Journal of Chemical and Petroleum Engineering (JChPE)
Print ISSN: 2423-673X Online ISSN: 2423-6721

Viscosity Reduction and Flowability Enhancement of Heavy Crude Oil Using Nano Biomaterial Additive and Microwave Irradiation

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ARTICLE INFO

Article History:
Received: 18 July 2025
Revised: 03 October 2025
Accepted: 07 October 2025
Published: 07 October 2025

Article type: Research

Keywords:
Biomaterial,
Electromagnetic,
Nano,
Okra Powder,
Reduction,
Viscosity

ABSTRACT

As conventional oil and gas supplies are becoming depleted, the need to reduce the viscosity of heavy crude oil has become increasingly significant. This work aims to clarify the mechanism of viscosity reduction in heavy crude oil using a new method: microwave irradiation assisted by okra powder nanomaterial. For this purpose, two setups are designed. The first setup was designed to measure the effect of prepared okra powder (1030.6 nm) on heavy crude oil, with the aim of determining optimal conditions for flowability enhancement. The second setup was designed to show the effect of electromagnetic heating on viscosity reduction. To investigate the microstructure, effective functional groups, and particle size distribution of the prepared powder, Scanning Electron Microscopy (SEM) with Energy-Dispersive X-ray Spectroscopy (EDX), a Particle Size Analyzer (PSA), and Fourier Transform Infrared Spectroscopy (FTIR) were used. For the first setup, the results showed that the optimum conditions were achieved at 100 ppm addition, with a viscosity of 19.21 cP. Whilst for the second setup, at a power of 800 Watts and 4 min treatment time, the viscosity reduced to 17.52 cP, while with the use of both nano biomaterial and electromagnetic heating, the reduction achieved was 15.02 cP, which shows the high effectiveness of the electromagnetic heating mechanism on preserving low viscosity and improving flow characteristics even at moderate temperatures. This indicates a viscosity reduction of around 28.68%.

Introduction

Heavy crude oil is a category of crude oil characterized by its difficulty to flow, typically exhibiting API values of 10-20 °C and high viscosity [1, 2]. Heavy crude oil and extremely heavy crude oil are gaining popularity as unconventional petroleum resources are exploited. However, in addition to supporting rapid production development, determining how to transport heavy crude oil via pipelines efficiently and cost-effectively is becoming increasingly vital. Currently, research on heavy crude oil in pipeline transportation has primarily focused on viscosity reduction and the rheological properties of crude oil and its blends [3, 4]. The methods for reducing the viscosity of heavy crude oil include preheating the oil and adding drag-reducing chemicals. Other methods used in pipeline transportation of heavy crude oil emphasize drag reduction by incorporating a second phase. Examples of typical methods include water-assisted oil core circular flow, gas/steam infusion transport, and dilution with lighter crude oils or alcohols [5, 6]. As a result, many procedures are utilized to lower the viscosity of heavy oil prior to pipeline transit. Some popular methods for stabilizing emulsions include dilution with

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Journal of Chemical and Petroleum Engineering, 2026, 60(1): 3-21.
Publisher: University of Tehran Press *DOI: 10.22059/jchpe.2025.398861.1649*

lighter crudes or alcohols, heating, and adding surfactants. Heating is a common strategy used to address the issues of transporting heavy oil via pipeline [7]. The viscosity of heavy oil is lowered, making it easier to pump. Also, microwave heating reduces interfacial tension by increasing the temperature of aqueous phases, reducing viscosity, and conserving energy [4]. Experiments confirm this hypothesis by constructing a model of droplet formation. As a result, it is critical to heat the oil until its viscosity is significantly decreased. One major disadvantage of using heated pipes over extended distances is the high construction and operational costs [8]. Furthermore, submerged pipeline transport of heavy oil through heated pipelines is exceedingly challenging owing to the cooling effect of surrounding water and the practical difficulties of maintaining pumping and heating stations [9, 10]. Drag refers to the pressure loss due to turbulent flow in pipelines, requiring more energy to pump and transport crude oil [11]. The Blasius equation proposes a link between friction factor (*f*) and Reynolds number (*Re*) as in Eq. 1 below:

$$f = \frac{0 \cdot 079}{Re^{0 \cdot 25}} \tag{1}$$

Fluid velocity is a significant factor in both the Reynolds number and the friction factor relationships. Both fluid velocity and Reynolds number impact the pipe pressure drops.

To prevent turbulent eddies and breaches of the laminar layer during pipeline transmission, the viscosity of heavy crude oil must be reduced. Various strategies are utilized to reduce pumping energy, increase efficiency, and improve crude oil flow performance through pipelines [12-16].

Numerous techniques have been devised to decrease the viscosity of heavy crude oil and enhance its flowability, which is essential for effective transportation and processing. Chemical additives, including polymers and surfactants, have been extensively utilized to modify the molecular structure of oil, improving dispersion and reducing viscosity. Recently, natural biomaterials such as okra powder have attracted interest for their environmentally sustainable properties and capacity to alter fluid dynamics via surface-active agents. Unlike lignocellulose residues (e.g., rice husk, palm fibers, egg shells) that are primarily composed of inert cellulose and lignin, it is high in mucilage polysaccharides, which have a high density of functional groups, hydroxyl (–OH), carboxyl (–COOH), and methoxyl (–OCH_3) that may interact with heavy crude oil, specifically asphaltenes and resins. Because of its amphiphilic character, okra can stabilize asphaltene aggregates. Besides natural treatments, physical approaches such as microwave irradiation have demonstrated efficacy by providing rapid heating and molecular disruption, thereby reducing viscosity. The integration of Nano-biomaterial additives, particularly okra powder, with microwave irradiation presents an innovative and sustainable strategy to significantly reduce the viscosity of heavy crude oil and improve flowability, overcoming some constraints of conventional techniques.

The challenges of using chemicals for viscosity reduction include recovering them from crude oil, dissolving them in heavy oil, and determining the optimal dosage to achieve the desired pressure reduction. Polymer additives, such as high-molecular-weight poly-isobutylene diluted with kerosene, were explored to reduce drag [12]. This suggested a significant reduction in the friction coefficient. A compound containing esterified copolymers and fatty alcohol was produced and added to Indian crude oil to reduce drag and lower pour points. The results indicate an improvement in flow characteristics [15]. Polyacrylamide was shown to be effective as a drag-reduction additive, with higher polymer concentrations yielding greater drag-reduction factors [17]. Several researchers have shown that surfactants can increase crude oil flow ability [18, 19]. Implementing these approaches remains challenging due to polymer breakdown and reduced efficiency. Certain chemicals, including surfactants and polymers, may harm the environment [20]. Date palm plants are cultivated in several countries worldwide. Arab nations have an estimated 105 million date palm trees, including over 51 million in the Arab Gulf nations (GCC), resulting in abundant waste biomass. The primary biomass is made up of palm leaves, bark, and date seeds. GCC date palm plants produce around 1.013 million tons of palm leaves, 574.8 thousand tons of cull dates, and 345 thousand tons of seeds yearly, according to a recent inventory. Date palm leaves are readily accessible as a byproduct of yearly cleaning and trimming operations [21].

This study aimed to test the effectiveness of employing bio-waste materials, including okra powder, to reduce the viscosity of Iraqi heavy crude oil. Additionally, investigating how these compounds affect the viscosity and rheological qualities of crude oil. Niazi et al. aimed to simulate turbulent flow in pipes containing drag-reducing fluids using a non-Newtonian model and a non-Newtonian damping function [22]. The results were compared to Pinho simulations and experimental data. The study used computational fluid dynamics software to account for near-wall effects and optimize parameters. The model improved at predicting critical flow parameters, such as the friction factor and mean axial velocity, but had limitations in predicting turbulent kinetic energy. The average error in calculating the friction factor was 5.45%, compared to 32.49% for the Pinho model.

Okra powder was selected as a natural nanobiomaterial additive due to its nontoxicity, biodegradability, and high polysaccharide content, along with surface-active properties that reduce intermolecular interactions in heavy crude oil, thereby reducing viscosity and improving flowability. Microwave irradiation was used as a physical treatment technique due to its ability to provide rapid, uniform heating, efficiently breaking down complex molecular structures and enhancing the efficacy of the additive. The amalgamation of okra powder with microwave irradiation presents a sustainable and effective method for reducing the viscosity of heavy crude oil

Rheology

Rheology studies the flow and deformation of materials under stress, with Newtonian fluids having constant viscosity and resistance, while non-Newtonian fluids exhibit viscosity that varies with shear rate and resistance to flow [23]. Non-Newtonian fluids can follow one of the following models:

- Thixotropic shear thinning occurs when the initial yield stress is less than one, $n < 1$. Shear increases with preliminary yield stress (rheopactic), $n > 1$.
- Bingham plastic (viscoplastic), $n = 1$.
- Shear thinning (pseudoplastic), $n < 1$.
- Shear thickening (dilatant), $n > 1$.

The aforementioned models take the following general form, Eq. 2:

$$\tau = \beta + k\left(\frac{\mathrm{du}}{\mathrm{dy}}\right)^{\mathrm{n}} \tag{2}$$

where k = consistency coefficient, n = power law index, β= yield stress.

The inclusion of water-based components altered the fluid's rheological characteristics. Crude oil's rheological properties significantly impact drilling, production, and pipeline transit. Crude oil can exhibit both Newtonian and non-Newtonian behavior, depending on wax concentration and viscosity. The impact of asphaltenes on Venezuelan crude oil has been studied by Pierre et al. At low temperatures, crude oil exhibits shear-thinning behavior, but at high temperatures, asphaltenes act like Newtonian fluids [24].

Experimental Work

Materials

Iraqi heavy crude oil (HO) was used in the present investigation; it was sourced from the AL-Dorah refinery, with a density of 0.886 g/mL, an API gravity of 19.5 at 40 °C, and a water content of 0.1 vol.%. Table 1 provides details on the crude oil used.

Table 1. Iraqi heavy crude oil specifications

Result	Test
Kinematic viscosity @ 40 ºC (cSt)	22.77
Dynamic viscosity (cP)	21.06
API gravity @ 40°C	19.5
Water content (Vol. %)	0.1
Salt content (Wt. %)	0.0098
Density @ 15°C (g/cm^3)	0.925
R.V.P (kg/cm$^{2)}$	0.600

Experimental Tools

The experimental test was conducted using the system shown in Fig. 1, which was specially manufactured for this work to measure the time required for heavy crude oil to transfer before and after the application of nanobiomaterials for viscosity reduction.

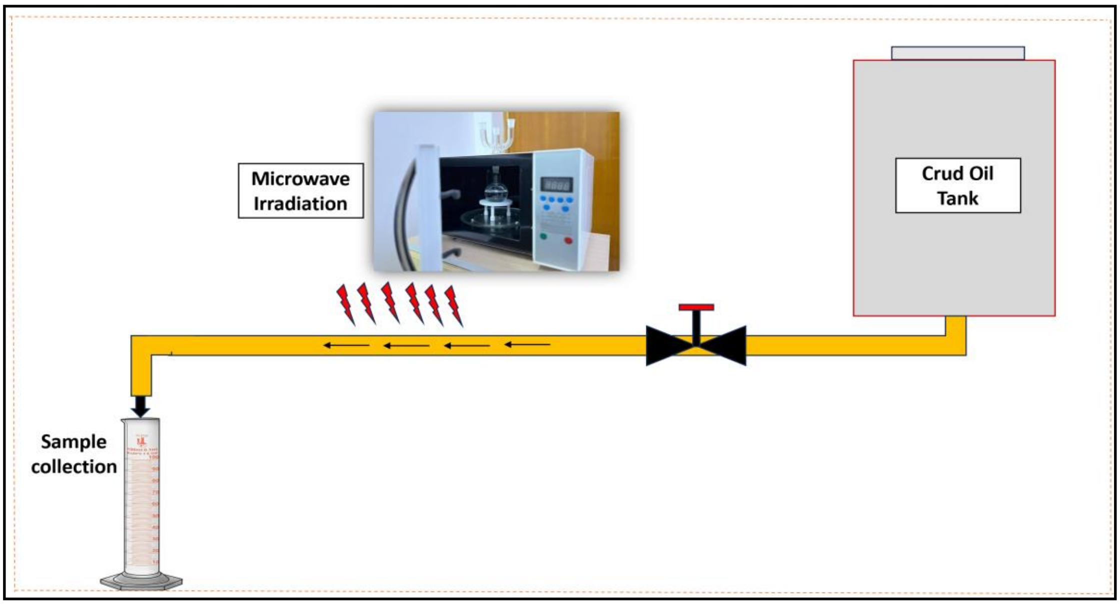


Fig. 1. Schematic presentation of the experimental system

Also, a microwave reactor was used in this work to measure the effect of dielectric heating on viscosity drop at optimal nano-biomaterial additions.

Specifications and Preparation of Okra Powder

This study presents the application of nanobiomaterials to reduce the viscosity of Iraqi heavy crude oil, thereby enhancing pipeline flowability. Okra powder was used in the work as a nano-biomaterial. Okra powder is a unique biopolymer that reduces the viscosity of heavy crude oil due to its distinct molecular and chemical properties. The powder's modest molecular weight and partial solubility avoid excessive viscosity buildup, resulting in a balanced colloidal interaction. Okra is biodegradable, readily available, and inexpensive, making it an eco-friendly alternative to synthetic flow improvers. Its application as a value-added additive derived from agricultural byproducts promotes green chemistry and provides an ecologically friendly alternative to synthetic flow improvers. Overall, okra powder is an excellent biopolymer for heavy crude oil. For the preparation of okra powder, the okra was first washed thoroughly with water, dried in an oven for 5h at 70 ℃, and ground using a professional nutrition blender model SC-1589, 220V, 50Hz, and 2500W [25]. The practical steps are described in Fig. 2.

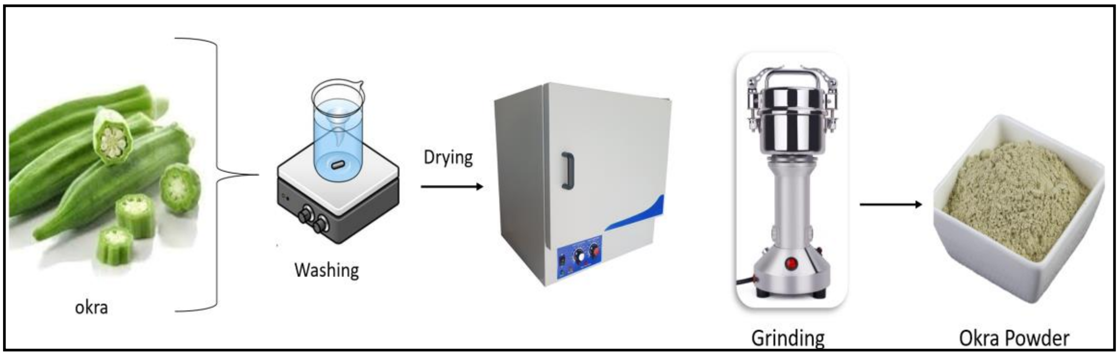


Fig. 2. Practical steps of okra powder preparation

Experimental Procedures

Five concentrations (0 ppm, 50 ppm, 100 ppm, 150 ppm, and 200 ppm) were accurately weighed using an electronic balance with an error range of ±0.001 g to ±0.002 g. Each concentration was thoroughly mixed with crude oil for 10 minutes using a magnetic stirrer to ensure homogeneous dispersion. Upon completion of mixing, the prepared mixtures were transferred to the oil tank. Key parameters, including velocity, time, viscosity, density, flow rate, and Reynolds number, were subsequently determined and are summarized in Table 2 below.

Table 2. Results of experimental work

Velocity (cm/s)	Concentration (ppm)	Vol. (cm^3)	Time (s)	Kinematic viscosity (cSt)	Density (g/cm^3)	Flow rate (cm^3/s)	Reynold No.	Dynamic viscosity (cP)
48.189	0	400	6.77	22.77	0.925	59.08	2.688	21.06
53.401	50	400	6.11	21.12	0.923	65.47	3.211	19.49
54.739	100	400	5.96	20.89	0.920	67.11	3.328	19.22
54.380	150	400	6.00	21.50	0.927	66.67	3.212	19.93
52.789	200	400	6.18	21.91	0.933	64.72	3.049	20.45

Experimental Calculation

Velocity (u) (cm/s), flow rate (Q) (cm^3/s), and Reynolds number are all calculated by the following equations [26]:

$$Velocity = \frac{Q}{A} \quad (3)$$

$$\mathrm{Q} = \frac{\mathrm{v}}{t} \quad (4)$$

$$\gamma = \frac{\mu}{\rho} \quad (5)$$

$$Re = \frac{u \times d \times \rho}{\mu} \quad (6)$$

where A is represented by Area (cm2), V is represented by volume (cm3), t is the time (sec), γ is represented by kinematic viscosity (cSt), μ is viscosity (cP), ρ is density (g/cm^3), and d is diameter (cm).

Tests

Scanning Electron Microscopy (SEM)

Thermo Scientific Axia Chemi SEM was used to examine the surface morphology of the okra nanoparticle sample, with magnification error ranging from 5-10%, using a high-performance vacuum system [27]. The instrument has a chamber with an inner width of 280 mm and an analytical working distance of 10 mm. It supports a continuously adjustable beam current and operates within an accelerating voltage range of 200 V to 30 kV. The Axia Chemi SEM includes five ports and supports real-time elemental mapping via Chemi SEM mode.

Particle Size Analyzer (PSA)

The Particle Size Analyzer was used to measure the particle size distribution error range <1% of okra plant nano partials, which works as a natural supplement for reducing crude oil viscosity. Proper measurement of particle size is essential as it affects dispersion behavior, surface area, and interaction with the oil matrix.

Essential specifications are:

- Measurement range: about 0.01 µm to 2000 µm
- Measurement technique: Laser diffraction
- Sample classification: Dehydrated botanical powder
- Output: Particle size distribution (D10, D50, D90) and mean particle size

These experiments evaluate the physical parameters of okra powder that influence its efficacy as a viscosity-reducing agent.

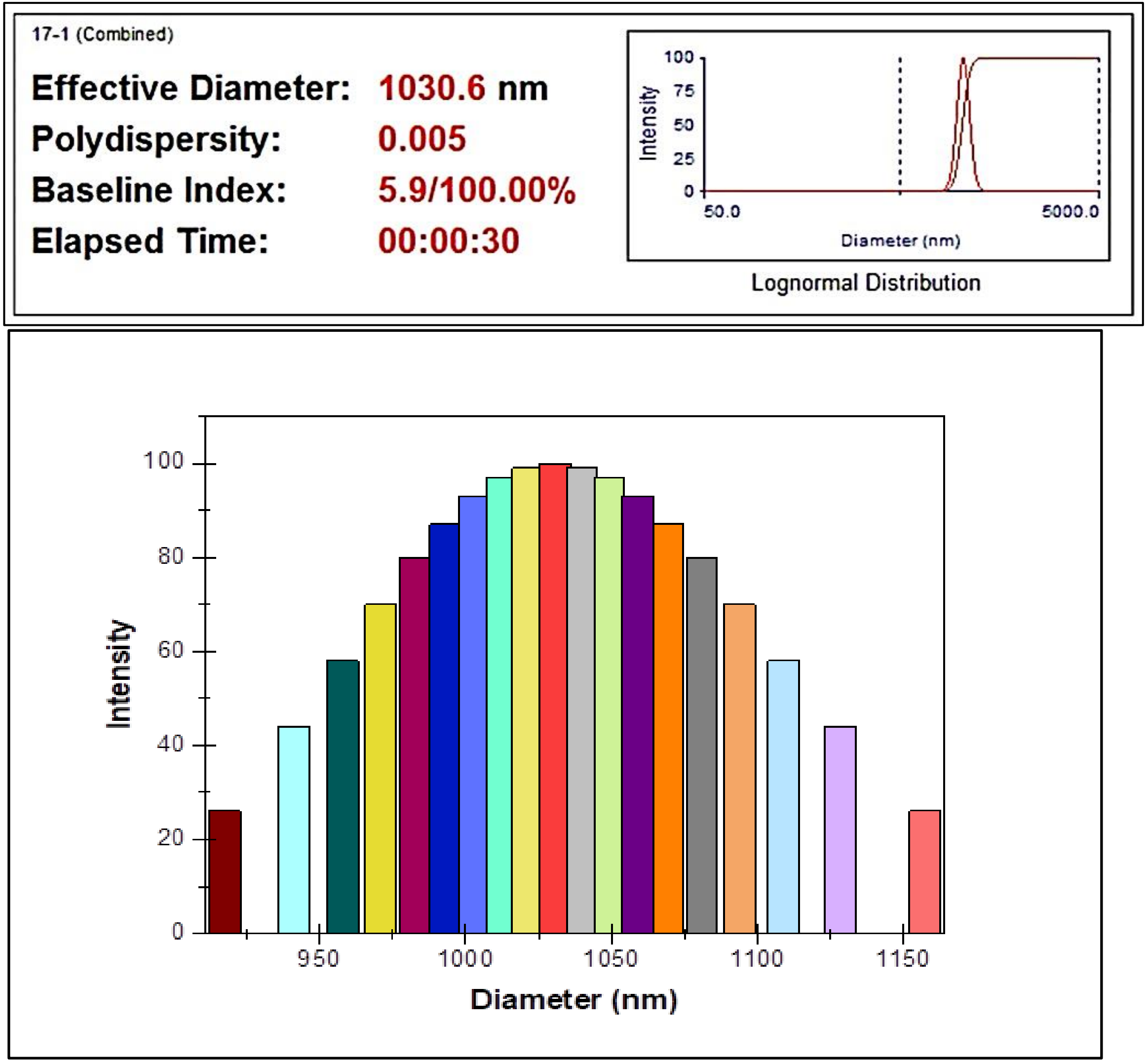
Fourier Transform Infrared Spectroscopy (FTIR) Analysis

In the context of viscosity studies, Fourier Transform Infrared Spectroscopy (FTIR) is an essential analytical technique widely used to analyze the composition and chemical structure of crude oil before and after treatment, with an error of ±0.01 cm^{-1}. This study involved compressing the mixture into a transparent circular flake. The Shimadzu Company of Japan used the Model IR infrared spectrophotometer to obtain the FTIR spectrum of crude oil in the region of 400 to 4000 cm^{-1}.

Results and Discussion

Particle Size Analyzer (PSA)

The PSA shows that the ground biomaterial was obtained in the particle size range of 50–5000 nm (Fig. 3), and the effective size was 1030.6 nm, measured using a particle size device in the USA.



17-1 (Combined)

Effective Diameter: 1030.6 nm

Polydispersity: 0.005

Baseline Index: 5.9/100.00%

Elapsed Time: 00:00:30

Fig. 3. Long normal distribution of particle size for okra powder

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX)

Fig. 4 shows the SEM of okra powder, which was used to analyze its microstructural characteristics. The SEM images of the okra powder display a structure characterized by irregularly shaped particles featuring rough and porous surfaces. This porosity markedly increases the surface area, thereby augmenting the powder's contact with fluids such as crude oil. A network of tiny natural fibers is discernible within the particles, aiding in the absorption and stabilization of denser components when the powder is used to reduce oil viscosity. Particle sizes fluctuate, spanning from a few micrometers to many tens of nanometers, facilitating improved dispersion when combined with fluids. The interplay of surface roughness, his surface roughness increases the likelihood of contact with heavy crude components, including asphaltenes. Porosity and fiber networks enable okra powder to efficiently adsorb heavy constituents in crude oil, reducing agglomeration and improving its flow through pipelines.

The distinctive microstructure supports the functional effectiveness of okra powder as a natural viscosity-reducing agent in oil transport.

Fig. 5 & 6 illustrate the elemental composition of okra powder. Table 3 shows that okra powder's organic matter consists predominantly of carbon, nitrogen, and oxygen, with trace amounts of potassium, calcium, and magnesium. The elements represent the polysaccharide–protein matrix of okra mucilage, abundant in polar functional groups that can interact with heavy crude oil constituents.

Microwave irradiation influences the biopolymer by breaking hydrogen bonds, partly depolymerizing polysaccharide chains, and enhancing the accessibility of polar groups such as –OH, –COOH, and $–NH_2$. This improves solubility, surface reactivity, and the accessibility of naturally occurring metal ions, thereby enhancing colloidal stability.

The structural and chemical modifications enhance the dispersibility of okra powder, aiding in the breakdown of asphaltene and resin aggregates in heavy crude oil, thereby reducing viscosity. Excessive microwave treatment can damage functional groups or enhance crosslinking, potentially reducing its efficiency.

Microwave-treated okra powder has significant potential as a natural, environmentally friendly viscosity-reducing agent, with optimal efficacy dependent on precise control of irradiation parameters.

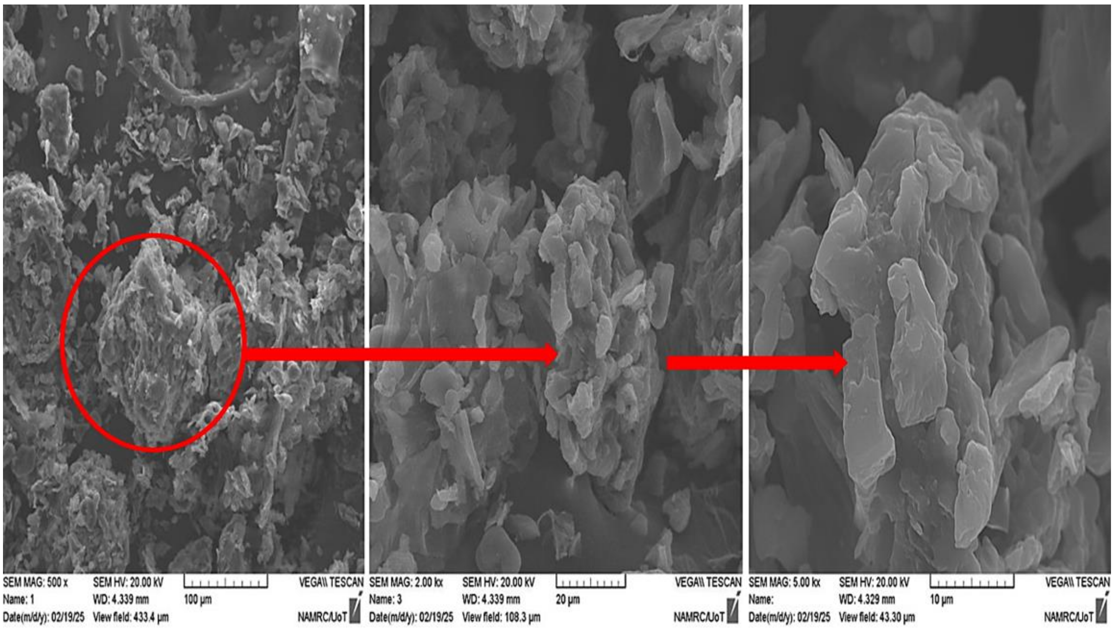


Fig. 4. SEM of okra powder

Table 3. Elemental composition of okra powder

S	Atomic %	Atomic Error %	Weight %	Weight Error %
C	34.3	0.7	27.6	0.6
N	11.7	1.4	11.0	1.3
O	51.3	0.9	54.9	1.0
Mg	0.6	0.1	1.0	0.1
K	1.5	0.0	4.0	0.1
Ca	0.6	0.0	1.6	0.1

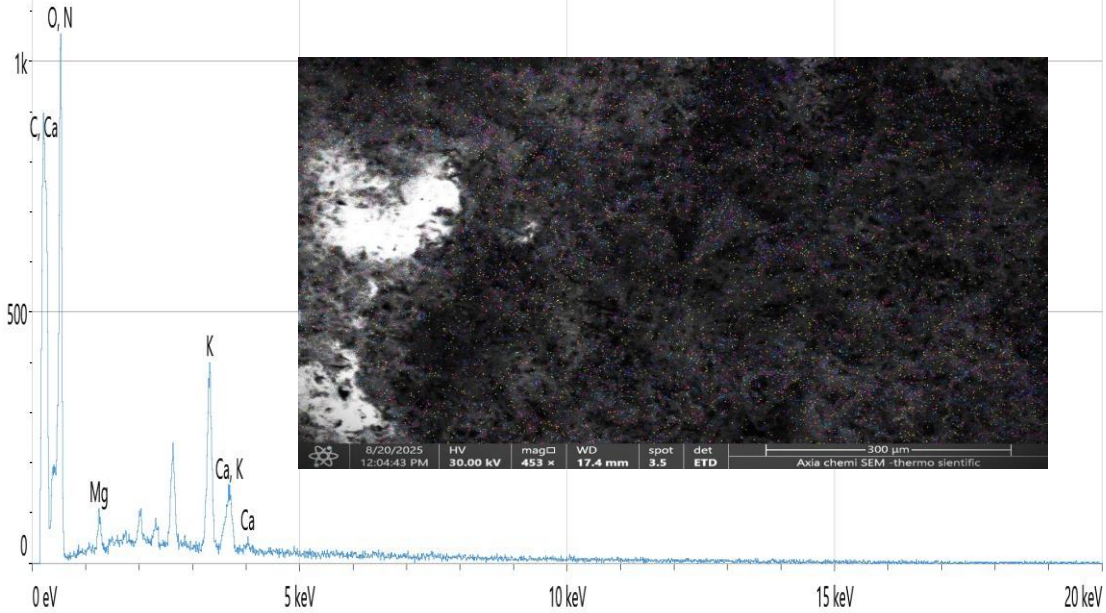


Fig. 5. Elemental distribution of okra powder

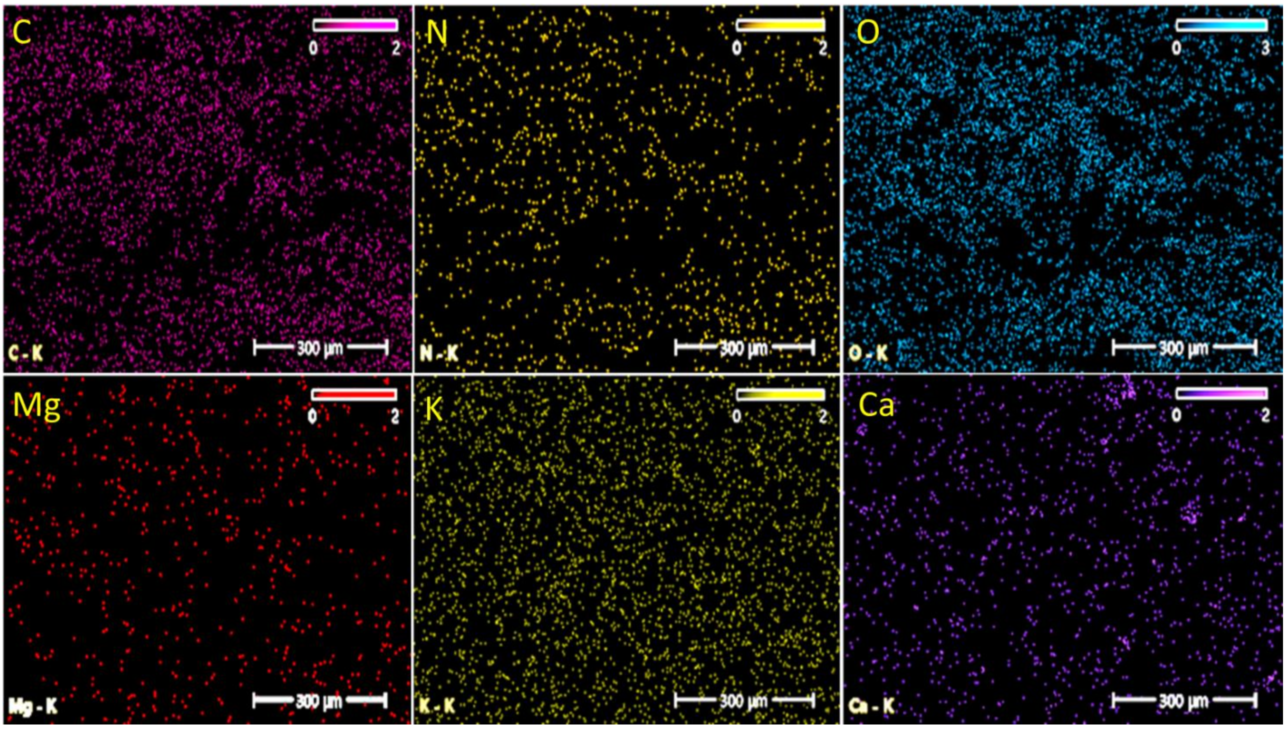


Fig. 6. Mapping of Elemental distribution of okra powder

Fourier Transform Infrared Spectroscopy (FTIR) Analysis of Crude Oil

Crude oil viscosity is a major challenge in its transportation and processing. Various techniques are used to reduce viscosity, including the addition of natural materials. The effect of dried okra powder on crude oil properties was analyzed by using FTIR spectroscopy, as shown in Fig. 7 and Table 4.

The FTIR spectra of the okra powder exhibited distinctive peaks at around 3410 cm^{-1} (O–H stretching), 2920 cm^{-1} (C–H stretching), and 1230–1050 cm^{-1} (C–O stretching), thus affirming the existence of polysaccharides abundant in hydroxyl and acetyl groups. These functional groups are essential for enabling hydrogen bonding and adsorption interactions with the polar components of crude oil, including resins and asphaltenes. Alterations in these peaks—and variations in their intensities post-treatment indicate alterations in chemical bonding that reflect interactions between okra-derived nanoparticles and components of crude oil. The spectrum alterations substantiate the concept of nanoparticle-induced disruption of asphaltene aggregates and validate the process of viscosity decrease through adsorption-driven microstructural degradation.

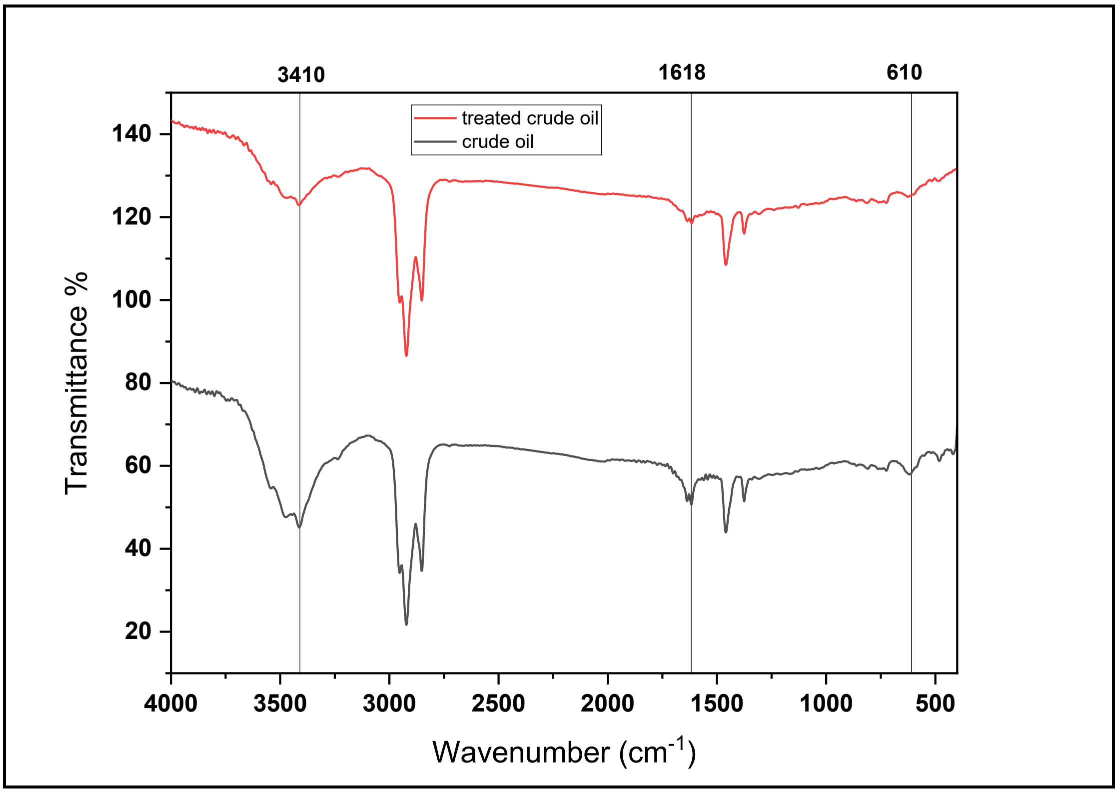


Fig. 7. FTIR spectroscopy

Table 4. FTIR comparison between crude oil sample and okra-treated sample

Wavenumber (cm⁻¹)	**Sample before treatment**	**Sample after treatment**	**Interpretation**
3410	Very weak	Strong	O–H groups from okra (sugars, phenolics)
2920	Present	Present	C–H stretching in alkanes
2850	Present	Present	C–H stretching in alkanes
1618	Very weak	Strong	Carbonyl (C=O) from carboxylic acids or esters
1615, 1540	Present	Present	N–H or C=C bonds
1460, 1375	Present	Present	CH_2 and CH_3 bending
610	Very weak	Present	Plant-derived compounds or ring structures

Fig. 8 illustrates the interaction between functional groups in okra powder, specifically carbonyl (C=O) and hydroxyl (O–H) groups, and hydrocarbon chains in crude oil. These interactions diminish intermolecular forces, such as Van der Waals forces, between hydrocarbon chains and enhance molecular mobility, thereby decreasing viscosity.

Okra mucilage is abundant in natural polysaccharides containing hydroxyl and carboxyl functional groups, which are apt to bind at the oil-water interface. This adsorption [28] could reduce interfacial energy by substituting high-energy oil-water contacts with lower-energy oil-biopolymer interactions. Nano-cellulosic and plant-derived biopolymer nanoparticles have been demonstrated to function through Pickering mechanisms, adsorbing at oil-water interfaces, decreasing interfacial tension, and stabilizing emulsions via steric and electrostatic effects.

The viscosity of crude oil is mechanistically reduced by the polymeric dispersion activity of okra powder's mucilage using a double stabilization approach. The polar carboxyl (COOH) and hydroxyl (OH) groups facilitate early adsorption by serving as powerful anchors to the polar surface of asphaltenes and resins, predominantly through hydrogen bonding and, to a lesser degree, electrostatic interactions. Substantial steric hindrance occurs when the methoxyl (OCH_3) groups and the expansive, non-polarizing polymer backbone of the mucilage penetrate the non-polar crude oil phase following anchorage. The steric repulsion disrupts the high-viscosity network, ensuring steady dispersion by preventing asphaltene nanoparticles from approaching one another and aggregating. Utilizing chemically modified mucilage to separate steric effects, with FTIR spectroscopy for assessing hydrogen bonding and adsorption isotherm modeling for determining steric layer thickness, enables the experimental separation of these effects.

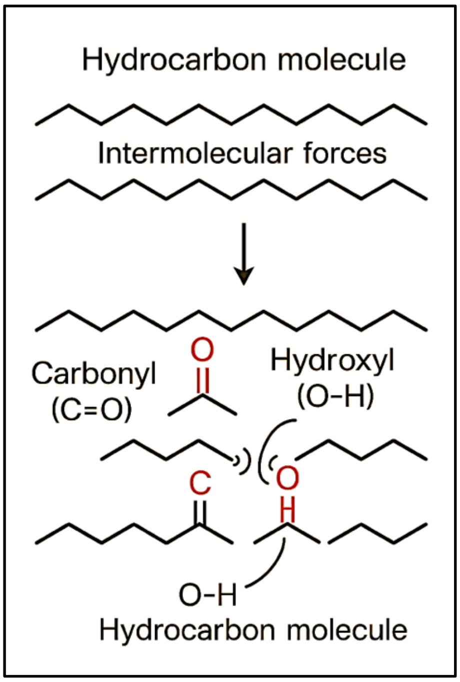


Fig. 8. Interaction of the functional group of okra powder in crude oil

Effect of Okra Powder on Viscosity

Four concentrations (50, 100, 150, and 200 ppm) of okra powder with a particle size of 1030.6 nm have been used to assess the effects on velocity, viscosity, density, flow rate, and Reynold number. Fig. 9 indicates the effect of okra powder on the viscosity reduction. We noticed a gradual decrease in viscosity with increasing okra powder concentration, with a reversal at 50 ppm (19.49 cP) and at 100 ppm (19.22 cP). Viscosity is a fluid's resistance to flow from one layer to another. Fibers form longitudinal chains that allow fluid layers to slide over one another, reducing viscosity. At 150 ppm, viscosity increased progressively. It's gradually increased at 150 ppm and 200 ppm to 19.93 cP and 20.45 cP, respectively, with increasing concentrations of okra powder, indicating an extrusive relationship between concentration and viscosity. The viscosity rise above ~100 ppm is attributable to the structured fluid character of okra mucilage, especially to concentration-induced self-association or polymer network development, rather than to okra particle aggregation or to asphaltene-binding site saturation. This is consistent with research indicating that: (1) Okra mucilage naturally forms viscoelastic, pseudoplastic, shear-thinning networks that become stronger with concentration. (2) Increased concentrations produce increased viscosity even under shear, as seen in an improved oil recovery study with okra bio-polymers.

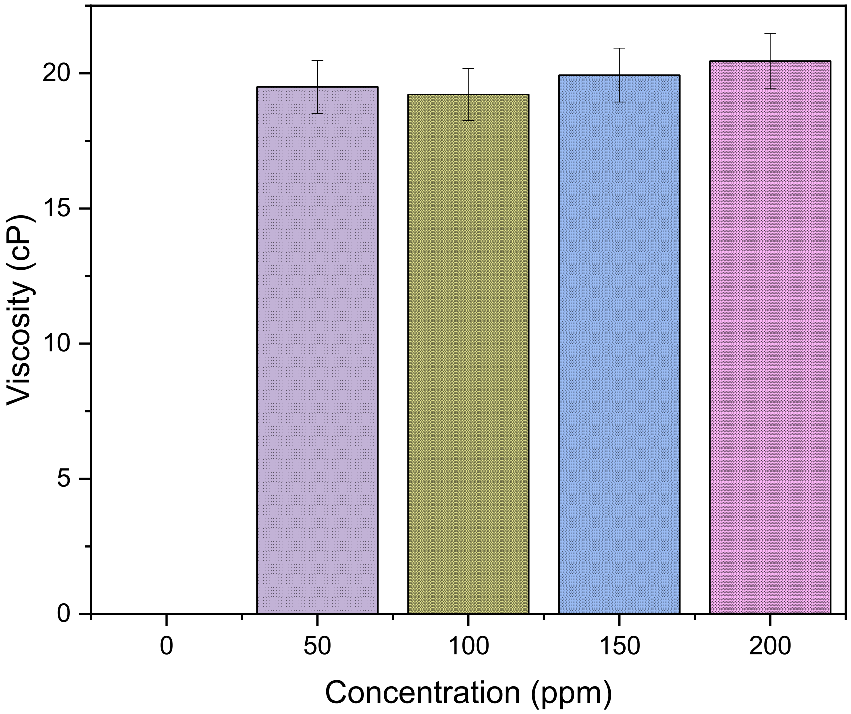


Fig. 9. Effect of okra powder on viscosity reduction

Effect of Okra Powder on Flow Rate and Velocity

The blue line in Fig. 10 shows the effect of okra powder concentration on the fluid flow rate. At 0 ppm, the flow rate was 59.08 ml/s. After that, it increased to 65.47 ml/s at 50 ppm and continued to increase to 67.11 ml/s at 100 ppm. After this point, it decreased to 66.67 ml/s at 150 ppm and 64.72 ml/s at 200 ppm. Since the viscosity decreases with the addition of the powder, drag is associated with the obstruction of flow and the interactions of fluid molecules, and it is directly proportional to the friction within the pipe; hence, a reduction in friction results in less drag and, therefore, increases the flow rate. While the red line shows the effect of okra powder, which improves crude oil velocity by lowering its viscosity, breaking down heavy hydrocarbons. The velocity increased to 54.739 cm/s at 100 ppm due to the effect of okra powder. Its polysaccharides (mucilage, pectin, and cellulose) alter rheology, enhancing flow. Natural surfactants reduce interfacial tension, thereby preventing asphaltene aggregation and facilitating mobility. It creates a lubricating coating, which reduces pipeline friction and pressure decreases. Furthermore, it promotes microbial biodegradation, which converts heavy parts into lighter, faster-flowing components. This eco-friendly, cost-effective biomaterial enhances pipeline efficiency and crude oil transportation without the use of toxic chemicals.

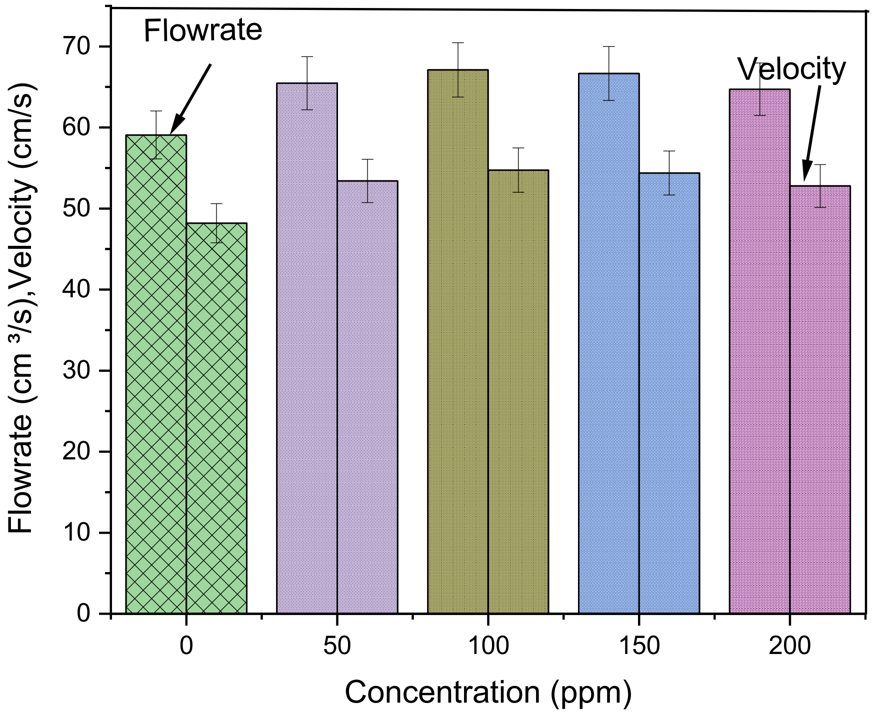


Fig. 10. Effect of okra powder on flow rate and velocity

6.6 Effect of Okra Powder on Reynolds Number and Density

The blue line in Fig. 11 illustrates the influence of okra powder concentration on the Reynolds number, which varies from 2.688 without any addition to 3.328 inside the turbulent flow regime at a concentration of 100 ppm of 1030.6 nm powder. After that, it decreased to 3.212 and 3.049 at 150 ppm and 200 ppm, respectively. The red line shows the effect of okra powder on reducing crude oil density, dispersing heavy hydrocarbons, and inhibiting asphaltene agglomeration. At 50 ppm addition, the density was 0.923; at 100 ppm, it decreased to 0.920. After this point, it increased from 150 and 200 ppm to 0.927 and 0.933, respectively, due to the effect of the nano biomaterials. Its polysaccharides affect oil rheology, lowering viscosity and increasing flow. Natural surfactants in okra improve oil mobility, while its bio-stimulant characteristics promote microbial breakdown of heavy components. This eco-friendly and cost-effective biomaterial enhances crude oil processing and enhanced oil recovery (EOR).

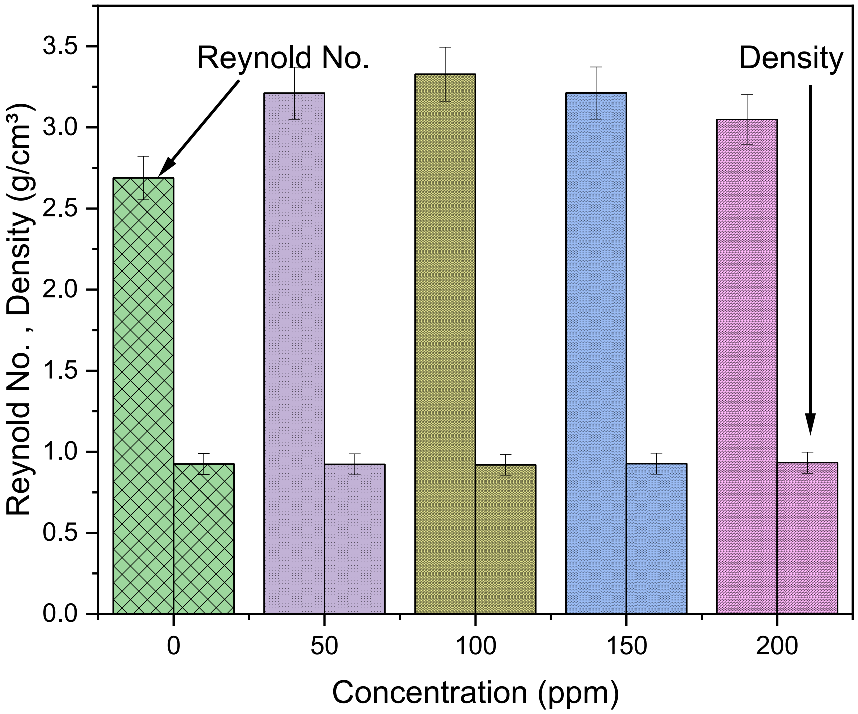


Fig. 11. Effect of okra powder on Reynold number

Effect of Electromagnetic Heating on Viscosity

Electromagnetic heating was used to enhance viscosity reduction in samples to increase flowability. The samples were irradiated at 800 W for 4 minutes, the optimal conditions used by Mowea et al. [3]. The viscosity reduced to 17.52 cP with electromagnetic heating alone; the decrease was due to the heating-induced vibration of polar molecules in heavy crude oil, generating internal heat. The sample temperature before the process was 28.8 oC and after the process, it increased to around 97.2 °C. This causes a consistent temperature rise, weakening the strong molecular connections, significantly lowering viscosity, and occasionally triggering minor molecular modifications [3, 4]. After these results, another sample was tested under the same irradiation conditions, with the addition of 100 ppm of okra powder. The viscosity reduced to 15.02 cP, indicating the effect of nanobiomaterials on viscosity reduction. The use of electromagnetic heating with okra powder nanoparticles results in a significant decrease in the viscosity of heavy crude oil. Electromagnetic heating raises the crude's temperature, breaking intermolecular interactions, while okra nanoparticles stabilize the dispersed heavy fractions via hydrogen bonding and steric hindrance. This synergy inhibits re-aggregation of asphaltenes and waxes, preserving low viscosity and improving flow characteristics, as shown in Fig. 12.

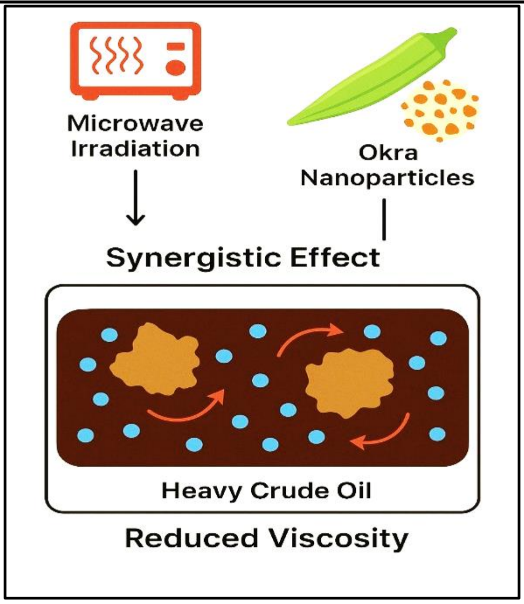


Fig. 12. Effect of Electromagnetic heating on viscosity

Stability of Okra Treated Heavy Crude Oil: Viscosity vs Aging Time

The stability of viscosity decrease was assessed using static aging. After 15 days, the viscosity drops to 100 ppm. This partial loss is due to the sluggish reassociation of asphaltenes in the absence of shear. However, after static aging, the treated crude showed a smaller increase in viscosity, suggesting that this may not affect the overall enhancement, indicating that okra polysaccharides act through reversible, weak interactions with asphaltenes/resins, and that mechanical energy aids dispersion. Thus, okra's impact is robust over timescales ranging from days to weeks and is practically useful for pipeline transport, where constant flow or periodic boosting naturally maintains dispersion. Long-term stability under reservoir-like conditions is a key focus for future research. Fig. 13 shows the effect of aging days on the viscosity of crude oil at an okra powder concentration of 100 ppm, indicating a slow, low increase over time.

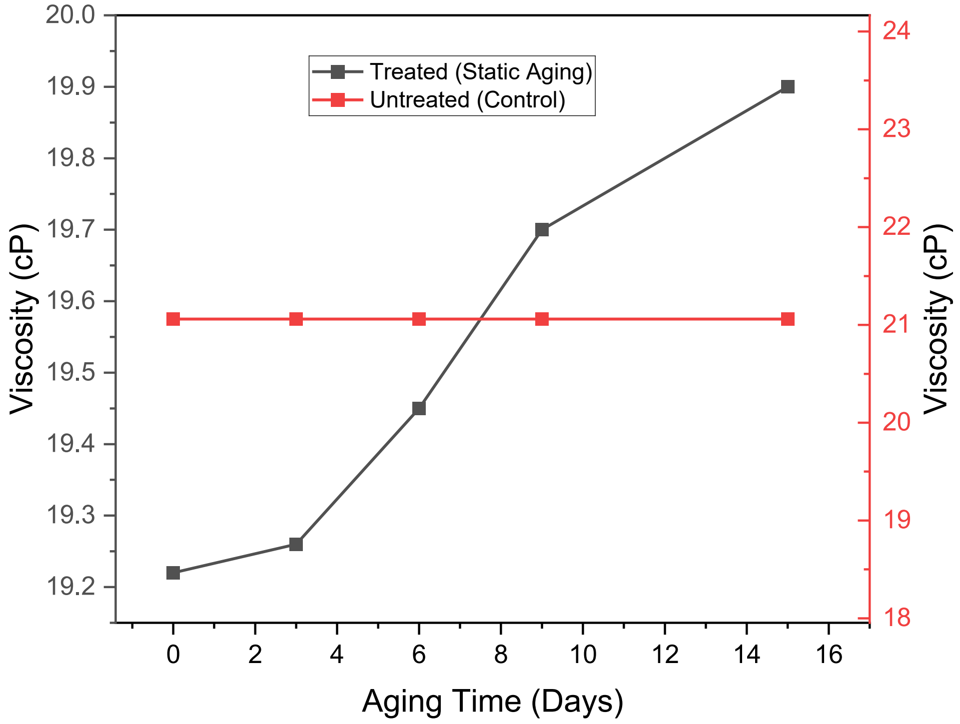


Fig. 13. Viscosity vs aging time

Conclusion

- SEM investigation indicates that the distinctive structure of okra powder significantly reduces crude oil viscosity, hence enhancing the efficiency and cost-effectiveness of pipeline transportation.
- Okra powder functions as a sustainable substitute for traditional chemical agents employed in viscosity reduction.
- FTIR studies indicated that dried okra powder included polar functional groups such as C=O and O–H. These groups substantially facilitated the breakdown of intermolecular connections in crude oil, hence decreasing its viscosity. This demonstrates the prospective application of natural plant-derived materials as sustainable alternatives in petroleum processing.
- It provides a cost-effective solution, particularly in areas where okra is plentiful.
- By diminishing the viscosity of oil, the pressure needed in pipelines is decreased, resulting in reduced energy consumption and maintenance expenses.
- Electromagnetic heating reduces heavy crude oil viscosity by increasing volumetric heating, reducing intermolecular connections, and improving flow properties, enabling efficient transportation and processing.
- The combination of electromagnetic heating with okra powder-based nanoparticles has a synergistic impact on viscosity reduction. Electromagnetic heating disrupts the aggregated structures of heavy fractions, while okra nanoparticles stabilize the scattered species via hydrogen bonding and steric hindrance. This integrated strategy not only boosts viscosity reduction but also improves the stability and flow behavior of heavy crude oil across a broader range of operational situations.

- Okra powder presents benefits in cost, availability, and performance when compared to other natural materials, including date seed, palm fibers, and xanthan gum. The polysaccharide content, particularly after irradiation, significantly reduces the viscosity of heavy crude oil even at low levels, making it a viable and effective alternative for industrial use.

Acknowledgments

The authors express their gratitude to the College of Chemical Engineering, University of Technology, Baghdad, Iraq, for providing laboratory facilities.

Nomenclature

k	Constant coefficient
n	Power low index
β	Yield stress
Q	Flow rate (cm^3/s),
A	Area (cm^2).
V	Volume (cm^3)
t	time (sec)
γ	Kinematic Viscosity (cSt),
μ	Dynamic Viscosity (cP)
ρ	Density (g/cm^3)
Re	Reynold number
d	Diameter (cm)

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How to cite: Khazaal S.H, Ibrahim R, Mowea W. Viscosity Reduction and Flowability Enhancement of Heavy Crude Oil Using Nano Biomaterial Additive and Microwave Irradiation. Journal of Chemical and Petroleum Engineering 2026; 60(1): 3-21.