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

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 for heavy crude oil using a new method, the microwave irradiation technique assisted with 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 to achieve the optimum conditions of 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 prepared powder, Scanning Electron Microscopy (SEM)-Energy Dispersive X-ray Spectroscopy (EDX), Particle Size Analyzer (PSA), and Fourier Transform Infrared Spectroscopy (FTIR) have been used. For the first setup, the results showed that the optimum conditions achieved were at 100 ppm addition with 19.21 cP viscosity. Whilst for second setup, at a power of 800 Watt 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%.

Keywords Biomaterial, Electromagnetic, Nano, Okra powder, Reduction, Viscosity.

1. Introduction

Heavy crude oil refers to a category of crude oil characterized by its difficulty in flow, typically exhibiting lower API values ranging from 10° to 20° and possessing 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 in an efficient and cost-effective manner is becoming increasingly vital. Currently, research of heavy crude oil in pipeline transportation have mostly concentrated on viscosity reduction and the rheological characteristics of crude oil and its mixes [3-4]. The various methods for lowering the viscosity of heavy crude oil include preheating the crude oil, and adding drag-reducing chemicals. Other methods used in pipeline transportation of heavy crude oil emphasis drag reduction by incorporating a second phase. Examples of typical ways include water assisted oil core circular flow, gas/steam infusion transport, and diluting by lighter crude oils or alcohols as well [5-6]. As a result, many procedures are utilized to lower the viscosity of heavy oil prior to pipeline transit. Some popular ways for stabilizing emulsions include dilution with lighter crudes or alcohols, heating, and the addition of surfactants. Heating is a frequent strategy used to address the above-mentioned issues of carrying heavy oil via pipeline [7]. The viscosity of heavy oil is lowered, making it easier to pump, also microwave reduces interfacial tension by heating aquatic phases, reducing viscosity, and preserving energy [4]. Experiments confirm this hypothesis, constructing a model for 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 a heated pipeline is exceedingly challenging owing to the cooling influence of the surrounding water and the practical difficulties of maintaining pumping and heating stations [9,10]. Drag refers to the pressure loss caused by turbulent flow inside pipelines, which requires 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 Equ. 1 below:

$$f = \frac{0 \cdot 079}{Re^{0 \cdot 25}} \qquad (1)$$

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

To prevent turbulent eddies and breach the laminar layer during pipeline transmission, heavy crude oil viscosity 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 garnered interest due to their environmentally sustainable characteristics and their 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 like microwave irradiation have demonstrated efficacy by delivering fast heating and molecular disruption, resulting in viscosity reduction. 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 utilizing chemicals for viscosity reduction include recovering from crude oil, dissolving in heavy oil, and identifying the optimal dosage to sustain the desired pressure decrease. 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 leading to a higher drag reduction factor [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. [22] study's aimed to simulate turbulent flow in pipes containing drag-reducing fluids using a non-Newtonian model and a non-Newtonian damping function. 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 in predicting critical flow parameters like friction factor and mean axial velocity, but had limitations in predicting turbulent kinetic energy. The average error in calculating friction factor was 5.45%, compared to 32.49% for the Pinho model.

Okra powder was selected as a natural nano biomaterial addition because of its nontoxic characteristics, biodegradability, and high polysaccharide content with surface-active qualities that reduce intermolecular interactions in heavy crude oil, hence reducing viscosity and improving flowability. Microwave irradiation was utilized as a physical treatment technique due to its capacity for quick and uniform heating, which efficiently break down heavy molecular structures and enhances the additive's efficacy. The amalgamation of okra powder with microwave irradiation presents a sustainable and effective method for reducing the viscosity of heavy crude oil.

2. Rheology

Rheology studies material flow and deformation under stress, with Newtonian fluids having constant viscosity and resistance, while non-Newtonian fluids change viscosity 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 increasing 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].

3. Experimental Work

3.1 Materials

Iraqi heavy crude oil (HO) was used in the present investigation, it was assembled from AL-Dorah refinery, density 0.886 g/ml and API gravity 19.5 at 40 ℃ and water content of 0.1 vol.%. **Table.1** below shows the details of crude oil used.

Table 1. Iraqi heavy crude oil specifications

Result	Test
Kinematic Viscosity @ 40 °C (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

3.2 Experimental Tools

The experimental test done by using the system shown in **Fig.1** which was specially manufactured for this work, for the purpose of measuring the time needed for the heavy crude oil to transfer before and after using the nano biomaterials for the purpose of viscosity reduction.

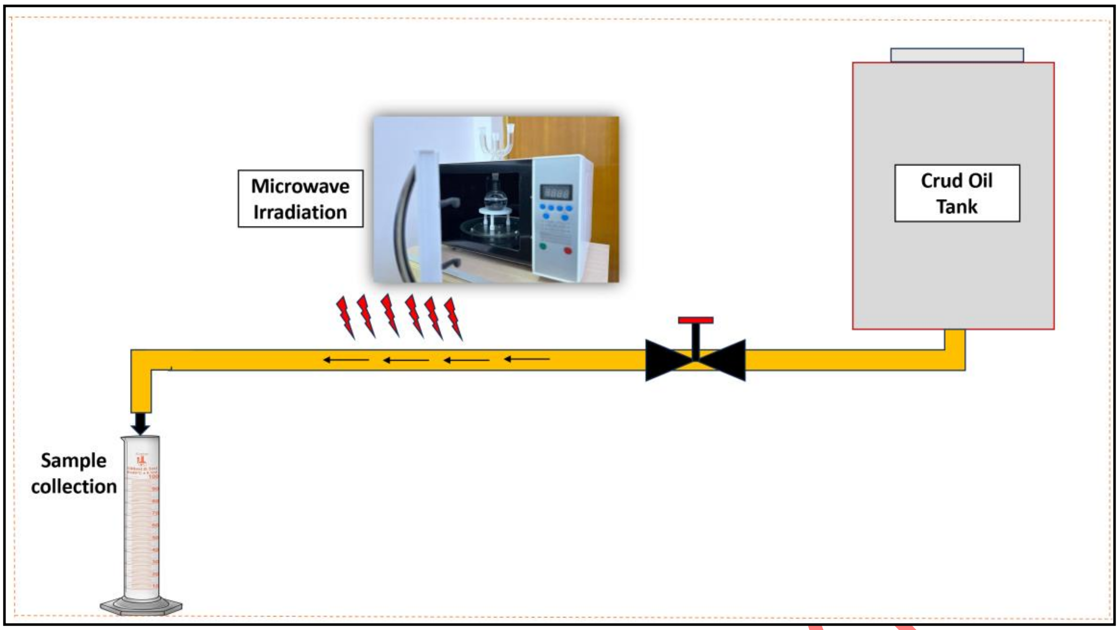

Fig. 1. Schematic presentation of experimental system

Also, the microwave reactor was used in this work for the purpose of measuring the effect of dielectric heating on enhancing the drop in viscosity at the optimum results of nano biomaterials additions.

3.3 Specifications and Preparation of Okra Powder

This study presents, the application of Nano-biomaterials as a material which has the potential to reduce the viscosity of Iraqi heavy crude oil for the purpose to enhance the followability in pipelines. Okra powder was used in the work as Nano-biomaterial, okra powder is a one of a kind biopolymer for reducing heavy crude oil viscosity 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 at first was washed by water thoroughly and dried by an oven for 5h at 70 ℃ and grinded by using professional nutrition blender model SC-1589, 220v, 50HZ and 2500W [25]. The practical steps described in **Fig.2**.

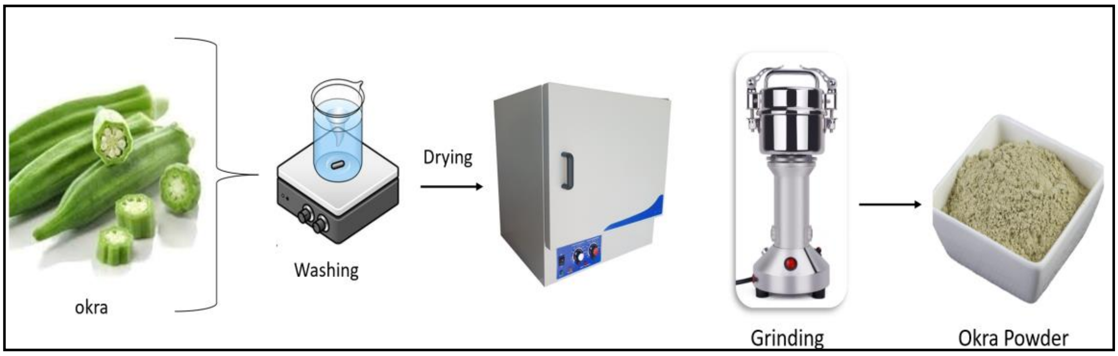

Fig. 2. Practical steps of okra powder preparation

3.4 Experimental Procedures

Five concentrations (0 ppm, 50 ppm, 100 ppm, 150 ppm, and 200 ppm) were accurately weighed using an electronic balance with error range about ±0.001 g to ±0.002 g. Each concentration was thoroughly mixed with crude oil for a duration of 10 minutes using a magnetic stirrer to ensure homogeneous dispersion. Upon completion of the mixing process, 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

4. Experimental Calculation

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

$$Velocity = \frac{Q}{A} \tag{3}$$

$$\mathrm{Q} = \frac{\mathrm{V}}{t} \tag{4}$$

$$\gamma = \frac{\mu}{\rho} \tag{5}$$

$$Re = \frac{u \times d \times \rho}{\mu} \tag{6}$$

Where:

A is represented Area (cm^2), V is represented volume (cm^3), t is the time (sec), γ is represented kinematic viscosity (cSt), μ is viscosity (cP), ρ is density (g/cm^3), and d is diameter (cm).

5.Tests

5.1 Scanning Electron Microscopy (SEM)

Thermo Scientific Axia Chemi SEM was used to examine the surface morphology, the magnification error of a SEM might range between 5-10%, of okra nano particle sample 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.

5.2 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:

- 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.

5.3 Fourier Transform Infrared Spectroscopy (FTIR) Analysis

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

6. Results and Discussion

6.1 Particle Size Analyzer (PSA)

The PSA shows that, the grinded biomaterial was obtained at particle size of rang (50 – 5000 nm) as shown in **Fig. 3**, and the effective size is1030.6 nm measured by particle size device, USA.

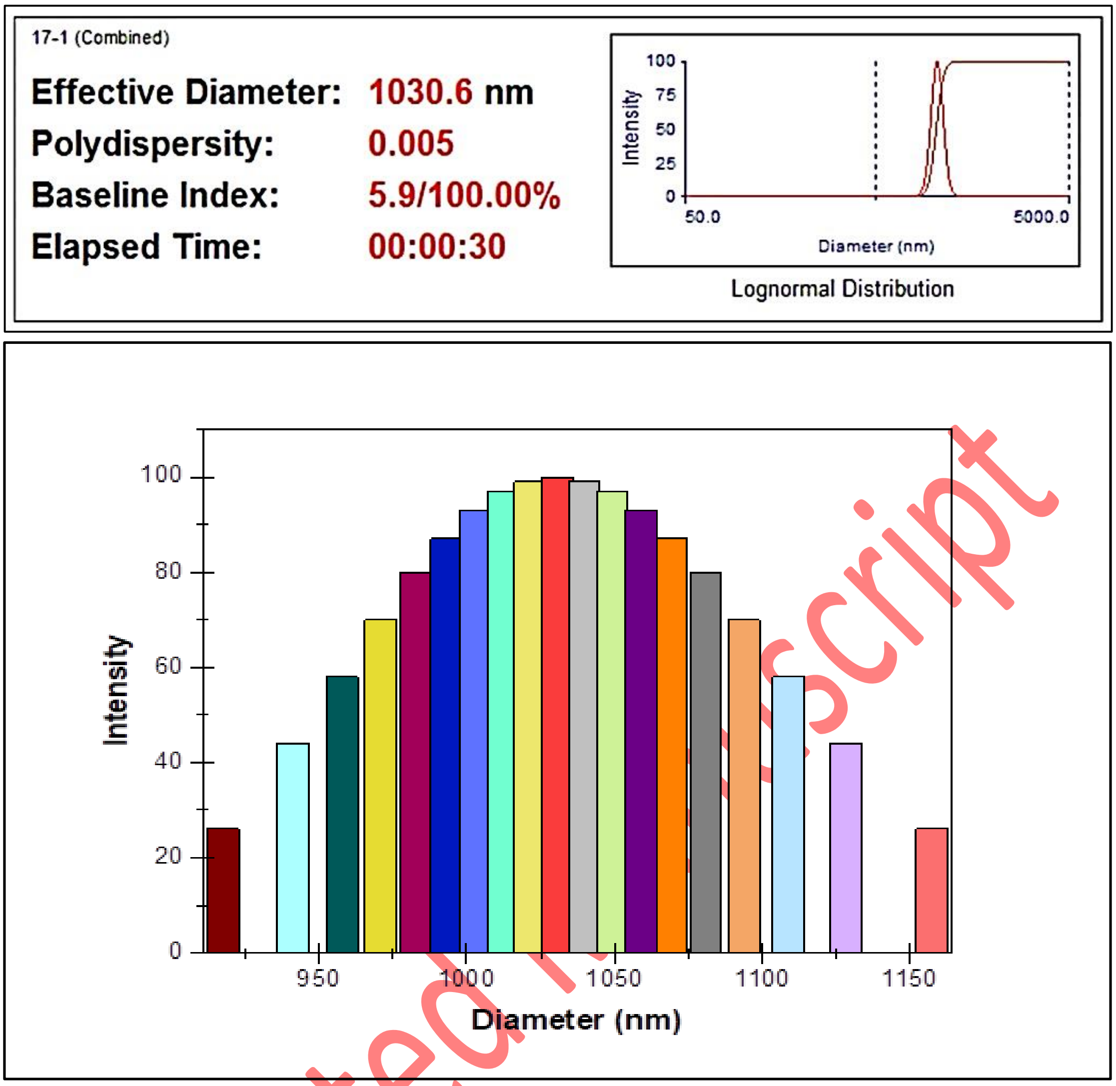

Fig. 3. Long normal distribution of particle size for okra powder

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

Fig. 4 shows the SEM of okra powder which has been employed to analyze the okra powder microstructural characteristic. 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, augmenting the powder's contact with fluids like crude oil. A network of tiny natural fibers is discernible inside the particles, aiding in the absorption and stability of denser components when the powder is employed to diminish oil viscosity. The particle sizes fluctuate, often 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 enables okra powder to efficiently absorb heavy constituents in crude oil, reducing agglomeration and enhancing its flow via pipelines.

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

Fig. 5 and **Fig. 6** illustrate the elemental composition of okra powder shows its organic origin, predominantly consisting of carbon, nitrogen, and oxygen, with trace amounts of potassium, calcium, and magnesium **Table 3**. 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, which aid in colloidal stability.

The structural and chemical modifications enhance the dispersing characteristics of okra powder, aiding in the breakdown of asphaltene and resin aggregates in heavy crude oil, thereby decreasing 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 reduction, with optimal efficacy reliant on precise regulation of irradiation parameters.

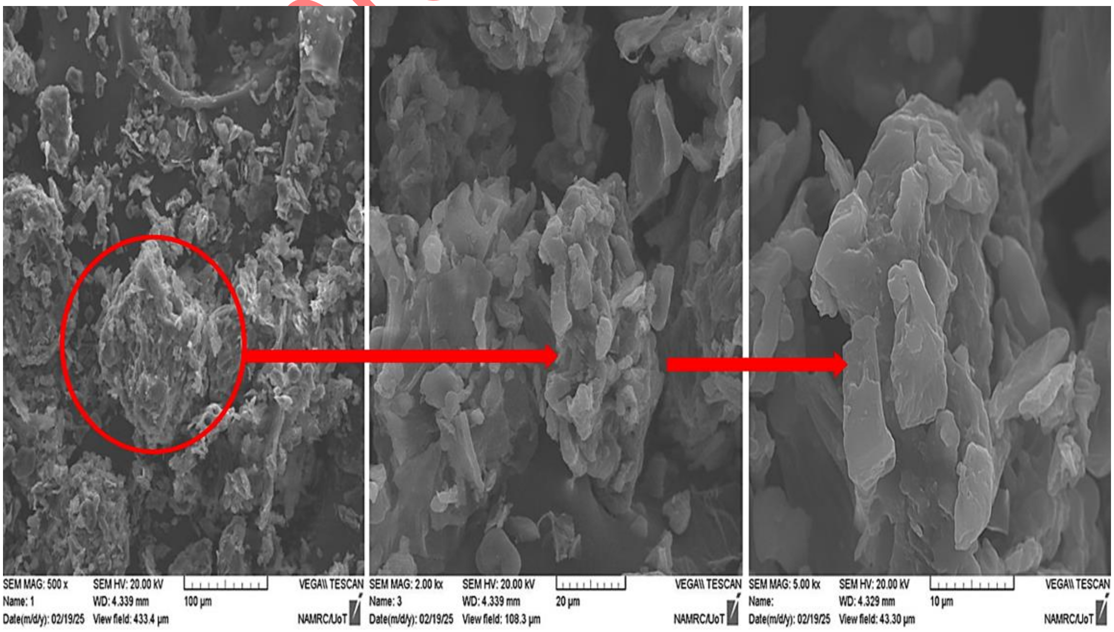

Fig.4. SEM of okra powder

Table 3. Elemental composition of okra powder

Element	**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

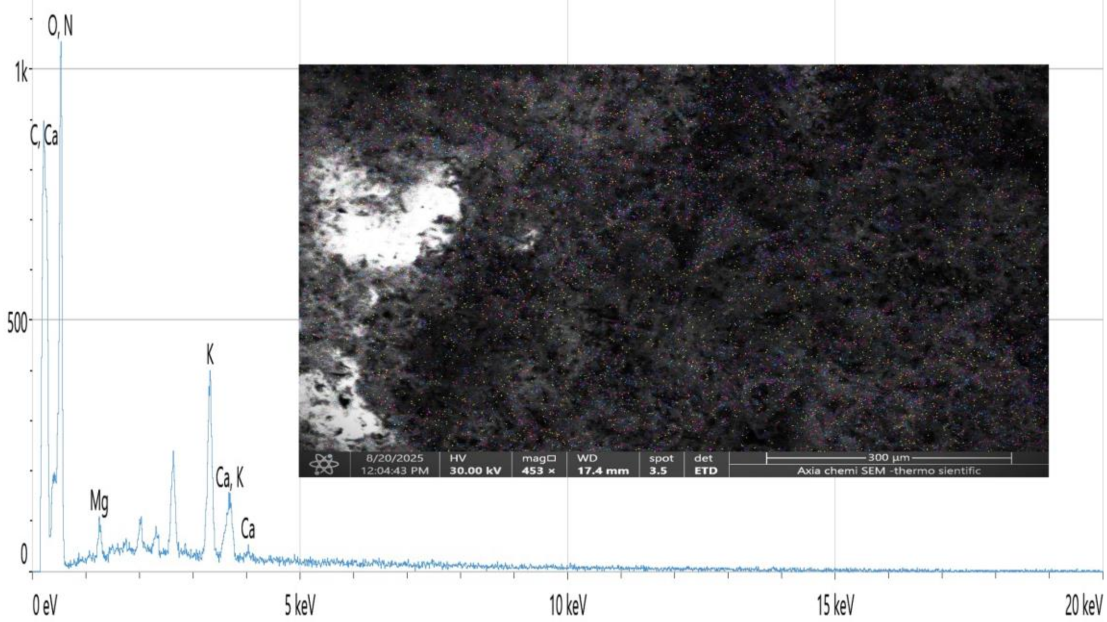

Fig. 5. Elemental distribution of okra powder

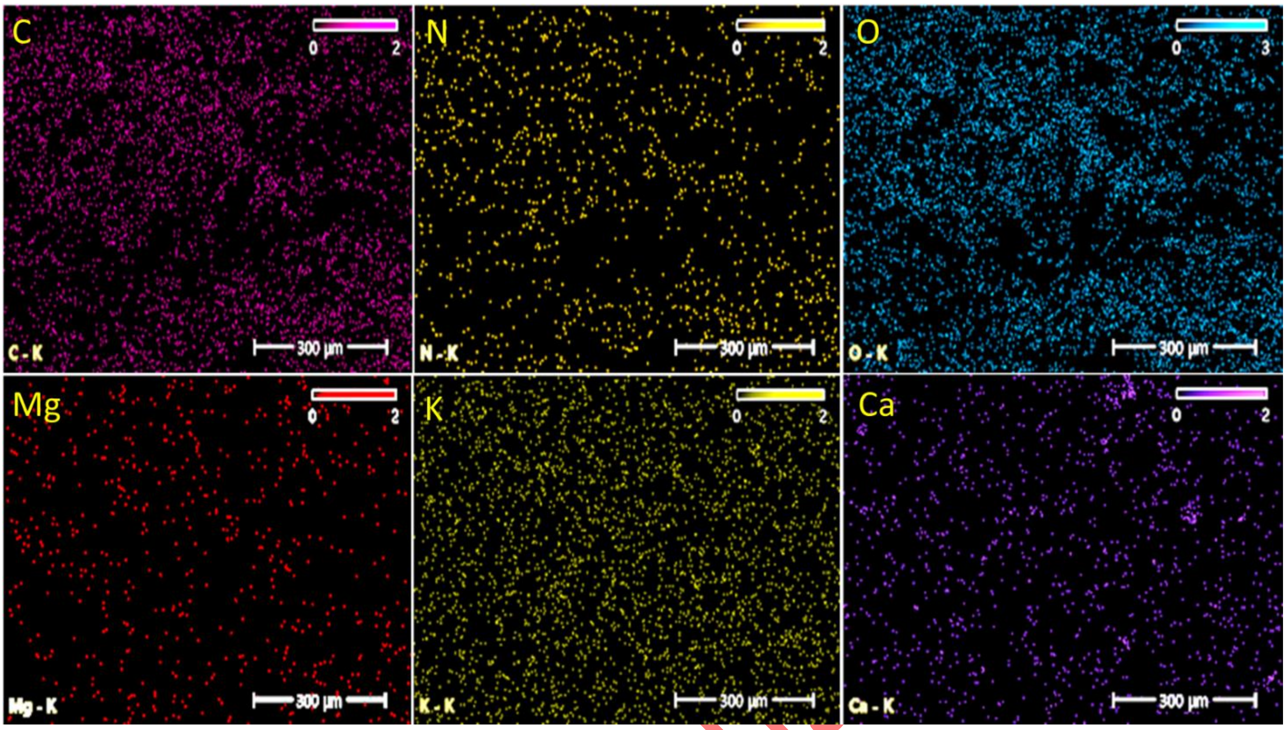

Fig. 6. Mapping of Elemental distribution of okra powder

6.3 Fourier Transform Infrared Spectroscopy (FTIR) Analysis of Crude Oil

Crude oil viscosity is one of the major challenges 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 the 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), so 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.

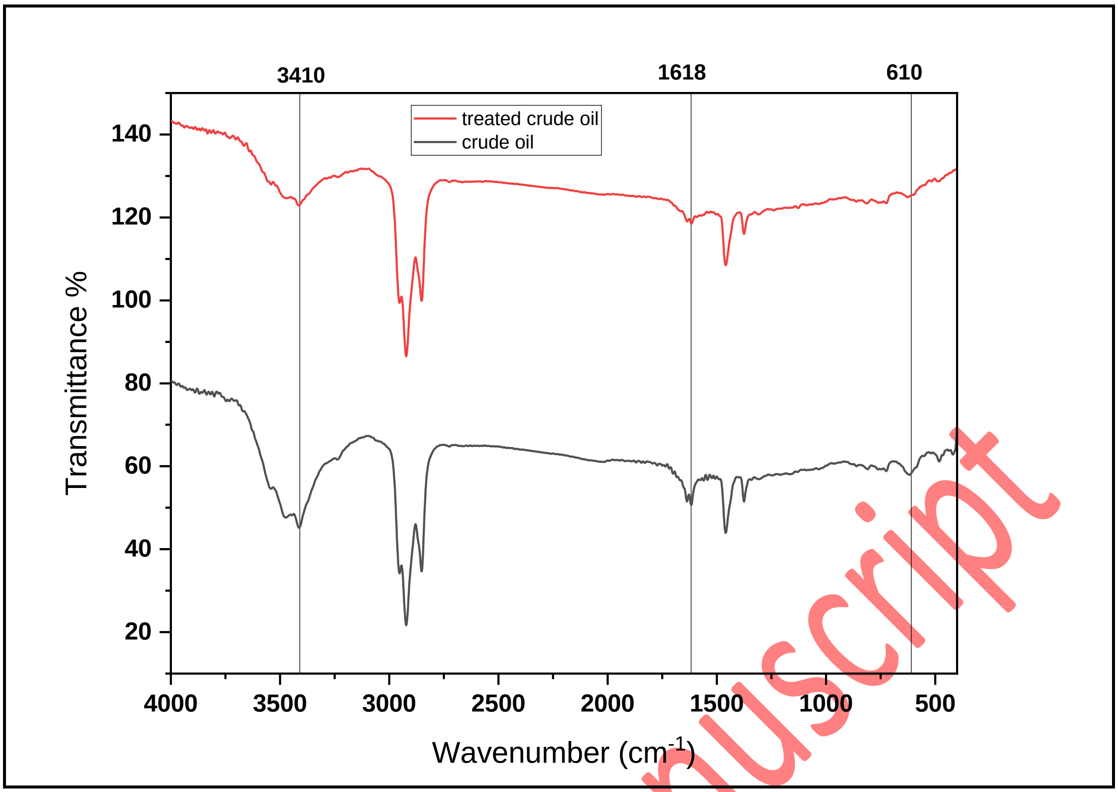

Fig. 7. FTIR spectroscopy

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 the intermolecular forces, such as Van der Waals forces, between hydrocarbon chains and enhance molecular mobility, resulting in decreased viscosity.

Okra mucilage is abundant in natural polysaccharides containing hydroxyl and carboxyl functional groups, which are apt to 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 and ensures steady dispersion by preventing the asphaltene nanoparticles from approaching one other 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.

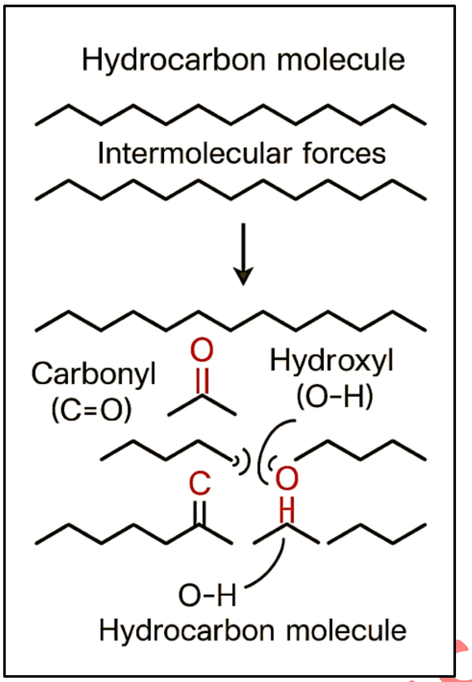

Fig. 8. Interaction of functional group of okra powder in crude oil

6.4 Effect of Okra Powder on Viscosity

Four concentrations (50,100,150,200) ppm have been used of okra powder in size of (1030.6 nm) to see the effect at the 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 the increasing in the concentration of okra powder, which causes a reversal effect on the viscosity at 50ppm where viscosity decreased to 19.49 cP and at 100 ppm it decreased to its lower point to 19.22 cP. Viscosity refers to the fluid's resistance to move from one layer to the next. Fibers create longitudinal chains that allow fluid layers to flow over each other, reducing viscosity. After 150 ppm, viscosity progressively increased. Its gradually increased at 150 ppm and 200 ppm with 19.93 cP and 20.45 cP the addition of more concentration of okra powder which it is extrusive relationship between concentrations and viscosity. The viscosity rise over ~100 ppm is attributable to the structured fluid character of okra mucilage, especially concentration-induced self-association or polymer network development, rather than okra particle aggregation or 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 improved oil recovery study with okra bio-polymers.

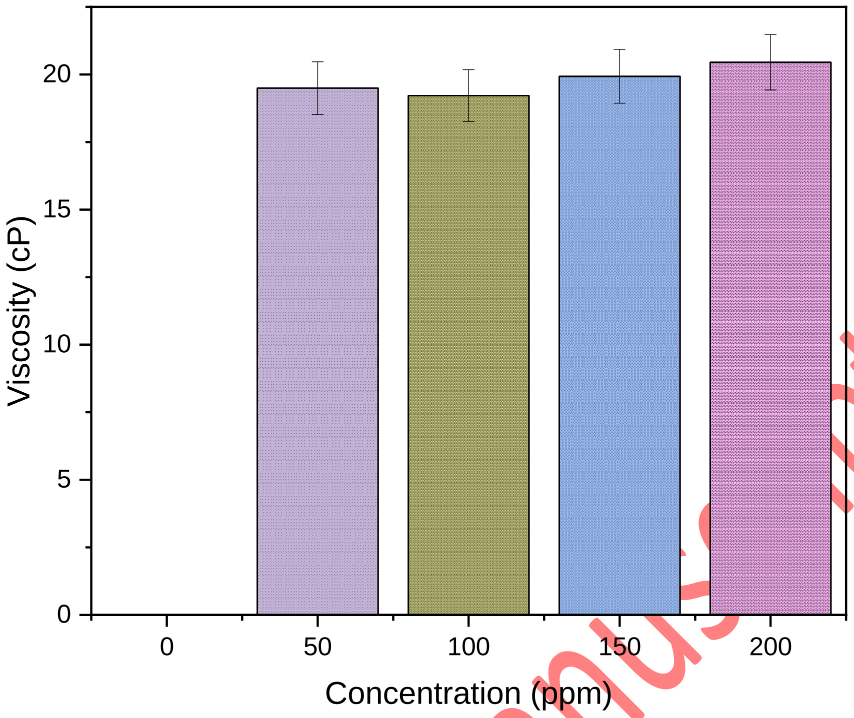

Fig. 9. Effect of okra powder on viscosity reduction.

6.5 Effect of Okra Powder on Flow Rate and velocity

The blue line in **Fig .10** shows the effect of okra powder concentrations on enhancing the flow rate of fluid. At 0 ppm the flow rate was 59.08 ml/s after that it increased to 65.47 ml/s at 50ppm, also it kept increasing to 67.11 ml/s at 100 ppm. After this point it started to decreeing at 150 ppm and 200 ppm to 66.67 ml/s and 64.72 ml/s respectively. Since the viscosity deceased with addition of the powder therefore drag is associated with obstruction in flow and interactions of fluid molecules, where drag is directly proportional to the friction within the pipe; hence, a reduction in friction results in less drag and therefore increasing 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 okra powder effect. Its polysaccharides (mucilage, pectin, and cellulose) alter rheology, enhancing flow. Natural surfactants reduce interfacial tension, which prevents asphaltene aggregation and facilitates 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 using toxic chemicals.

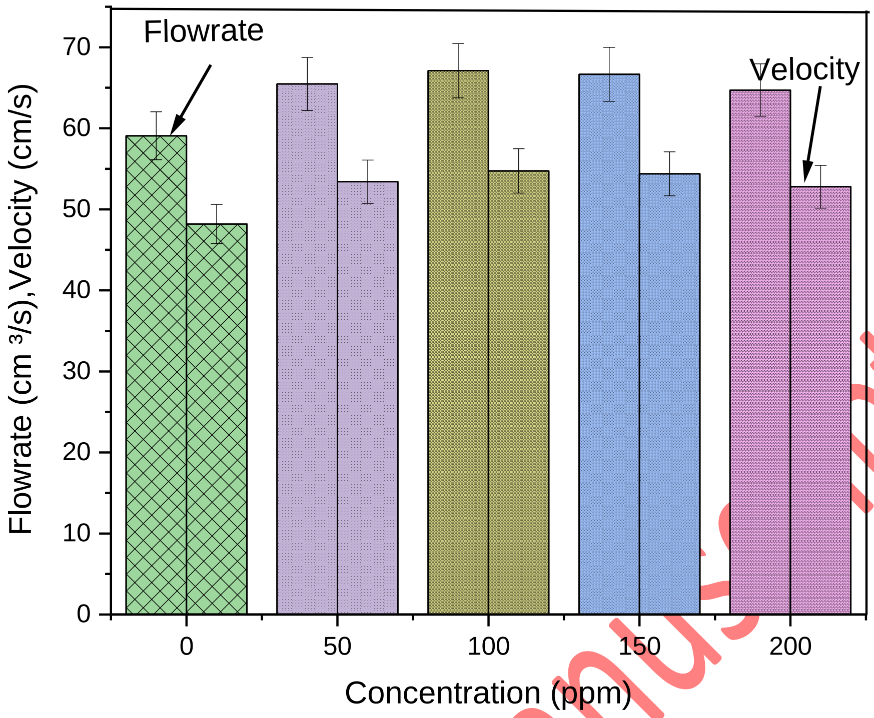

Fig. 10. Effect of okra powder on flowrate and velocity.

6.6 Effect of Okra Powder on Reynold 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 stared to decreeing to 3.212 and 3.049 at 150 ppm and 200 ppm respectively. While 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 while when increasing the addition to 100 ppm the density decreased to 0.920 after this point it started to increasing at 150 and 200 ppm to 0.927 and 0.933 due to effect of 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).

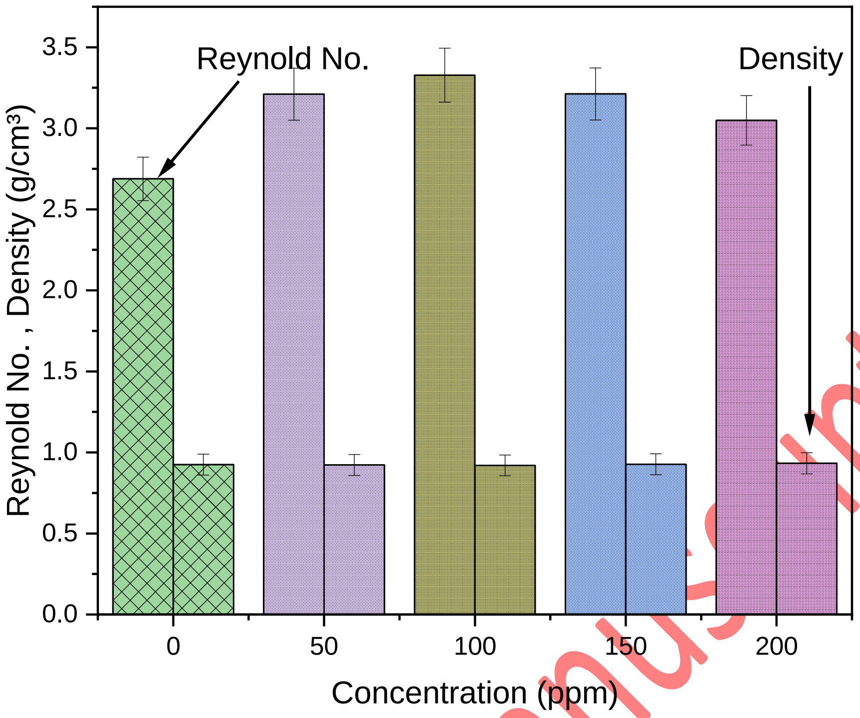

Fig. 11. Effect of okra powder on Reynold number.

6.7 Effect of Electromagnetic Heating on Viscosity

Electromagnetic heating was used to enhance the viscosity reduction of samples in order to increase the followability. The samples were irradiated under 800 Watt irradiation power and 4 minutes' treatment time optimum conditions that were used by Mowea. et al. [3], the viscosity reduced to 17.52 cP with the treatment of electromagnetic heating only, the decreasing occurred by causing polar molecules in heavy crude oil to vibrate, generating internal heat, the sample temperature before the process was 28.8°C 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 optimum conditions of irradiation with the addition of 100 ppm of okra powder the viscosity reduced to 15.02 cP this shows the effect of nano biomaterials on enhancing viscosity reduction. The use of electromagnetic heating with okra powder nanoparticles results in a considerable decrease in heavy crude oil viscosity. Electromagnetic heating raises the temperature of the crude, breaking intermolecular interactions, while okra nanoparticles stabilize the scattered heavy fractions via hydrogen bonding and steric hindrance. This synergy inhibits re-aggregation of asphaltenes and waxes, preserving low viscosity and improving flow characteristics **Fig. 12**.

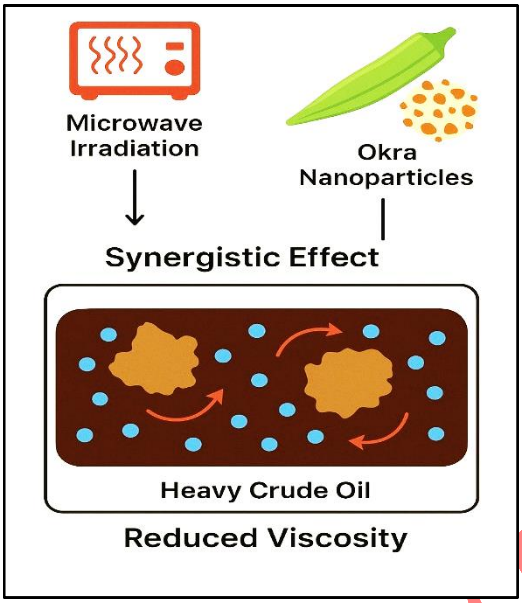

Fig. 12. Effect of Electromagnetic heating on viscosity

6.8 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 at 100 ppm remained. This partial loss is due to the sluggish re-association of asphaltenes when shear is absent. However, after static aging, the treated crude showed a smaller rise in viscosity, which may not have an influence on the overall enhancement, showing that okra polysaccharides work through reversible, weak interactions with asphaltenes/resins and that mechanical energy aids in 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** show the effect of aging days on the viscosity of crude oil at the optimum conditions od okra powder concentration 100 ppm where it shows a slow and low increasing in the viscosity over the time.

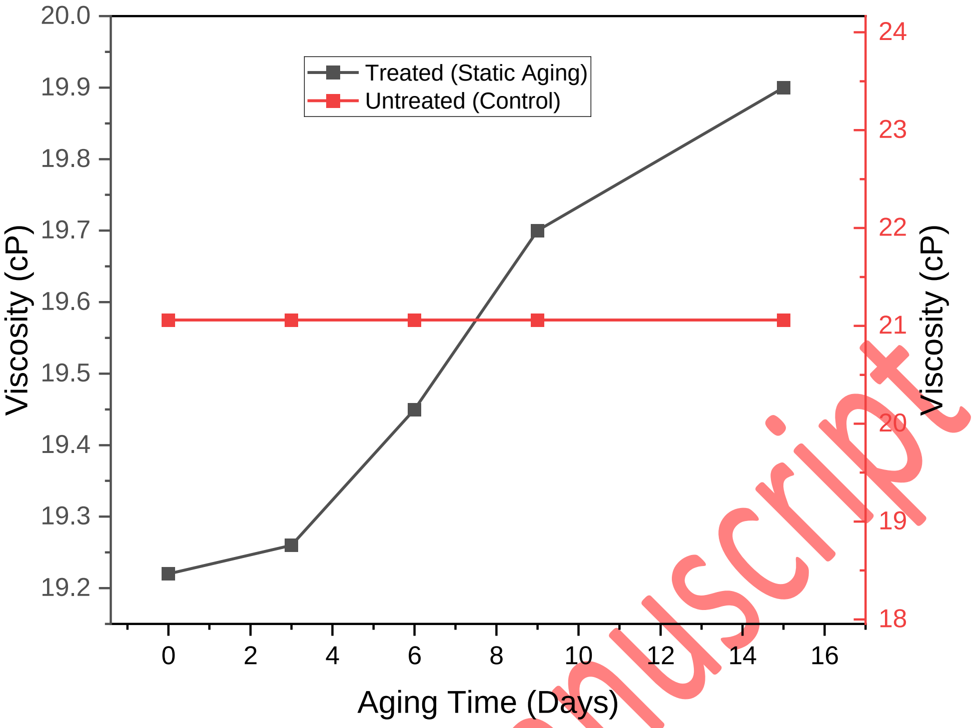

Fig.13. Viscosity vs Aging Time

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 destroys the aggregated structures of heavy fractions, while okra nanoparticles stabilize scattered species via hydrogen bonding and steric hindrance processes. 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 post-irradiation, significantly decreases the viscosity of heavy crude oil even at minimal quantities, rendering it a viable and effective alternative for industrial uses.

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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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