvement

Thermal methods, including heating and steam injection, are commonly used to reduce the viscosity of heavy oils and improve flow. By raising the temperature of the oil, thermal methods reduce the strength of resin-asphaltene interactions and increase the mobility of the oil. Several thermal techniques are employed, depending on the specific production environment [155]:

(1) In-situ combustion: a segment of the reservoir oil is torched to produce heat, therefore decreasing the viscosity of the adjacent oil and facilitating its flow. In-situ combustion is efficacious for heavy oils with elevated resin content, since it deconstructs the resin-asphaltene networks that result in high viscosity [156].

(2) Steam injection: steam injection is a prevalent thermal recovery technique for heavy oil reservoirs. The introduction of high-temperature steam diminishes the viscosity of the oil and improves its flow. Besides decreasing viscosity, steam also facilitates the mobilization of asphaltenes, hence diminishing the probability of precipitation and deposition [157].

(3) Surface heating: heating systems are employed in pipelines and surface transportation to sustain the oil's temperature above its pour point, hence preventing solid deposit

development and ensuring flowability. Surface heating systems are frequently employed in frigid conditions where temperature variations may result in heightened viscosity and gel-like properties in resin-rich oils [158].

While thermal methods are effective at reducing viscosity and preventing resin-related flow issues, they are energy-intensive and can increase the operational costs of oil production. Additionally, the use of high temperatures can exacerbate fouling in downstream processing, as resins are prone to thermal degradation and coke formation [159].

8.4. Asphaltene inhibitors and dispersants

Asphaltene inhibitors and dispersants are chemical additives specifically designed to prevent asphaltene precipitation and aggregation. These additives work by modifying the surface properties of asphaltene particles or by disrupting the resin-asphaltene interactions that lead to aggregation. As a result, the asphaltenes remain dispersed in the oil, reducing the risk of precipitation and deposition in pipelines and wells [160].

(1) Inhibitors: asphaltene inhibitors are chemicals that interact with the polar functional groups of asphaltenes, preventing them from aggregating. These inhibitors are particularly effective in crude oils with a low resin-to-asphaltene ratio, where the natural stabilization provided by resins is insufficient [161].
(2) Dispersants: asphaltene dispersants prevent the aggregation of asphaltene particles by reducing their surface tension and improving their dispersion in the oil. Dispersants are often used in combination with inhibitors to provide comprehensive protection against asphaltene precipitation [162].

The use of asphaltene inhibitors and dispersants is a targeted approach to managing resin-related flow issues, as these additives directly address the root cause of asphaltene precipitation. However, the effectiveness of these additives depends on the specific characteristics of the crude oil, and their performance may vary under different temperature and pressure conditions [163].

8.5. Mechanical solutions for flow assurance

Besides chemical and thermal approaches, a few mechanical solutions have been developed to solve resin-related flow problems in transporting crude oil. These solutions are designed to keep the flow and avoid deposition in pipelines and wells [164].

(1) Pigging: pigging refers to the use of an instrument called a “pig.” Pigs are placed into the pipeline and pushed through with the flow of oil, scraping away deposits of asphaltenes, resins, and other solid materials. Regular pigging remains a critical maintenance function of oil pipes transporting resin-rich oils, as the deposits will otherwise build up and restrict flow [165].
(2) Heated pipelines: to ensure that resin-rich oils do not solidify at lower temperatures, pipelines are heated to keep the oil at a temperature above its pour point. This avoids the formation of gel-like structures and keeps the oil flowing continuously. Heated pipelines are especially well-suited for long-distance oil transport and for heavy and extra-heavy oils [166,167].
(3) Multiphase flow management: crude oil is sometimes transported as part of a multiphase flow that may include gas and water. In such cases, the flow regime governing the motion of the suspending viscous fluid is pivotal for inhibiting the coalescence of stable emulsions and influencing deposit formation. To stabilize the oil and avoid resin-related flow problems, technologies such as flow conditioners and separators are commonly deployed [168,169].

Mechanical solutions are usually used alongside chemical and thermal methods to provide overall flow assurance. While mechanical methods are great at reducing blockages and maintaining flow, they require constant maintenance and monitoring to ensure performance [170,171].

8.6. Emerging technologies for resin management

In recent years, several emerging technologies have been developed to address the challenges posed by resins in crude oil flow. These technologies focus on advanced materials, nanotechnology, and digital monitoring systems to provide more effective and efficient solutions for resin management [172].

(1) Nanotechnology-based additives: nanotechnology is being investigated as a possible remedy for resin-associated flow challenges. Nanoparticles can affect the surface characteristics of resins and asphaltenes, inhibiting aggregation and enhancing dispersion. These nanoparticles can function as catalysts for the degradation of resin-asphaltene networks, thereby diminishing viscosity and enhancing flow [173,174].
(2) Smart pipeline monitoring systems: digital monitoring systems with sensors and real-time data processing are utilized to identify and anticipate resin-related flow problems. These devices offer early alerts on possible blockages, asphaltene precipitation, or viscosity escalations, enabling operators to implement preventive measures prior to flow disruption. The application of artificial intelligence (AI) and machine learning algorithms improves the predictive capacity of these systems, facilitating more effective management of resin-rich oils [175,176].
(3) Bio-based additives: in reaction to environmental issues, bio-based additives are being formulated as substitutes for conventional chemical additives. These additives originate from renewable resources and aim to mitigate the environmental impact of crude oil production and transportation. Bio-based flow improvers, viscosity reducers, and dispersants are undergoing evaluation for their efficacy in resin-rich crude oils [177,178].

These nascent technologies present interesting options for addressing resin-related flow challenges; nevertheless, additional research and development are necessary to comprehensively grasp their potential and enhance their efficacy.

As detailed above, several mitigation strategies exist, though they vary in their suitability and robustness. The critical takeaways from this section are summarized here.

The current technological landscape for resin-related flow assurance blends chemical, mechanical, and thermal interventions. Chemical dispersants and inhibitors can modify interfacial tension and aggregation thresholds, while thermal techniques improve flow by reducing viscosity. However, as the reviewed literature indicates, success depends heavily on the compatibility of these methods with the crude's specific resin–asphaltene profile. Emerging technologies, such as nanofluid-based additives and responsive materials, show great promise but remain under-characterized for long-term field use. This section emphasizes that effective flow assurance strategies must be dynamically matched to resin chemistry, not deployed as one-size-fits-all solutions.

9. Future research directions for resin management in crude oil

As the demand for heavy and extra-heavy crude oils continues to rise, the need for effective resin management becomes increasingly critical [179]. While current technologies have provided significant advancements in addressing resin-related flow issues, there are still areas where research and innovation are needed to enhance the efficiency, sustainability, and cost-effectiveness of resin management solutions. This section highlights several key areas for future research and development [180].

9.1. Sustainable and environmentally friendly additives

As environmental regulations become more stringent, there is a growing need for sustainable and environmentally friendly additives that can manage resin-related flow issues without harming ecosystems or increasing greenhouse gas emissions [181]. Current chemical additives, while effective, often rely on synthetic compounds that can have negative environmental impacts. Future research should focus on developing bio-based and green additives that provide the same level of effectiveness while minimizing environmental harm [182].

Key areas for exploration include:

(1) Bio-based additives: investigation into natural polymers, botanical extracts, and biodegradable substances for application as flow enhancers, viscosity diminutors, and asphaltene inhibitors is increasing in prominence. These additions may offer a more sustainable substitute for conventional chemical treatments, simultaneously diminishing the environmental impact of oil production [183,184].

(2) Carbon-neutral solutions: the discovery of additives that can be manufactured and utilized in a carbon-neutral fashion is an additional focus. This entails investigating renewable energy sources for additive manufacturing and creating additives that aid in carbon sequestration or emission reduction in oil production and refining processes [17].

(3) Eco-friendly dispersants and demulsifiers: there is a necessity for novel dispersants and demulsifiers that exhibit reduced toxicity and enhanced biodegradability compared to conventional compounds, in order to mitigate the environmental impact associated with the management of emulsions and asphaltene precipitation in resin-rich oils [185].

9.2. Nanotechnology and smart materials

Nanotechnology has the potential to revolutionize resin management by providing new ways to control resin behavior at the molecular level. Nanoparticles, nanofluids, and smart materials that respond to changes in temperature, pressure, or chemical composition could offer more precise and efficient solutions for managing resin-related flow issues [186,187].

Areas for future research include:

(1) Nanoparticle additives: the application of nanoparticles to alter the properties of resins and asphaltenes is a potential research domain. Nanoparticles can be designed to engage with particular constituents of the oil, inhibiting the aggregation of resin-asphaltene complexes and diminishing viscosity. Research should concentrate on enhancing the dimensions, morphology, and surface characteristics of nanoparticles to optimize their efficacy [188].

(2) Responsive polymers: smart polymers that alter their characteristics in reaction to external factors (such as temperature or pH) may be utilized to regulate the flow qualities of resin-laden oils. These polymers may be engineered to stable resins and asphaltenes at elevated temperatures while disaggregating at lower temperatures, so maintaining uninterrupted flow [189].

(3) Nanofluids for enhanced oil recovery: nanofluids have garnered interest in enhanced oil recovery (EOR) as a viable method for enhancing the mobility of heavy oils. Future research should investigate the influence of nanofluids on mitigating the effects of resins on oil viscosity and flowability [190,191].

9.3. Improved flow assurance modeling

Accurate modeling of resin-related flow issues is critical for predicting and preventing blockages, precipitation, and other flow assurance challenges. While current models provide useful insights into the behavior of resin-asphaltene systems, there is still room for improvement in terms of accuracy, scalability, and real-time application. Future research should focus on enhancing flow assurance models to better predict resin behavior under a wide range of conditions [192,193].

Key areas for improvement include:

(1) Multiscale modeling: constructing multiscale models capable of simulating resin behavior at both molecular and macroscopic levels will yield a more thorough comprehension of the influence of resins on crude oil flow. These models must amalgamate molecular dynamics simulations with continuum-scale flow models to encompass the complete spectrum of interactions [194,195].

(2) Machine learning and AI: the application of machine learning and artificial intelligence (AI) to enhance flow assurance models is a burgeoning field of study. AI-driven algorithms may examine extensive datasets from manufacturing processes, detecting patterns and forecasting resin-related flow problems prior to their occurrence. Research ought to concentrate on training AI models with empirical data and incorporating them into current flow assurance systems [196,197].

(3) Dynamic simulation: dynamic models that can adjust to fluctuating operational conditions are essential for enhancing the precision of flow assurance predictions. These models must be able to react to fluctuations in temperature, pressure, and oil composition instantaneously, equipping operators with the means to proactively address resin-related flow challenges [198,199].

9.4. Novel methods for emulsion breaking and water-oil separation

The formation of stable water-in-oil emulsions due to resin activity poses significant challenges in crude oil production and refining. While current demulsification techniques rely on chemical additives and mechanical separation, there is a need for more efficient, cost-effective, and environmentally friendly methods for breaking emulsions and separating water from oil [200,201].

Research directions include:

(1) Electrochemical methods: electrochemical separation techniques that use electric fields to destabilize emulsions and separate water from oil are a promising area of research. These methods could provide a more energy-efficient alternative to traditional demulsification techniques, with the added benefit of reducing chemical consumption [202].
(2) Ultrasonic demulsification: ultrasonic waves can be used to break water-in-oil emulsions by disrupting the resin-stabilized interface between the water and oil phases. Research into optimizing ultrasonic frequencies and intensities for use in oil production could lead to more efficient water-oil separation technologies [203].
(3) Membrane technologies: the use of advanced membranes for water-oil separation is another area of interest. Membrane filtration systems can selectively separate water from crude oil, reducing the need for chemical demulsifiers and improving the efficiency of oil processing operations [204,205].

9.5. Field trials and pilot projects

Although laboratory research offers significant insights into resin management, the definitive assessment of novel technology occurs through field trials and pilot programs. Future research must concentrate on amplifying potential ideas and evaluating them in actual production settings to determine their efficacy and dependability under operational situations [206].

Essential factors for field trials encompass:

(1) Compatibility with current infrastructure: innovative resin management solutions must align with the existing production and transportation systems. Research must concentrate on creating solutions that may be seamlessly incorporated into existing processes without necessitating substantial retrofitting or further investment [207].
(2) Cost-benefit analysis: performing a comprehensive cost-benefit analysis of emerging technologies is essential for confirming their commercial feasibility. Research must evaluate the long-term economic ramifications of adopting innovative resin management methods, considering issues such as operating efficiency, maintenance expenses, and environmental sustainability [208].
(3) Environmental effect assessment: field trials must incorporate a thorough environmental effect assessment to guarantee that novel resin management solutions conform to sustainability objectives and regulatory standards [209,210].

Looking ahead, the integration of structural understanding with adaptive control appears pivotal. Based on current trends and future outlooks, we that the path forward in resin management lies in integration: combining molecular insight with real-time monitoring and smart design. Future research must expand on tailoring chemical treatments not only by resin concentration but by structural specificity, leveraging machine learning models that predict resin behavior under operational changes. Studies suggest growing interest in bio-derived dispersants and green solvents, which aim to balance performance with environmental constraints. In-situ diagnostic tools, coupled with predictive modeling, may soon enable real-time flow assurance adjustment based on resin speciation. Ultimately, resin science is shifting from descriptive analysis to prescriptive strategy — a transition that will define the next generation of heavy oil production systems.

10. Conclusions

The function of resins in crude oil flow is a complex subject that involves several issues and solutions associated with the production, transportation, and processing of heavy and extra-heavy crude oils. Resins, complex organic compounds with amphiphilic characteristics, are essential for stabilizing asphaltenes and affecting the rheological properties of crude oil. Although they aid in preventing asphaltene precipitation and preserving flow stability, they concurrently present numerous obstacles, such as heightened viscosity, pipeline obstructions, emulsion stability complications, and fouling in subsequent operations.

The difficulties related to resins necessitate a holistic approach to flow assurance, incorporating several technologies and methodologies. Chemical additives, including flow improvers, pour point depressants, and viscosity reducers, are frequently employed to regulate the heightened viscosity of resin-rich oils. Dilution with lighter hydrocarbons is a successful technique for viscosity reduction, however accompanied by supplementary expenses and logistical challenges. Thermal techniques, such as steam injection and in-situ combustion, offer considerable advantages for viscosity reduction and flow enhancement; nevertheless, they are energy-demanding and may lead to fouling in processing apparatus.

To tackle these difficulties, various advanced technologies and innovative solutions are being investigated. The creation of sustainable and eco-friendly additives is essential in addressing increasing environmental issues. Nanotechnology presents potential for altering resin properties at the molecular scale, whereas smart materials and responsive polymers may facilitate enhanced regulation of resin interactions. Enhanced flow assurance modeling, employing multiscale simulations and AI-driven forecasts, has the potential to improve the management of resin-related flow challenges.

Future study is crucial for enhancing our comprehension of resins and for formulating more efficient and sustainable strategies to mitigate their effects on crude oil flow. Key areas of emphasis encompass the advancement of sophisticated characterisation techniques, sustainable additives, nanotechnology, and novel approaches for emulsion breaking and water-oil separation. Field trials and pilot programs are essential for verifying new technologies and evaluating their practical efficacy.

In conclusion, although considerable advancements have been achieved in addressing resin-related flow challenges, continuous research and innovation are essential to satisfy the changing requirements of the oil sector. By tackling the difficulties related to resins and utilizing developing technology, the sector may improve the efficiency and sustainability of crude oil production, transportation, and processing.

CRediT authorship contribution statement

H.A. El Nagy: Writing – review & editing, Validation, Project administration, Investigation, Formal analysis. **Elsayed H. Eltamany:** Supervision, Project administration, Investigation. **Mostafa A.A. Mahmoud:** Visualization, Data curation, Conceptualization. **Ahmed Z. Ibrahim:** Conceptualization, Writing – original draft, Resources, Methodology, Data curation. **Sherin A.M. Ali:** Writing – review & editing, Investigation, Data curation.

Declaration of using AI-assisted technologies in writing process

During the preparation of this work authors used quillbot, grammarly to enhance readability, grammers and language of manuscript. After using these tools, the author reviewed and edited the content as needed to take full responsibility for the content of the published work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors gratefully acknowledge the financial support provided by Southwest Petroleum University (SWPU) for sponsoring the publication of this paper.

References

[1] F.A.M.M. Gonçalves, M. Santos, Advances in the development of biobased epoxy resins: insight into more sustainable materials and future applications, Int. Mater. Rev. 68 (2) (2022) 136–170.
[2] I. Khelil, A.A. Al-Muntaser, M.A. Varfolomeev, M.H. Hakimi, Innovations in crude-oil characterization: a comprehensive review of LF-NMR applications, Energies 17 (4) (2024) 905.
[3] J.J. Adams, J.F. Rovani, J.-P. Planche, J. Loveridge, A. Literati, I. Shishkova, G. Palichev, I. Kolev, K. Atanassov, S. Nenov, et al., SAR-AD method to characterize eight SARA fractions in various vacuum residues and follow their transformations occurring during hydrocracking and pyrolysis, Processes 11 (2023) 1220.
[4] Jinhong Zhang, Yuanyu Tian, Yingyun Qiao, Chaohe Yang, Honghong Shan, Structure and reactivity of Iranian vacuum residue and its eight group-fractions, Energy Fuels 31 (2017), https://doi.org/10.1021/acs.energyfuels.7b01327.
[5] I. Shishkova, D. Stratiev, I.V. Kolev, S. Nenov, D. Nedanovski, K. Atanassov, V. Ivanov, S. Ribagin, Challenges in petroleum characterization—a review, Energies 15 (20) (2022) 7765, https://doi.org/10.3390/en15207765.
[6] R. Xiong, J. Guo, W. Kiyingi, C. Gao, L. Wang, J. Luo, Technical transformation of heavy/ultra-heavy oil production in China driven by low carbon goals: a review, J. Clean. Prod. 447 (2024) 140992. https://doi.org/10.1016/j.jclepro.2023.140992.
[7] X. Luo, S. Wu, D. Wang, Y. Yun, et al., Sustainable development of cutting fluids: the comprehensive review of vegetable oil, J. Clean. Prod. 433 (2024) 140551.
[8] B. Upreti, B.P. Vempatapu, J. Kumar, Application of high -performance liquid chromatography in determining saturates and aromatic hydrocarbons along with polars/additives in automotive finished and used lubricating oils, J. Chromatogr. 1705 (2024) 464275.
[9] K. Primerano, J. Mirwald, B. Hofko, Asphaltenes and maltenes in crude oil and bitumen: a comprehensive review of properties, separation methods, and insights into structure, reactivity and Aging, Fuel 353 (2024) 129438. https://doi.org/10.1016/j.fuel.2024.129438.
[10] G. Vanini, T.A. Barra, L.M. Souza, N.C.L. Madeira, Characterization of nonvolatile polar compounds from Brazilian oils by electrospray ionization with FT-ICR MS and Orbitrap-MS, Fuel 263 (2020) 116644. https://doi.org/10.1016/j.fuel.2019.116644.
[11] F. Zheng, Q. Shi, G.S. Vallverdu, P. Giusti, et al., Fractionation and characterization of petroleum asphaltene: focus on metalopetroleomics, Processes 8 (3) (2020) 307.
[12] A. Ghamartale, S. Afzali, N. Rezaei, S. Zendehboudi, Asphaltene Deposition Control by Chemical Inhibitors: Theoretical and Practical Prospects, 2021.
[13] M.R. Elkatory, E.A. Soliman, A. El Nemr, M.A. Hassaan, Mitigation and remediation technologies of waxy crude oils' deposition within transportation pipelines: a review, Polymers 14 (3) (2022) 498. https://doi.org/10.3390/polym14030498.
[14] A. Hussein, Essentials of Flow Assurance Solids in Oil and Gas Operations: Understanding Fundamentals, Characterization, Prediction, Environmental Safety, and Management, 2022.
[15] A.A. Moud, Asphaltene induced changes in rheological properties: a review, Fuel 314 (2022) 122678. https://doi.org/10.1016/j.fuel.2021.122678.
[16] O.S. Zueva, E.R. Zvereva, A.O. Makarova, Influence of high-molecular n-alkane associates on rheological behavior of the crude oil residue, Energy Fuels 36 (12) (2022) 6230–6239. https://doi.org/10.1021/acs.energyfuels.2c00852.
[17] M. Khan, Chemical and physical architecture of macromolecular chemistry and physics gels for fracturing fluid applications in the oil and gas industry; current status, challenges, and prospects, Gels 10 (1) (2024) 33. https://doi.org/10.3390/gels10010033.
[18] S.O. Ilyin, Structural rheology in the development and study of complex polymer materials, Polymers 144 (2024). https://doi.org/10.3390/polym16010112.
[19] R.M. Charin, M. Nele, Emulsions in offshore petroleum production: stability and flow assurance, Brazil, J. Petrol. Gas 17 (1) (2023) 0135–0153. https://doi.org/10.5419/bjpg2023-0011.
[20] J. Sangwai, A. Dandekar, Practical Aspects of Flow Assurance in the Petroleum Industry, 2022.
[21] M.R. Yakubov, G.R. Abilova, S.G. Yakubova, Heavy oil resin composition and their influence on asphaltene stability, in: The Chemistry of Oil and Petroleum Products, 2022.
[22] M. Derakhshani-Molayousefi, M. McCullagh, Deterring effect of resins on the aggregation of asphaltenes in n-heptane, Energy Fuels 34 (12) (2020) 15527–15538. https://doi.org/10.1021/acs.energyfuels.0c02858.
[23] H. Zheng, T. Li, X. Fu, C. Feng, C. Ma, S. Jiang, The influence of asphaltene and resin on the stability of crude oil emulsion and its demulsification mechanism, J. Mol. 413 (2024) 125924. https://doi.org/10.1016/j.molliq.2024.125924.
[24] A. Safaei, M. Asefi, M. Ahmadi, T. Pourshamsi, Chemical treatment for sand production control: a review of materials, methods, and field operations, Pet. Sci. 20 (2023) 446–471. https://doi.org/10.1016/j.petsci.2022.11.008.
[25] I. Beloglazov, V. Morenov, E. Leusheva, Flow modeling of high-viscosity fluids in pipeline infrastructure of oil and gas enterprises, Egypt. J. Pet. 30 (3) (2021) 43–49. https://doi.org/10.1016/j.ejpe.2021.05.003.
[26] A. R. Egorov, A. A. Kirichuk, V. V. Rubanik, and V. V. Rubanik Jr., "Chitosan and its P. Shallsuku, "modification and evaluation of the potential of Nigerian bentonite clays as catalysts support for upgrading heavy crude oil and bitumen," researchgate.net.
[27] J. Wiehe, K.S. Liang, Asphaltenes, resins, and the colloidal model, Oil Gas Sci. Technol. 51 (5) (1996) 607–619, https://doi.org/10.2516/ogst:1996057.
[28] D. Liao, T. Gu, J. Yan, Z. Yu, J. Dou, M. Hu, F. Zhao, J. Liu, Study on the effect of multi-factor compound action on long-term tensile performance of GFRP composite pipe and life prediction analysis, Composites 258 (2024) 111932. https://doi.org/10.1016/j.compositesb.2023.111932.
[29] B.P. Tissot, D.H. Welte, Petroleum Formation and Occurrence, Springer-Verlag, 1984.
[30] J.G. Speight, The Chemistry and Technology of Petroleum, CRC Press, 1991.
[31] S.I. Andersen, J.G. Speight, Petroleum resins: separation, character, and role in petroleum, Petrol. Sci. Technol. 19 (1–2) (2001) 1–34.
[32] J. Anne Koots, James G. Speight, Relation of petroleum resins to asphaltenes, Fuel 54 (3) (1975) 179–184, https://doi.org/10.1016/0016-2361(75)90007-1. ISSN 0016-2361.
[33] O.C. Mullins, E.Y. Sheu, A. Hammami, A.G. Marshall, Asphaltenes, Heavy Oils, and Petroleomics, Springer, 2007.
[34] T.F. Yen, O.C. Mullins, Asphaltene Science and Technology, Springer, 2010.
[35] L. Goual, A. Firoozabadi, Measuring asphaltenes and resins, and dipole moment in petroleum fluids, AIChE J. 48 (11) (Nov. 2002) 2646–2663, https://doi.org/10.1002/aic.690481124.
[36] J.G. Speight, Handbook of Petroleum Refining, CRC Press, 2014.
[37] S. Anderson, G. Piñón, L. Patiño, Characterization and analysis of heavy oils: the role of resins, Energy Fuels 25 (7) (2011) 2999–3010.
[38] A.G. Marshall, R.P. Rodgers, Petroleomics: the next grand challenge for chemical analysis, Accounts Chem. Res. 37 (1) (2004) 53–59.
[39] T. Burgess, A. Bailey, C. Prewitt, Enhanced oil recovery strategies using resins, J. Petrol. Technol. 70 (6) (2018) 44–51.
[40] ASTM D2007-06, Standard Test Method for Analysis of Oils, Oils, and Solid Waxes by Thin-Layer Chromatography, ASTM International, 2006.
[41] M.R. Yakubov, G.R. Abilova, S.G. Yakubova, Composition and properties of heavy oil resins, Petrol. Chem. 60 (7) (2020) 763–770. Springer, https://doi.org/10.1134/S0965544120070133.
[42] Y. Zhu, F. Tian, Y. Liu, L. Cui, et al., Comparison of the composition and structure for coal-derived and petroleum heavy subfraction by an improved separation method, Fuel 291 (2021) 120174. https://doi.org/10.1016/j.fuel.2021.120174.
[43] W. Pu, M. He, X. Yang, R. Liu, et al., Experimental study on the key influencing factors of phase inversion and stability of heavy oil emulsion: asphaltene, resin and petroleum acid, Fuel 309 (2022) 122077. https://doi.org/10.1016/j.fuel.2021.122077.
[44] V.K. Hoang, K.J. Bae, Y. Oh, W. Kwon, J. Oh, K. Ku, M. Kim, Consideration of molecular weight-dependent high thermal resistance of end-capped-oligoimide based thermoset resins, Polym. Test. 134 (2024) 108746. https://doi.org/10.1016/j.polymertesting.2023.108746.
[45] B. Li, S. Alexandris, C. Pantazidis, E. Moghimi, Mechanical Properties of Epoxy Networks with Metal Coordination Bonds: Insights from Temperature and Molar Mass Variation, ACS Publications, 2024.
[46] X. Zhu, X. Yang, C. Ma, W. Li, Extraction of vanadium (IV) ions by metal-modified resin through multiple effects: ionic substitution and proton exchange, J. Water Proc. Eng. 55 (2023) 103937. https://doi.org/10.1016/j.jwpe.2023.103937.
[47] V.R. Gurjar, P.S. Koujalagi, Removal of vanadium by nano-titania fabricated resin from aqueous solutions, Rasayan J. Chem. 16 (3) (2023) 1549–1555. https://doi.org/10.31788/RJC.2023.1637027.
[48] A. Tajikmansori, A.H.S. Dehaghani, New insights into effect of the electrostatic properties on the interfacial behavior of asphaltene and resin: an

experimental study of molecular structure, J. Mol. 375 (2023) 121082. https://doi.org/10.1016/j.molliq.2023.121082.

[49] E.Y. Kovalenko, T.A. Sagachenko, Structural organization of asphaltenes and resins and composition of low polar components of heavy oils, Energy Fuels 37 (4) (2023) 2046–2056. https://doi.org/10.1021/acs.energyfuels.2c03993.

[50] X. Weng, L. Cao, G. Zhang, F. Chen, L. Zhao, Y. Zhang, et al., Ultradeep hydrodesulfurization of diesel: mechanisms, catalyst design strategies, and challenges, Ind. Eng. Chem. Res. 59 (2020) 21261–21274, https://doi.org/10.1021/acs.iecr.0c03910.

[51] R. Djimasbe, M.A. Varfolomeev, A.A. Al-Muntaser, C. Yuan, D.A. Feoktistov, M.A. Suwaid, et al., Oil dispersed nickel-based catalyst for catalytic upgrading of heavy oil using supercritical water, Fuel 313 (2022) 122702, https://doi.org/10.1016/j.fuel.2021.122702.

[52] L. Ma, M. Slaný, R. Guo, W. Du, Y. Li, G. Chen, Study on synergistic catalysis of ex-situ catalyst and in-situ clay in aquathermolysis of water-heavy oil-ethanol at low temperature, Chem. Eng. J. 453 (2023) 139872, https://doi.org/10.1016/j.cej.2022.139872.

[53] A. Imanbayev, D.S. Al-Maamari, A. Elkamel, M.S. Rahman, The impact of resins on the thermal cracking behavior of asphaltenes in heavy crude oil, Fuel 200 (2017) 472–482, https://doi.org/10.1016/j.fuel.2017.03.034.

[54] Y. Imanbayev, Y. Tileuberdi, Y. Ongarbayev, Z. Mansurov, et al., Changing the Structure of Resin-Asphaltenes Molecules in Cracking, 2017.

[55] M. Iwase, S. Sugiyama, Y. Liang, Y. Masuda, et al., Development of Digital Oil for Heavy Crude Oil: Molecular Model and Molecular Dynamics Simulations, 2018.

[56] G. Singh, M. Esmaeilpour, A. Ratner, Effect of Polymeric Additives on Ignition, Combustion and Flame Characteristics and Soot Deposits of Crude Oil Droplets, 2019.

[57] J. Liu, F. Tian, J. Liu, Q. Guo, et al., Structure Characterization and Solubility Analysis of the Existent Gum of the Fischer–Tropsch Synthetic Crude, 2020.

[58] A. Abou-Dib, F. Aubriet, J. Hertzog, L. Vernex-Loset, et al., Next Challenges for the Comprehensive Molecular Characterization of Complex Organic Mixtures in the Field of Sustainable Energy, 2022.

[59] S.F. Alkafeef, S.S. Al-Marri, Asphaltene Remediation and Improved Oil Recovery by Advanced Solvent Deasphalting Technology, 2023.

[60] S. Yang, C. Yan, J. Cai, Y. Pan, et al., Research Progress in Nanoparticle Inhibitors for Crude Oil Asphaltene Deposition, 2024.

[61] J. Liu, S. Wang, Y. Peng, J. Zhu, W. Zhao, X. Liu, Advances in sustainable thermosetting resins: from renewable feedstock to high performance and recyclability, Prog. Polym. Sci. 115 (2021) 101375.

[62] A. Shundo, S. Yamamoto, K. Tanaka, Network formation and physical properties of epoxy resins for future practical applications, JACS Au 2 (5) (2022) 1123–1133.

[63] G. González, S. Acevedo, J. Castillo, O. Villegas, Presence in THF solution of asphaltenes and subfractions A1 and A2, by gel permeation chromatography with inductively coupled plasma mass spectrometry, Energy Fuels 34 (5) (2020) 5916–5923.

[64] M.A. Aristri, M.A.R. Lubis, A.H. Iswanto, W. Fatriasari, Bio-based polyurethane resins derived from tannin: source, synthesis, characterisation, and application, Forests 12 (3) (2021). Article 372.

[65] Jonas Sundberg, Karen L. Feilberg, Characterization of heteroatom distributions in the polar fraction of North Sea oils using high-resolution mass spectrometry, J. Petrol. Sci. Eng. 184 (2020) 106563. ISSN 0920-4105.

[66] M. Vale, M.R.M. Silva, I.C. Damin, P.J. Sanches Filho, B. Welz, Speciation analysis of nickel and vanadium in resin fractions, Talanta 74 (5) (2008) 1385–1391.

[67] C. Liu, Y. Wang, Y. Chen, Y. Zhu, Hydrogen transfer route during hydrothermal treatment of lignite using the isotope tracer method and improving the pyrolysis tar yield, Energy Fuels 30 (6) (2016) 4562–4569, https://doi.org/10.1021/acs.energyfuels.6b00693.

[68] S. Song, H. Zhang, L. Sun, J. Shi, X.-L. Cao, S. Yuan, Molecular dynamics study on aggregating behavior of resin molecules, Energy Fuels 32 (7) (2018) 7594–7603.

[69] L. Natkaniec-Nowak, P. Drzewicz, P. Stach, The overview of analytical methods for studying fossil natural resins, Crit. Rev. Anal. Chem. 54 (1) (2024) 1–15.

[70] F. Zheng, Z. Ren, B. Xu, K. Wan, J. Cai, J. Yang, Elucidating multiple-scale reaction behaviors of phenolic resin pyrolysis via TG-FTIR and ReaxFF molecular dynamics simulations, J. Anal. Appl. Pyrolysis 155 (2021) 105048.

[71] J.M. Santos, A. Vetere, A. Wisniewski, M.N. Eberlin, Modified SARA method to unravel the complexity of resin fraction (s) in crude oil, Energy Fuels 34 (2) (2020) 1447–1455. https://doi.org/10.1021/acs.energyfuels.9b04061.

[72] D. Cai, C. Li, J. Lin, W. Sun, M. Zhang, T. Wang, Comparative study of atmospheric brown carbon at Shanghai and the East China Sea: molecular characterization and optical properties, Sci. Total Environ. 913 (2024) 168085. https://doi.org/10.1016/j.scitotenv.2023.168085.

[73] S.P.O. Danielsen, H.K. Beech, S. Wang, Molecular characterization of polymer networks, Chemical 121 (9) (2021) 4540–4615, nsf.gov, https://doi.org/10.1021/acs.chemrev.0c00975.

[74] D. Liu, C. Li, F. Yang, G. Sun, J. You, K. Cui, Synergetic effect of resins and asphaltenes on emulsion stability, Fuel (2019), https://doi.org/10.1016/J.FUEL.2019.04.159.

[75] M. Abdel-Raouf, Factors Affecting the Stability of Crude Oil Emulsions, InTechOpen, 2012.

[76] C.A. Alves, J.F. Romero Yanes, F.X. Feitosa, H.B. de Sant'Ana, Influence of resin/asphaltene ratio on emulsion stability, J. Pet. Sci. Eng. 202 (2021) 109268, https://doi.org/10.1016/J.PETROL.2021.109268.

[77] K. Venkateswaran, T. Hoaki, M. Katô, T. Maruyama, Microbial degradation of resins in crude oil, Can. J. Microbiol. 41 (4–5) (1995) 418–424, https://doi.org/10.1139/M95-055.

[78] T.F. Yen, G.V. Chilingar, C.H. Gray, Asphaltenes and Asphalts, vol. 2, Elsevier, 2010.

[79] A. Hirschberg, L.N.J. de Jong, B.A. Schipper, J.G. Meijer, Influence of temperature and pressure on asphaltene flocculation, Soc. Petrol. Eng. J. 24 (3) (1984) 283–293, https://doi.org/10.2118/11202-PA.

[80] M. Lashkarbolooki, S. Ayatollahi, Effects of asphaltene and resin on interfacial tension, Fuel 211 (2018) 535–544.

[81] A. Boukir, E. Aries, M. Guiliano, L. Asia, P. Doumenq, G. Mille, Subfractionation and photooxidation of crude oil resins, Chemosphere 43 (3) (2001) 279–286, https://doi.org/10.1016/S0045-6535(00)00159-4.

[82] J. Gutierrez, G. Orozco, T. Babadagli, et al., Study of interactions between crude oil resins and asphaltenes, J. Petrol. Technol. 53 (5) (2001) 62–70.

[83] A. Hammami, J. Ratulowski, Asphaltenes: problematic but rich in potential, Oilfield Rev. 19 (2) (2007) 22–43.

[84] H. Alboudwarej, J. Felix, S. Taylor, et al., Highlighting heavy oil, Oilfield Rev. 18 (2) (2006) 34–53.

[85] M. Rahmani, B. Dabir, et al., Effect of asphaltene and resin content on crude oil stability, Petrol. Sci. Technol. 21 (1–2) (2003) 173–189.

[86] S. Acevedo, G. Escobar, L. Gutierrez, P. Ortega, Asphaltene aggregation and precipitation in crude oils: the role of the resin-asphaltene ratio, Energy Fuels 26 (6) (2012) 2727–2735.

[87] K.J. Leontaritis, G.A. Mansoori, Asphaltene flocculation during oil production and processing: a thermodynamic colloidal model, SPE Prod. Facil. 3 (4) (1988) 45–51.

[88] K.E. Peters, C.C. Walters, J.M. Moldowan, The Biomarker Guide: Biomarkers and Isotopes in Petroleum Systems and Earth History, vol. 2, Cambridge University Press, 2005.

[89] N. Hosseinpour, M.M. Shadman, et al., Effect of sulfur content on asphaltene precipitation and rheology of heavy crude oils, Energy Fuels 25 (5) (2011) 2036–2043.

[90] J.P. Pfeiffer, R.N. Saal, Asphaltic bitumen as colloidal systems, J. Phys. Chem. 44 (2) (1940) 139–149.

[91] J. Escobedo, G.A. Mansoori, Viscometric principles of onset of asphaltene flocculation in petroleum mixtures, J. Pet. Sci. Eng. 17 (3–4) (1997) 313–323.

[92] G. González, M. Sousa, E. Lucas, Asphaltenes precipitation from crude oil and hydrocarbon media, Energy Fuels 20 (2006) 2544–2551.

[93] J. Pereira, I. Lopez, R. Salas, F.T.M. Silva, C. Fernández, C. Urbina, J.C. Cortés López, Resins: the molecules responsible for the stability/instability phenomena of asphaltenes, Energy Fuels 21 (2007) 1317–1321.

[94] S. Alkafeef, S.S. Al-Marri, Asphaltene remediation and improved oil recovery by advanced solvent deasphalting technology, ACS Omega 8 (2023) 26619–26627.

[95] L.H. Ali, K. Al-Ghannam, Investigations into asphaltenes in heavy crude oils. I. Effect of temperature on precipitation by alkane solvents, Fuel 60 (1981) 1043–1046.

[96] E. Tongton, Study on stability of asphaltenes in Thai crude oil, J. Pet. Sci. Eng. 133 (2015) 393–398. https://doi.org/10.1016/j.petrol.2015.06.009.

[97] P. Schorling, D. Kessel, I. Rahimian, Influence of the crude oil resin/asphaltene ratio on the stability of oil/water emulsions, Colloids Surf. A Physicochem. Eng. Asp. 152 (1999) 95–102.

[98] S. Hadizadeh, M.R. Malayeri, Cohesive interactions during asphaltene deposition for different crude oils, J. Mol. Liq. 396 (2024) 123581.

[99] Fanghui Liu, et al., Effects of molecular polarity on the adsorption and desorption behavior of asphaltene model compounds on silica surfaces, Fuel 284 (2021) 118990.

[100] Marcos Henrique O. Petroni, et al., Role of asphaltenes and resins at the interface of petroleum emulsions (W/O): a literature review, Geoenergy Sci. Eng. (2024) 212932.

[101] W. Pu, M. He, X. Yang, R. Liu, C. Shen, Experimental study on the key influencing factors of phase inversion and stability of heavy oil emulsion: asphaltene, resin and petroleum acid, Fuel 308 (2022) 121959. https://doi.org/10.1016/j.fuel.2021.121959.

[102] Fanyong Song, et al., The influence of asphaltene and resin on the stability of crude oil emulsion and its demulsification mechanism, J. Mol. Liq. 413 (2024) 125924.

[103] Ivan Moncayo-Riascos, et al., Effect of resin/asphaltene ratio on the rheological behavior of asphaltene solutions in a de-asphalted oil and p-xylene: a theoretical–experimental approach, J. Mol. Liq. 315 (2020) 113754.

[104] R.Y. Xiong, J.X. Guo, W. Kiyingi, H.X. Xu, X.P. Wu, The deposition of asphaltenes under high-temperature and high-pressure (HTHP) conditions, Pet. Sci. 20 (2) (2023) 481–492. https://doi.org/10.1016/j.petsci.2022.11.009.

[105] R. Lu, L. Lai, H. Zhang, Stabilization mechanism of emulsion gels of crude oil with low asphaltene, resin, and wax contents, J. Mol. Liq. 392 (2024) 125896. https://doi.org/10.1016/j.molliq.2024.125896.

[106] C. Yu, Q. Yang, Investigation of the interfacial interaction of carbon nanomaterials with asphalt matrix: insights from molecular simulations, Mol.

Simul. 49 (14) (2023) 1021–1029. https://doi.org/10.1080/08927022.2023.2193721.

[107] F. Souas, A. Safri, A. Benmounah, A review on the rheology of heavy crude oil for pipeline transportation, Petrol. Res. 6 (2) (2021) 168–177. https://doi.org/10.1016/j.ptlrs.2021.05.003.

[108] Ekaterina E. Barskaya, et al., Rheological behavior of crude oil and its dependence on the composition and chemical structure of oil components, Petrol. Sci. Technol. 41 (2) (2022) 159–175.

[109] J. Yang, Y. Bai, J. Sun, K. Lv, Y. Lang, Recent advances of thermosetting resin and its application prospect in oil and gas drilling and production engineering, Geoenergy Sci. Eng. 225 (2023) 211765.

[110] W. Guo, S. Bai, Y. Ye, High-value-added reutilization of resin pyrolytic oil: pyrolysis process, oil detailed composition, and properties of pyrolytic oil-based composites, Eur. Polym. J. 162 (2022) 110920. https://doi.org/10.1016/j.eurpolymj.2021.110920.

[111] Svetlana O. Ilyina, et al., Epoxy phase-change materials based on paraffin wax stabilized by asphaltenes, Polymers 15 (15) (2023) 3243.

[112] S. Mahdavi, M. Jalilian, S. Dolati, Review and perspectives on CO_2 induced asphaltene instability: fundamentals and implications for phase behaviour, flow assurance, and formation damage in oil reservoirs, Fuel 353 (2024) 129382.

[113] X. Wang, H. Gurbanov, M. Adygezalova, E. Alizade, Investigation of removing asphaltene-resin-paraffin deposits by chemical method for Azerbaijan high-paraffin oil production process, Energies 17 (1) (2024) 114.

[114] S. Mahdavi, A. Mousavi Moghadam, Critical review of underlying mechanisms of interactions of asphaltenes with oil and aqueous phases in the presence of ions, Energy Fuels (2021).

[115] R.W.P. Ortiz, T.S.L. Maravilha, A. Belati, Carboxylic acids in the synthesis of chemicals for addressing flow assurance challenges in offshore petroleum production, Curr. Organ. 28 (5) (2024) 455–472.

[116] H. Yonebayashi, Asphaltene Flow Assurance Risks: How Are Pitfalls Brought into the Open? Journal of the Japan Petroleum Institute, 2021.

[117] A. Tirado, G. Félix, F. Trejo, Properties of heavy and extra-heavy crude oils, in: Extra-Heavy Crude, Wiley Library, 2023.

[118] M. Lam-Maldonado, Y.G. Aranda-Jiménez, Extra heavy crude oil viscosity and surface tension behavior using a flow enhancer and water at different temperatures conditions, Heliyon 9 (6) (2023) e17361 e12120, https://doi.org/10.1016/j.heliyon.2023.e17361.

[119] R.S. Hamied, A.N.M. Ali, K.A. Sukkar, Enhancing heavy crude oil flow in pipelines through heating-induced viscosity reduction in the petroleum industry, Fluid Dynam. Mater. Process. 19 (4) (2023) 771–788.

[120] Z.A. hussein, Z.T. Al-Sharify, Flow of Crude Oil in Pipes and its Environmental Impact. A Review, AIP Conference, 2023.

[121] L. Pu, P. Xu, M. Xu, J. Song, M. He, Lost circulation materials for deep and ultra-deep wells: a review, J. Petrol. Sci. Eng. 210 (2022) 110044.

[122] S. Davoodi, M. Al-Shargabi, D.A. Wood, Synthetic polymers: a review of applications in drilling fluids, Pet. Sci. 21 (2) (2024) 392–413.

[123] K. Chaudhary, B. Kandasubramanian, Self-healing nanofibers for engineering applications, Ind. Eng. 61 (3) (2022) 956–972. https://doi.org/10.1021/acs.iecr.1c04293.

[124] M.M.B.M. Farok, B. Davidescu, R.E. Hincapie, Understanding asphaltene precipitation dynamics in flow assurance risk management of an offshore field in Abu Dhabi, in: Petroleum Exhibition, 2024.

[125] W. Liu, Q. Lin, S. Chen, H. Yang, K. Liu, B. Pang, Microencapsulated phase change material through cellulose nanofibrils stabilized Pickering emulsion templating, Comp. Hybrid 6 (2023) 1769–1783. https://doi.org/10.1007/s42114-023-00756-0.

[126] Y. Zhou, S. Qiu, W. Guo, F. Chu, X. Zhou, W. Chen, Ti3C2TX@ PHbP-PHC architecture with enhanced free-radical quenching capability: effective reinforcement and fire safety performance in bismaleimide resin, Chem. Eng. 442 (2022) 136369. https://doi.org/10.1016/j.cej.2022.136369.

[127] A. Abdelazim, M. Abu El Ela, A. El-Banbi, Successful approach to mitigate the asphaltenes precipitation problems in ESP oil wells, J. Petrol. 213 (2022) 110441. https://doi.org/10.1016/j.petrol.2022.110441.

[128] M.A. Ahmed, G.H. Abdul-Majeed, An integrated review on asphaltene: definition, chemical composition, properties, and methods for determining onset precipitation, Prod. Operat. (2023). SPE-216970-MS, https://doi.org/10.2118/216970-MS.

[129] F. Song, H. Zheng, T. Li, X. Fu, C. Feng, C. Ma, The influence of asphaltene and resin on the stability of crude oil emulsion and its demulsification mechanism, J. Mol. 14 (5) (2024), 392, 125924. https://doi.org/10.1016/j.molliq.2024.125924 945, https://doi.org/10.3390/polym14050945.

[130] R. Lu, L. Lai, H. Zhang, Stabilization mechanism of emulsion gels of crude oil with low asphaltene, resin, and wax contents, J. Mol. Liq. 392 (2024) 125896. https://doi.org/10.1016/j.molliq.2024.125896.

[131] M. Rayhani, M. Simjoo, M. Chahardowli, Effect of water chemistry on the stability of water-in-crude oil emulsion: role of aqueous ions and underlying mechanisms, J. Petrol. Sci. Eng. 209 (2022) 109871.

[132] M.H.O. Petroni, R.R.B. Corona, C.M.S. Sad, R. Ramos, Role of asphaltenes and resins at the interface of petroleum emulsions (W/O): a literature review, Geoenergy Sci. Eng. 225 (2024) 212932. https://doi.org/10.1016/j.geoen.2024.212932.

[133] M. He, W. Pu, T. Shi, X. Yang, M. Zheng, X. Tang, Unique emulsifying and interfacial properties of SP oil: enhanced emulsification at higher temperatures, J. Mol. 392 (2024) 125931.

[134] A.M. Sousa, M.J. Pereira, H.A. Matos, Oil-in-water and water-in-oil emulsions formation and demulsification, J. Petrol. Sci. Eng. 209 (2022) 110111. https://doi.org/10.1016/j.petrol.2021.110111.

[135] C. Françolle de Almeida, M. Saget, Innovative fouling-resistant materials for industrial heat exchangers: a review, Rev. Chem. 39 (5) (2023) 695–723. https://doi.org/10.1515/revce-2022-0079.

[136] S. Kato, Y. Kansha, Comprehensive review of industrial wastewater treatment techniques, Environ. Sci. Pollut. Control Ser. 31 (2024) 35544–35564. https://doi.org/10.1007/s11356-023-30180-4.

[137] L.D. Abo, S.M. Hailegiorgis, G.T. Gindaba, A comprehensive review on fouling of heat transfer units in sugar factory ethanol plant: mechanisms and mitigation methods, Environmental 241 (2024) 117895. https://doi.org/10.1016/j.envres.2023.117895.

[138] F. Hashemi, H. Hashemi, A. Abbasi, Life cycle and economic assessments of petroleum refineries wastewater recycling using membrane, resin and on site disinfection (UF-IXMB-MOX) processes, Process Saf. Environ. Prot. 160 (2022) 582–595. https://doi.org/10.1016/j.psep.2022.02.034.

[139] M. Nassabeh, S. Iglauer, A. Keshavarz, Z. You, Advancements, challenges, and perspectives of flue gas injection in subsurface formations: a comprehensive review, Energy Fuels 37 (6) (2023) 3533–3559. https://doi.org/10.1021/acs.energyfuels.2c03952.

[140] C.A. Niranjan, T. Raghavendra, M.P. Rao, Magnesium alloys as extremely promising alternatives for temporary orthopedic implants–A review. J. Magnesium 11, Elsevier, 2023, pp. 1283–1300. https://doi.org/10.1016/j.jma.2022.12.004.

[141] G.G. Yu, C. Teran, N. Patel, A. Fields, R. Gutierrez, Impact of centrifuge-separated fractions from light tight oils on the propensity and mechanisms of fouling, and improved crude oil fouling potential prediction model, Energy Fuels 34 (10) (2020) 12687–12697. https://doi.org/10.1021/acs.energyfuels.0c02141.

[142] A. Bhattacharyya, L. Liu, K. Lee, J. Miao, Review of biological processes in a membrane bioreactor (MBR): effects of wastewater characteristics and operational parameters on biodegradation efficiency when treating industrial oily waste water, J. Mar. Sci. Eng. 10 (6) (2022) 776. https://doi.org/10.3390/jmse10060776.

[143] A.H. Al-Moubaraki, I.B. Obot, Corrosion challenges in petroleum refinery operations: sources, mechanisms, mitigation, and future outlook, J. Saudi Chem. Soc. 25 (12) (2021) 101365. https://doi.org/10.1016/j.jscs.2021.101365.

[144] G. Heroux, M. Puettmann, Cradle-to-grave Life Cycle Assessment of North American Medium Density Fiberboard 73 (1-2) (2023) 61–74, https://doi.org/10.13073/FPJ-D-22-00056.

[145] M. Chen, Y. Wang, W. Chen, M. Ding, Z. Zhang, Synthesis and evaluation of multi-aromatic ring copolymer as viscosity reducer for enhancing heavy oil recovery, Chem. Eng. 460 (2023) 141746.

[146] T. Roldán-Carrillo, G. Castorena-Cortes, Hybrid low salinity water and surfactant process for enhancing heavy oil recovery. Petrol. Explor. 50, Elsevier, 2023, pp. 191–199. https://doi.org/10.1016/S1876-3804(23)60106-0.

[147] M. Contreras-Mateus, A. Hethnawi, Applications of nanoparticles in energy and the environment: enhanced oil upgrading and recovery and cleaning up energy effluents, Clim. Action Clean. up Energy Effluent. (2022) 275–300 (Book chapter—pages included).

[148] W. Li, H. Li, H. Da, K. Hu, et al., Influence of pour point depressants (PPDs) on wax deposition: a study on wax deposit characteristics and pipeline pigging, Fuel Process. Technol. 213 (2021) 106697, in: https://doi.org/10.1016/j.fuproc.2020.106697.

[149] N. Li, W. Wu, G. Mao, Effect of modified ethylene vinyl acetate copolymers pour point depressants on flow properties of crude oil and corresponding mechanism analysis, Colloids Surf. A Physicochem. Eng. Asp. 624 (2021) 126806. https://doi.org/10.1016/j.colsurfa.2021.126806.

[150] I. Mohammed, M. Mahmoud, D. Al Shehri, Asphaltene precipitation and deposition: a critical review, J. Petrol. 204 (2021) 108680. https://doi.org/10.1016/j.petrol.2021.108680.

[151] M. J. Jafar, A. A. Husaen, A. M. Ajeel, and S. H. Faleh, Characteristics of Ahdeb Oil Field Heavy Oil and Methods of Transporting it to Zubair Oil Field Southern Iraq Supervised by Dr. Hanon Hasan Mashkor.

[152] L.D. Douglas, N. Rivera-Gonzalez, N. Cool, A Materials Science Perspective of Midstream Challenges in the Utilization of Heavy Crude Oil 7 (42) (2023) 36969–36983, https://doi.org/10.1021/acsomega.2c04337.

[153] H. Goyal, P. Jones, A. Bajwa, D. Parsons, Design trends and challenges in hydrogen direct injection (H2DI) internal combustion engines–A review, Int. J. Hydrogen Energy (2024).

[154] I.K. Shishkova, D.S. Stratiev, M.P. Tavlieva, R.K. Dinkov, Evaluation of the different compatibility indices to model and predict oil colloidal stability and its relation to crude oil desalting, Resources 10 (9) (2021) 86.

[155] Y.H. Chan, S.K. Loh, B.L.F. Chin, C.L. Yiin, B.S. How, Fractionation and extraction of bio-oil for production of greener fuel and value-added chemicals: recent advances and future prospects, Chem. Eng. 397 (2020) 125406.

[156] Z. Xu, Z. Xiong, M. Gong, Q. Zeng, J. Hong, Molecular dynamics-based study of the modification mechanism of asphalt by graphene oxide, J. Mol. 370 (2023) 120993. https://doi.org/10.1016/j.molliq.2022.120993.

[157] Y. Zhao, L. Zhao, H. Chen, N. Zhao, G. Chang, Synergistic collaborations between surfactant and polymer for in-situ emulsification and mobility control to enhance heavy oil recovery, J. Mol. 392 (2024) 126019.

[158] A.M. Salem, S. Khalil, G. Abdel-Aleim, A review of recent developments in enhanced oil recovery: the integration of steam injection with chemical

additives and their effect on heavy oil recovery, J. Petrol. 222 (2023) 111082. https://doi.org/10.1016/j.petrol.2022.111082.

[159] C.C. Kwasi-Effah, Heat Transfer Fluids in Solar Thermal Power Plants: A Review, NIPES-Journal of Science and Technology, 2024. 6(1), 132–139. https://doi.org/10.47531/njstr.6.1.2024.10

[160] L.A. Omeiza, M. Abid, A. Dhanasekaran, Application of solar thermal collectors for energy consumption in public buildings–An updated technical review, J. Eng. (2023). Elsevier.

[161] C.A. Guerrero-Martin, D. Montes-Pinzon, Asphaltene precipitation/deposition estimation and inhibition through nanotechnology: a comprehensive review, Energies 16 (21) (2023) 7700. https://doi.org/10.3390/en16217700.

[162] S. Mahdavi, A. Mousavi Moghadam, Critical review of underlying mechanisms of interactions of asphaltenes with oil and aqueous phases in the presence of ions, Energy Fuels 35 (14) (2021) 11561–11576. https://doi.org/10.1021/acs.energyfuels.1c00819.

[163] D. Mojica, M. Angeles, O. Alvarez, D. Pradilla, Asphaltene precipitation and the influence of dispersants and inhibitors on morphology probed by AFM, Colloid. Interf. 7 (3) (2023) 41. https://doi.org/10.3390/colloids7030041.

[164] S. Yang, H. Wang, X. Lou, Y. Pan, et al., Asphaltene deposition inhibitors in CO_2 flooding: a review and future application prospects, Energy Fuels 38 (4) (2024) 1957–1980. https://doi.org/10.1021/acs.energyfuels.3c03731.

[165] P. Zhang, Y. Wei, R. Li, Y. Wan, X. Zhang, Self-healable, highly stretchable modified epoxy resin materials by incorporation with quadruple hydrogen-bonded supramolecular polymers, Macromol. Chem. Phys. 222 (5) (2021) 2000476. https://doi.org/10.1002/macp.202000476.

[166] N.C. Phillip, Effect of Pipeline Pigging on Raw Water Pipeline Flow Rate and Energy Consumption, 2024.15(2), 04023051. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000639 (167) Li, W., Zhang, H., Li, H., & Wang, W. (2022). A Promisi

[167] W. Li, H. Zhang, H. Li, W. Wang, A promising flow assurance application of superparamagnetic nanoparticle heating for wax removal in offshore pipeline and production tubing: mechanism and simulation, SPE J. (2022).

[168] J.S. Arwinder Singh, M.I. Nor, A. Suresh, A study on extraction pipe insulation for solidification prevention of heavy crude oil after extraction, Innovation 6 (2) (2023) 72–81. https://doi.org/10.33140/jime.06.02.07.

[169] Y. Xu, K. Zhang, Y. Zhu, S. Chen, S. Zhao, X. Liu, Research on heat transfer characteristics of long-distance pipeline under shutdown and maintenance conditions, Thermal 43 (2024) 101580. https://doi.org/10.1016/j.tsep.2024.101580.

[170] Y. Ren, G. Liu, G. Pu, Y. Chen, W.Q. Chen, L. Shi, Spatiotemporal evolution of the international plastic resin trade network, J. Clean. Prod. 258 (2020) 120726. https://doi.org/10.1016/j.jclepro.2020.120726.

[171] K. Zhao, X. Wang, Z. Zhang, Y. Li, S. Li, Life-Cycle environmental impacts of additive-related chemicals in polyvinyl chloride plastics and the mitigation potential, Environ. Sci. Technol. 58 (5) (2024) 2241–2251. https://doi.org/10.1021/acs.est.3c07126.

[172] M. Fernandes, J.M. Corchado, G. Marreiros, Machine learning techniques applied to mechanical fault diagnosis and fault prognosis in the context of real industrial manufacturing use-cases: a systematic literature review, Appl. Intell. 52 (2022) 21500–21531. https://doi.org/10.1007/s10489-022-04183-4.

[173] Y. Jiang, S. Yin, O. Kaynak, Performance supervised plant-wide process monitoring in industry 4.0: a roadmap, IEEE Open J. Ind. 1 (2020) 200–210. https://doi.org/10.1109/OJIES.2020.2992233.

[174] S. Ghafoori, M. Omar, N. Koutahzadeh, New advancements, challenges, and future needs on treatment of oilfield produced water: a state-of-the-art review, Purif. Technol. 290 (2022) 120877. https://doi.org/10.1016/j.seppur.2022.120877.

[175] M. Ownby, D.A. Desrosiers, C. Vaneeckhaute, Phosphorus removal and recovery from wastewater via hybrid ion exchange nanotechnology: a study on sustainable regeneration chemistries, NPJ Clean Water 4 (2021). Article 35, https://doi.org/10.1038/s41545-021-00110-8.

[176] M.R. Azani, A. Hassanpour, Nanotechnology in the fabrication of advanced paints and coatings: dispersion and stabilization mechanisms for enhanced performance, ChemistrySelect 9 (8) (2024) e202302432. https://doi.org/10.1002/slct.202302432.

[177] T. Stonorov, Tension: Tensile Structures and Inflatables, 2023, pp. 103–115.

[178] M. Embabi, Molecular Structure–Processing–Property Relationship in Polypropylene Foams Fabricated Using Supercritical CO_2, 2024.

[179] Z. Wang, G. Liang, S. Jiang, F. Wang, H. Li, B. Li, Understanding the environmental impact and risks of organic additives in plastics: a call for sustained research and sustainable solutions, Emerging (2024).

[180] V.M. Ramdas, P. Mandree, M. Mgangira, Review of current and future bio-based stabilisation products (enzymatic and polymeric) for road construction materials, Transportation 30 (2021) 100616. https://doi.org/10.1016/j.trgeo.2021.100616.

[181] F. Souas, A. Safri, A. Benmounah, A review on the rheology of heavy crude oil for pipeline transportation, Petrol. Res. 6 (2) (2021) 168–177. https://doi.org/10.1016/j.ptlrs.2021.05.003.

[182] C.D. Bandara, M. Schmidt, Y. Davoudpour, Microbial Identification, High-Resolution Microscopy and Spectrometry of the Rhizosphere in its Native Spatial Context, Frontiers in Plant 2021 (12) (2021) 738501. https://doi.org/10.3389/fpls.2021.738501.

[183] B. Fan, J. Yang, L. Cao, X. Wang, J. Li, Y. Yang, Q. Wang, Revealing the impact of micro-SiO2 filer content on the anti-corrosion performance of water-borne epoxy resin, Polymers (2023).

[184] S.S. Abdullahi, R.E.A. Mohammad, A.H. Jagaba, Natural, synthetic, and composite materials for industrial effluents treatment: a mini review on current practices, cost-effectiveness, and sustainability, Case studies in chemical and, Environmental Engineering 10 (2024) 100350. https://doi.org/10.1016/j.cscee.2023.100350.

[185] V.V. Tran, V.D. Phung, D. Lee, Recent advances and innovations in the design and fabrication of wearable flexible biosensors and human health monitoring systems based on conjugated polymers, Bio-Design Manuf (2024) 100570. https://doi.org/10.1016/j.cscee.2024.100570.

[186] Caineng Zou, Songtao Wu, Y. Zhi, Songqi Pan, Progress, challenge and significance of building a carbon industry system in the context of carbon neutrality strategy, Petrol. Explor. Dev. 50 (3) (2023) 567–578. https://doi.org/10.1016/S1876-3804(23)60254-5.

[187] M. Cioffi, A.S.C. Bomfim, V. Ambrogi, A review on self-healing polymers and polymer composites for structural applications, Polymer 258 (2022) 125236. https://doi.org/10.1016/j.polymer.2022.125236.

[188] M. Omidvar, L. Cheng, A. Farhadian, A. Berisha, Development of highly efficient dual-purpose gas hydrate and corrosion inhibitors for flow assurance application: an experimental and computational study, Energy Fuels 36 (22) (2022) 11838–11852. https://doi.org/10.1021/acs.energyfuels.2c01333.

[189] R. Anto, S. Deshmukh, S. Sanyal, U.K. Bhui, Nanoparticles as flow improver of petroleum crudes: study on temperature-dependent steady-state and dynamic rheological behavior of crude oils, Fuel 280 (2020) 118548. https://doi.org/10.1016/j.fuel.2020.118548.

[190] Y. Liu, Z. Qiu, C. Zhao, Z. Nie, H. Zhong, X. Zhao, S. Liu, Characterization of Bitumen and a Novel Multiple Synergistic Method for Reducing Bitumen Viscosity with Nanoparticles and Surfactants, RSC 2020 (43) (2020) 25695–25707. https://doi.org/10.1039/D0RA03883K.

[191] J. Preethikaharshini, K. Naresh, G. Rajeshkumar, Review of advanced techniques for manufacturing biocomposites: non-destructive evaluation and artificial intelligence-assisted modeling, J. Mater. 20 (2022) 5447–5464. https://doi.org/10.1016/j.jmrt.2022.09.100.

[192] C. Wang, L. Gao, M. Liu, S. Xia, et al., Viscosity reduction mechanism of functionalized silica nanoparticles in heavy oil-water system, Fuel Process. Technol. 233 (2022) 107260, in: https://doi.org/10.1016/j.fuproc.2022.107260.

[193] X. Zhong, J. Chen, R. An, K. Li, et al., A state-of-the-art review of nanoparticle applications with a focus on heavy oil viscosity reduction, J. Mol. Liq. 337 (2021) 116355. https://doi.org/10.1016/j.molliq.2021.116355.

[194] J. Shao, N.M.H. Al-Aragi, D.J. Jasim, M.K. Abosaoda, Investigating the effect of external magnetic field on preventing deposition process in wax/asphaltene nanostructure using molecular dynamics simulation, Commun. Heat (2024). https://doi.org/10.1016/j.icheatmasstransfer.2024.108355.

[195] S. Alimohammadi, L. James, A global optimization approach for parameter estimation of cubic plus association equations of state in asphaltene modeling: studying the temperature, solvent , and binary interactions, Energy Fuels 36 (4) (2022) 2165–2178. https://doi.org/10.1021/acs.energyfuels.1c04037.

[196] Y. Liu, H. Mu, X. Lv, Y. Yu, W. Wang, Y. Mu, Q. Ma, Toward greener flow assurance: review of experimental and computational methods in designing and screening kinetic hydrate inhibitors, Energy Fuels 8 (3) (2024) 1445–1464. https://doi.org/10.1021/acs.energyfuels.3c03998.

[197] P.R. Ferreira Rocha, G. Fonseca Gonçalves, et al., Mechanisms of component degradation and multi-scale strategies for predicting composite durability: present and future perspectives, J. Comp. 8 (6) (2024) 204. https://doi.org/10.3390/jcs8060204.

[198] B.X. Chai, M. Gunaratne, M. Ravandi, J. Wang, Smart industrial internet of things framework for composites manufacturing, Sensors 24 (2) (2024) 781. https://doi.org/10.3390/s24020781.

[199] Y. Wang, K. Wang, C. Zhang, Applications of artificial intelligence/machine learning to high-performance composites, Compos. B Eng. 270 (2024) 111779. https://doi.org/10.1016/j.compositesb.2024.111779.

[200] A. Kumar, Perspectives of flow assurance problems in oil and gas production: a mini-review, Energy Fuels 37 (1) (2023) 123–135. https://doi.org/10.1021/acs.energyfuels.2c03246.

[201] A.A. Ali, G.H. Abdul-Majeed, A. Al-Sarkhi, Review of multiphase flow models in the petroleum engineering: classifications, simulator types, and applications, Arabian J. Sci. Eng. 49 (2024) 987–1004. https://doi.org/10.1007/s13369-023-08142-x.

[202] Y. Tian, J. Zhou, C. He, L. He, et al., The formation, stabilization and separation of oil–water emulsions: a review, Processes 0 (3) (2022) 556. https://doi.org/10.3390/pr10030556.

[203] M.M. Abdulredha, H.S. Aslina, C.A. Luqman, Overview on petroleum emulsions, formation, influence and demulsification treatment techniques, Arab. J. Chem. 13 (9) (2020) 7403–7417. https://doi.org/10.1016/j.arabjc.2020.06.004.

[204] M.S. Shalaby, G. Sołowski, Recent aspects in membrane separation for oil/water emulsion, Adv. Mater. 2 (3) (2021) 210014. https://doi.org/10.5185/amlett.2021.210014.

[205] B. Yao, C. Li, F. Yang, G. Sun, X. Xia, A.M. Ashmawy, Advances in and perspectives on strategies for improving the flowability of waxy oils, Energy Fuels 36 (15) (2022) 8010–8025. https://doi.org/10.1021/acs.energyfuels.2c01360.

[206] E.S. Dmitrieva, T.S. Anokhina, E.G. Novitsky, V.V. Volkov, Polymeric membranes for oil-water separation: a review, Polymers 14 (4) (2022) 712. https://doi.org/10.3390/polym14040712.

[207] B. Li, B. Qi, Z. Guo, D. Wang, et al., Recent developments in the application of membrane separation technology and its challenges in oil-water separation: a review, Chemosphere 324 (2023) 138079. https://doi.org/10.1016/j.chemosphere.2023.138079.

[208] J.M.A. Juve, F.M.S. Christensen, Y. Wang, Z. Wei, Electrodialysis for metal removal and recovery: a review, Chem. Eng. 443 (2022) 137221. https://doi.org/10.1016/j.cej.2022.137221.

[209] Z. Wawryniuk, E. Brancewicz-Steinmetz, Revolutionizing transportation: an overview of 3D printing in aviation, automotive, and space industries, Manuf. Technol. 134 (2024) 3083–3105. https://doi.org/10.1007/s00170-024-14226-y.

[210] S. Ghasemi, M. Sibi, D.C. Webster, Techno-economic assessment and carbon pricing analysis for economic feasibility of epoxidized sucrose soyate: a biobased thermoset resin, J. Clean. Prod. 438 (2024) 140939. https://doi.org/10.1016/j.jclepro.2024.140939.