Evaluation of Wax Inhibition in Crude Oil Pipelines Using Extracts from Moringa Seeds and Lime

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Abstract

Wax deposition in crude oil pipelines is a significant operational challenge, particularly in low-temperature environments such as offshore installations, where wax crystallization hinders flow. Traditional wax inhibitors, such as xylene, are effective but raise environmental concerns due to their hazardous nature. This study explores the use of Moringa Seed Extract (MSE) and Lemon Extract as eco-friendly, bio-based alternatives to conventional inhibitors. Fourier-transform infrared (FTIR) spectroscopy was utilized to characterize the functional groups in these inhibitors alongside xylene. The FTIR analysis confirmed the presence of hydroxyl and carboxyl groups, which are critical for wax inhibition. Both MSE and Lemon Extract demonstrated functional similarities to xylene in their inhibitory capabilities.

Physicochemical analysis of the crude oil was conducted to establish a baseline for evaluating inhibitor performance, revealing a specific gravity of 0.860, API gravity of 33.035, kinematic viscosity of 8.14 cSt, and dynamic viscosity of 7.01 cP. Cloud and pour point tests, simulating sub-ambient offshore conditions, were used to assess wax inhibition. Results showed that MSE, at a 9 mL concentration, achieved a pour point of 17°C and a cloud point of 19°C, outperforming xylene, which recorded a pour point of 19°C and a cloud point of 20°C at the same concentration. Lemon Extract also proved effective, achieving a pour point of 22°C and a cloud point of 23°C, though its performance was slightly below that of MSE and xylene.

This study highlights the superior wax inhibition capability of MSE over conventional inhibitors like xylene, presenting it as a sustainable and environmentally friendly alternative for pipeline transportation. The concentration-dependent effectiveness of MSE underscores its potential for commercialization, with further optimization of concentration levels recommended for large-scale applications. Additionally, a comprehensive environmental impact assessment is suggested to validate its safety. These findings provide valuable insights into bio-based wax control methods, encouraging the adoption of greener practices in the petroleum industry.

Introduction

Wax deposition in crude oil pipelines poses a critical challenge to the oil and gas industry, particularly in cold environments and deepwater fields. As crude oil flows through pipelines, its temperature often drops below the wax appearance temperature (WAT), leading to the precipitation of paraffin waxes from the oil. These waxes adhere to the pipeline walls, forming deposits that progressively reduce the effective pipeline diameter. This deposition results in increased pressure drops, diminished flow rates, and, in severe cases, complete pipeline blockages (Olajire 2021). The operational and economic implications of wax build-up are significant, as they

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necessitate frequent maintenance, the use of inhibitors, or remedial interventions to restore pipeline functionality (Kiyingi et al. 2022).

To ensure smooth operations, various methods of wax mitigation and control have been developed. Methods for inhibiting wax buildup include physical techniques such as preheating pipelines (Haj-Shafiei et al. 2014; Srivastava et al. 1992; Cao et al. 2022; Yang et al. 2022), applying internal pipeline coatings (Lei et al. 2023; Li et al. 2020; Yang et al. 2021; Goncalves et al. 2004; Bingfan et al. 2019), using heated transportation (Liu et al. 2022; Bingfan et al. 2019) and dilution methods (Tang et al. 2022). Chemical approaches include adding coagulants (Soedarmo et al. 2017; Taheri-Shakib et al. 2018; Akinyemi et al. 2016) and drag-reducing agents (Akinyemi et al. 2018; Deka et al. 2020). However, both predictive models and inhibitors face limitations in universal application due to variations in crude oil composition, flow conditions, and fluid properties across different regions. Pigging, though effective at removing wax deposits, can cause operational disruptions and is costly in deepwater or long-distance pipelines (Singh et al. 2000). Heating pipelines is energy-intensive and environmentally unsustainable. Chemical inhibitors, while commonly used, pose significant environmental risks due to their non-biodegradable nature. Furthermore, the continuous use of chemical inhibitors increases operational costs, making this approach less attractive for long-term solutions (Lee 2008).

A comprehensive wax management strategy typically involves a combination of these methods, depending on the specific characteristics of the crude oil, pipeline conditions, and environmental factors. The high cost and environmental impact of conventional wax inhibition methods have prompted a search for more sustainable alternatives. One promising solution is the use of natural, biodegradable wax inhibitors derived from locally available plant materials. Natural inhibitors can potentially reduce the environmental footprint and provide a cost-effective means of addressing wax deposition. For example, plant-based materials like fatty acids and essential oils have shown promise in altering the crystallization behaviour of waxes, preventing their agglomeration, and reducing deposition on pipeline walls (Alpandi et al. 2022).

In this study, the use of locally sourced natural inhibitors, such as Moringa oleifera (Moringa) seed extracts and lime extracts, has emerged as a potentially viable solution. Moringa seeds are rich in bioactive compounds, such as fatty acids and proteins, that exhibit surfactant and dispersant properties (Chis et al. 2024). Lime, on the other hand, contains citric acid and essential oils that can modify the surface properties of wax crystals, preventing their adhesion to pipeline walls (Cruz-valenzuela et al. 2015). Despite their potential, there is a notable lack of comprehensive research evaluating the effectiveness of these natural inhibitors in real-world pipeline conditions, particularly in regions like the Niger Delta, where wax deposition is a recurring issue. The primary problem addressed in this study is the lack of environmentally sustainable and cost-effective methods for controlling wax deposition in crude oil pipelines. Given the environmental impact and economic burden associated with conventional wax inhibitors, there is an urgent need for alternative solutions that are both effective and eco-friendly. While natural inhibitors like Moringa seed and lime extracts hold potential, their application in the oil and gas industry has not been extensively studied, and their effectiveness compared to conventional methods remains unclear.

Materials And Method

Materials. **Table 1** outlines the materials used in the study and their specific functions. Crude oil serves as the primary subject of the research, providing the medium for wax deposition and inhibition tests. Xylene is employed as a solvent for dissolving and extracting wax components from crude oil samples, enabling further analysis. Filter paper is used to separate solid impurities from extracted oils during the Soxhlet extraction process. Ice blocks are essential for maintaining low temperatures in wax deposition experiments, simulating sub-ambient conditions commonly encountered in offshore environments. Finally, wax inhibitors, which include locally sourced and conventional options, function as surfactants to mitigate wax deposition in crude oil pipelines. **Figure 1** illustrates Xylene, a conventional chemical solvent widely used in wax inhibition studies, known for its effectiveness in dissolving and extracting waxes from crude oil samples. These materials represent the core components used in this study to evaluate the performance of locally sourced and conventional wax inhibitors.

Table 1—Materials used and their functions.

S/N	Materials	Functions
1	Crude Oil	The primary subject of the study.
2	Xylene	Serves as a solvent for dissolving and extracting wax from crude oil samples.
3	Filter Paper	Used to filter out solid particles and impurities while extracting the oil in the Soxhlet Extractor.
4	Ice-block	Utilized to maintain low temperatures in the wax deposition experiments.
5	Wax Inhibitors	Acts as surfactant to prevent or reduce wax deposition.

Figure 1—Xylene.

Table 2 categorizes the wax inhibitors used in the study into locally sourced and conventional types. The locally sourced inhibitors include lemon extract and moringa extract, both of which are bio-based alternatives investigated for their wax inhibition performance. The conventional inhibitor used is xylene (XY), a widely recognized industrial solvent for wax control. This classification highlights the comparative focus of the study on evaluating the effectiveness of wax inhibitors.

Table 2—Wax inhibitors.

S/N	Locally Sourced Inhibitor	Convention Inhibitor
1	Lemon Extract	Xylene (XY)
2	Moringa Extract	

Figure 2(a) depicts Grinded Moringa seed, which was prepared by cleaning, drying, and grinding the seeds into a fine powder to maximize the surface area for efficient extraction of bioactive compounds. **Figure 1(b)** shows Lemon Peel, which was similarly processed by peeling, air-drying, and grinding to obtain a powdered form suitable for extraction.

(a)Grinded Moringa seed

(b)Lemon peel

Figure 2—Locally sourced inhibitors.

Equipment. In this study, equipment used are as follows.

1. Soxhlet Extractor: A laboratory apparatus designed for the continuous extraction of a specific compound from a solid material. The Soxhlet extractor is commonly used in oil analysis and other chemical extractions, utilizing a solvent that is heated, condensed, and cycled through the sample to maximize extraction efficiency (**Figure 3**).

Figure 3—Soxhlet extraction apparatus.

2. Dry Water-Bath: A temperature-controlled laboratory instrument used for heating samples uniformly. It provides precise heating without direct contact with liquids, making it ideal for processes such as incubation, digestion, or chemical reactions.
3. Standing Clamp: A versatile support tool used in laboratory setups to hold equipment like glassware, thermometers, or tubing securely in place during experiments. It is essential for ensuring stability and safety in experimental procedures.
4. Thermometer: An instrument used to measure temperature accurately in laboratory experiments. It is particularly critical for monitoring and maintaining precise temperature conditions during chemical processes or sample testing.
5. Rotary Evaporator: A sophisticated device used to remove solvents from samples through evaporation under reduced pressure. It is widely used in the concentration of solutions, solvent recovery, and sample purification in chemical and oil-related studies (**Figure 4**).

Figure 4—Rotary evaporator.

6. Pour Point/Cloud Point Base: A specialized instrument used to determine the pour point (the lowest temperature at which a liquid can flow) and cloud point (the temperature at which wax crystals first appear in oil). These parameters are crucial for assessing the flow properties of crude oil and petroleum products at low temperatures.
7. Hydrometer: A device used to measure the specific gravity (density) of liquids. In petroleum studies, it is commonly employed to determine the density of crude oil or other petroleum-derived fluids, aiding in quality control and classification.
8. Tubes: General-purpose laboratory tubes used for holding, mixing, or heating samples. They are essential for conducting small-scale chemical reactions, sample storage, or analysis in controlled environments.

Sourcing of Materials. The moringa seeds and lemons used in this study were procured from a local market in Owerri, Imo State, ensuring accessibility and cost-effectiveness of the natural materials. The conventional inhibitor, used as a comparison in this study, was obtained from an industrial chemical store also located in Owerri, Imo State. This local sourcing approach aligns with the goal of exploring readily available and sustainable materials for enhanced oil recovery applications.

Extraction Process for Local Inhibitor. The extraction of bioactive compounds from natural sources, such as lemon peels and moringa seeds, for use as wax inhibitors requires an efficient and effective method. The Soxhlet extraction technique is a widely adopted process for isolating oils and other soluble compounds from plant materials due to its ability to maximize extraction efficiency. The procedure is outlined as follows:

Preparation of Plant Material. For the lemon extract, fresh lemons were peeled, and the peels were air-dried to eliminate residual moisture. For the moringa extract (Figure 6), seeds were carefully removed from the pods and cleaned to ensure the absence of debris or contaminants. Once dried, the lemon peels and moringa seeds were ground into a fine powder using a blender. This step increases the surface area of the plant material, facilitating more efficient extraction.

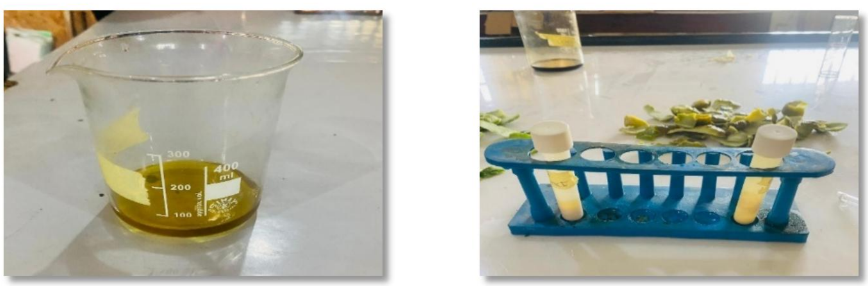
Loading Soxhlet Extractor. The ground plant material (lemon peels or moringa seeds) was placed into a thimble, which serves as a porous solid filter. The thimble ensures that the plant material remains contained while allowing the solvent to flow through. The thimble was then securely positioned in the main chamber of the Soxhlet extractor.

Solvent Addition. Hexane (250 mL) was measured and poured into a round-bottom flask, which acts as the solvent reservoir. The round-bottom flask was then carefully attached to the base of the Soxhlet extractor.

Assembly the Soxhlet Extraction Apparatus. The Soxhlet apparatus was assembled by connecting the Soxhlet extractor to a condenser at the top and the round-bottom flask containing the solvent at the bottom. The condenser was connected to a cold-water source to ensure continuous cooling and condensation of the solvent vapor during the extraction process. This setup allows the solvent to circulate through the plant material in a repetitive cycle, optimizing the extraction of bioactive compounds.

Heating and Extraction. The extraction process begins with the assembly of the Soxhlet apparatus on a water bath. The round-bottom flask containing the solvent is heated, typically to a temperature range of 60-70°C. As the solvent heats, it vaporizes and rises into the condenser at the top of the apparatus. In the condenser, the vapor cools and condenses into liquid form, dripping back onto the plant material contained within the thimble. The condensed solvent percolates through the plant material, extracting the bioactive compounds in the process. Once the solvent becomes saturated with the extracted compounds, it flows back into the round-bottom flask through the siphon arm, completing one full extraction cycle. This cyclical process ensures efficient and continuous extraction of the desired bioactive components from the plant material.

Continuous Extraction Process. The process of continuous extraction involves the Soxhlet extractor cycling the solvent through the plant material repeatedly over several hours. During this process, the bioactive compounds are gradually extracted, and the color of the solvent in the thimble fades. When the solvent becomes colorless, it indicates that the extraction is complete. To recover the extracted oil, a distillation apparatus is employed to separate the oil from the hexane solvent. The solvent-oil mixture is heated in the round-bottom flask, causing the hexane to evaporate due to its lower boiling point. The evaporated hexane is condensed and collected in a separate container for reuse in future extractions, ensuring minimal waste. The remaining oil, either moringa seed oil or lemon extract (**Figure 5**), is retained in the flask as the final product. This method ensures an efficient and sustainable approach to extracting bioactive compounds.



(a) Moringa Extract (b)Lemon Extract

Figure 5—Extraction product of local inhibitor.

Method

The method utilized for the study includes sample characterization, crude oil properties analysis and wax appearance evaluation.

Sample Characterization. Fourier Transform Infrared (FTIR) Spectroscopy is a powerful analytical technique used to identify functional groups and characterize the molecular composition of organic materials. In this study, FTIR is employed to characterize both lemon extract and moringa seed oil, focusing on identifying specific bioactive compounds that contribute to their potential as wax inhibitors in crude oil pipelines. Both extracts are prepared in their pure form for FTIR analysis, ensuring that they are devoid of any impurities or remaining solvent that could interfere with the characterization process. The FTIR spectra are recorded over the wavenumber range of 4000 cm^{-1} to 400 cm^{-1}, covering the range where most functional groups show characteristic absorption peaks.

Crude Oil Properties Analysis. Physiochemical analysis was carried out on the crude oil utilized for this study. The physiochemical properties analysed includes specific gravity, API gravity and viscosity.

Specific Gravity. Specific gravity (SG) is defined as the ratio of the density of crude oil to that of water, which serves as a universal reference. The procedure for determining the SG of crude oil is as follows:

1. A 250 mL sample of crude oil was poured into a clean, dry measuring cylinder.
2. A hydrometer, calibrated for the specific SG range of the crude oil, was gently placed into the measuring cylinder and allowed to stabilize for 10 minutes to ensure accurate reading.
3. As the hydrometer floated, the principle of buoyancy came into effect, generating an upward force that lifted the hydrometer to a specific level corresponding to the SG of the crude oil.
4. The SG was determined by reading the value indicated on the graduated scale of the hydrometer at the point where it intersected the liquid surface.
5. The temperature of the crude oil in the measuring cylinder was subsequently measured and recorded, as temperature variations can affect the SG reading.

This procedure ensures accurate determination of the specific gravity, a critical parameter for characterizing crude oil properties in petroleum engineering applications.

API Gravity. API Gravity is a globally recognized standard for classifying and characterizing crude oil based on its density. It is calculated using the following formula:

$$API^{o}(T) = \frac{141.5}{SG^{@}(T)} - 131.5, \quad (1)$$

where SG is the specific gravity of the crude oil, determined at 60°F. This dimensionless parameter provides a measure of the oil's density relative to water. Crude oils with higher API gravity are lighter and generally considered of higher quality, as they typically yield more valuable products such as gasoline and diesel during refining. Conversely, lower API gravity indicates heavier crude, which is denser and requires more complex processing. API gravity is a critical property used in the petroleum industry for reservoir evaluation, refining processes, and transportation planning.

Viscosity. Viscosity, a key property of crude oil, defines its resistance to flow or deformation under applied stress. To measure the viscosity of crude oil, a capillary tube viscometer (Ostwald's Viscometer) was employed, following the steps outlined below:

1. Crude oil was carefully introduced into Ostwald's Viscometer until the specified graduation level was reached.
2. The efflux time was recorded by measuring the average time required for the oil to flow between two designated graduations in the capillary tube.
3. The kinematic viscosity of the crude oil was calculated by multiplying the measured efflux time by the capillary constant specific to the viscometer.
4. The dynamic (or absolute) viscosity was then determined by multiplying the kinematic viscosity by the crude oil's density.

This procedure provides an accurate assessment of both kinematic and dynamic viscosity, which are critical parameters for understanding the flow behavior of crude oil in reservoirs, pipelines, and processing facilities.

Wax Appearance Test. The effectiveness of both locally formulated and conventional wax inhibitors in preventing wax formation was evaluated through cloud point and pour point tests. These tests determine the temperature at which the first wax crystals (cloud point) appear and the temperature at which crude oil ceases to flow (pour point). These parameters are crucial for simulating offshore conditions where temperatures can drop below ambient, potentially causing wax deposition.

Table 3 presents the inhibitor formulations used in this study, detailing the ratios of inhibitor to crude oil (ml) for three types of wax inhibitors: Xylene (XY), Moringa Seed Extract (MSE), and Lemon Peel Extract (LPE). Each inhibitor was prepared at varying concentrations, with ratios ranging from 1:50 to 9:50, representing the volume of inhibitor relative to crude oil. These formulations were used to evaluate the effectiveness of each inhibitor in reducing wax deposition under controlled experimental conditions. This systematic approach ensures a comprehensive comparison of conventional and bio-based inhibitors in terms of performance and efficiency.

Table 3—Inhibitor formulation

S/N	Inhibitors	Inhibitor: Crude Oil (ml)				
1	Xylene (XY)	1:50	3:50	5:50	7:50	9:50
2	Moringa Seed Extract (MSE)	1:50	3:50	5:50	7:50	9:50
3	Lemon Peel Extract (LPE)	1:50	3:50	5:50	7:50	9:50

The experimental procedure is outlined as follows:

1. Ice blocks were placed in the chamber of the pour and cloud point apparatus to create a controlled cooling environment.
2. Six test tubes, each containing 50 mL of crude oil, were prepared.
3. Inhibitor formulations, as specified in Table 3, were added to five test tubes, while one test tube was left as a control without any inhibitors.
4. A thermometer was inserted into each test tube through a wooden cork, which was securely fastened to ensure isolation from room temperature.
5. The sealed test tubes were placed in the cooling chamber of the pour and cloud point apparatus. Observations were made every three minutes to identify the cloud point (appearance of wax crystals) and the pour point (when the oil ceases to flow).
6. The wax inhibition performance of each inhibitor was calculated using a standard formula to quantify the effectiveness of the formulations in reducing wax formation.

$$\%\text{Wax Temperature Reduced} = \frac{\text{Pour Point}_{\text{Control crude}} - \text{Pour Point}_{\text{Inhibited crude}}}{\text{Pour Point}_{\text{Control Crude}}}, \quad (2)$$

7. The procedure was repeated for each of the wax inhibitors.

This methodology provides a reliable evaluation of wax inhibitors under controlled conditions, offering insights into their suitability for preventing wax deposition in crude oil under low-temperature environments.

Result And Discussion

The presented results offer an extensive analysis of the FTIR characterization, physicochemical properties of the crude oil sample, and the performance of locally formulated and conventional inhibitors in reducing wax formation through pour and cloud point tests. Each aspect of the data provides insights into the effectiveness of the inhibitors and highlights key molecular and physical characteristics that influence wax deposition tendencies in crude oil.

FTIR Characterization. The FTIR spectra for Xylene (XY), Moringa Seed Extract (MSE), and Lemon Extract reveal critical functional groups responsible for the effectiveness of these compounds as wax inhibitors. Functional group analysis is essential to understand the interactions between the inhibitors and the wax constituents in crude oil.

Sample A. **Table 4** presents the FTIR spectra interpretation for Sample A (XY), highlighting key functional groups and associated chemical compounds identified at specific wavelengths. This analysis provides critical insights into the molecular structure of the sample, which is essential for understanding its chemical properties and potential applications. Each functional group corresponds to characteristic absorbance bands, indicating the presence of compounds such as alkyl halides, aromatics, carboxylic acids, and primary amines, among others.

The table further illustrates the diversity of functional groups, including hydroxyl (O-H), carbonyl (C=O), and amine (N-H) groups, which are significant in determining the reactivity and behavior of the sample under various conditions. These findings establish a foundation for further analysis and practical applications of the sample.

Xylene showed a diverse range of peaks, indicating the presence of functional groups such as alkyl halides (C-CL), aromatic compounds (C-H, C-C stretches), amines (N-H stretches), anhydrides (C=O stretch), thiocyanates (N=C=S stretch), carbon dioxide (O=C=O), and alcohols (O-H stretches) as seen in **Figure 8**. These functional groups are characteristic of xylene, which has notable solvent properties, enabling it to dissolve wax components effectively.

Table 4—FTIR spectra interpretation for Sample A (XY).

Wavelength	Functional Group	Compounds
777.8818	C-CL	Alkyl Halides
852.4089	C-H	Aromatics
1287.615	C-H (-CH2X)	Alkyl Halides
1415.616	C-C	Aromatics stretch (in ring)
1627.491	N-H	1 Amines Bend
1850.431	C=O	Anhydride Stretch
2017.684	N=C=S	Isothiocyanate Stretch
2171.732	S-C=N	Thiocyanate Stretch
2454.658	O=C=O	Carbon Dioxide Stretch
2529.809	O-H	Carboxylic Acid Stretch
2623.411	O-H	Carboxylic Acid Stretch
2766.342	O-H	Alcohol Stretch
2861.215	C-H	Alkane Stretch
2988.119	N-H	Amine Salt Stretch
3118.272	O-H	Alcohol Stretch
3263.587	N-H	Aliphatic Primary Amines Stretch
3437.153	N-H	Primary Amines Stretch
3479.116	N-H	Primary Amines Stretch

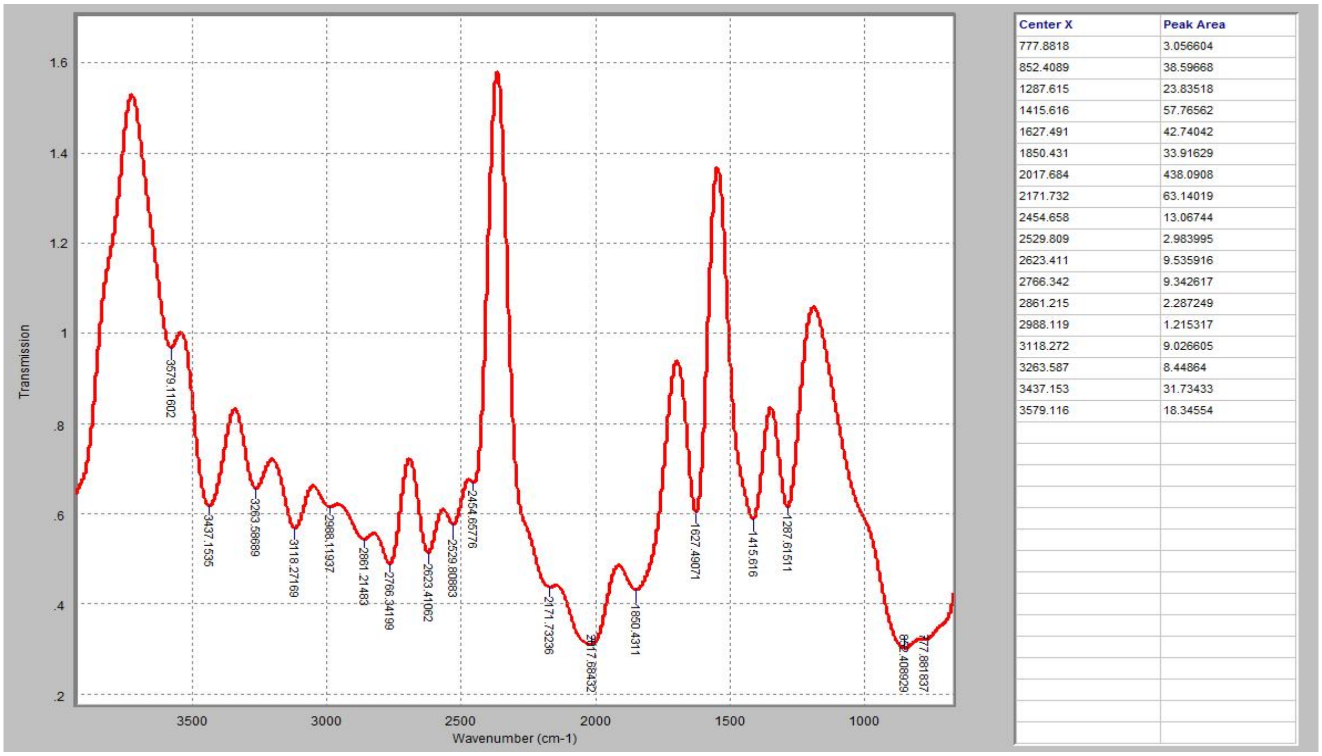


Figure 8—FTIR spectra for sample A (XY)

Sample B. **Table 5** provides a detailed interpretation of the FTIR spectra for Sample B, derived from Moringa Oleifera seed extract. The table identifies key wavelengths corresponding to specific functional groups and their associated chemical vibrations, along with relevant descriptions. Notable findings include the presence of -OH stretching vibrations (ester, alcohol, carboxylic acid, and ether groups) at 3433 cm^{-1} and 3452 cm^{-1}, indicative of the extract's hydroxyl-rich structure. Aromatic stretching vibrations related to bioactive compounds and proteins are observed at 1034 cm^{-1}, while a characteristic absorption band for magnesium oxide (MgO particles) is detected at 442 cm^{-1} and 438 cm^{-1}. These features highlight the chemical complexity and potential bioactivity of the extract.

The accompanying FTIR spectrum (**Figure 9**) visually supports the above findings, showcasing transmittance as a function of frequency (cm^{-1}). Key absorption peaks, such as the broad band near 3420 cm^{-1} corresponding to -OH stretching, aligning with the data in the table. Peaks at 3433 cm^{-1} and 3452 cm^{-1} indicate ester, alcohol, carboxylic acid, and ether groups, which provides polar functional sites capable of interacting with wax molecules. The presence of bioactive compounds and proteins, as seen in the aromatic stretching at 1034 cm^{-1}, contributes to MSE's ability to act as a stabilizing agent for wax particles, effectively reducing wax aggregation. Additional peaks, including those at 2923 cm^{-1} and 2852 cm^{-1}, represent C-H stretching vibrations, while the peaks near 1600-1800 cm^{-1} are associated with carbonyl (C=O) stretching vibrations, signifying esters or carboxylic acids. The smaller peaks at lower frequencies confirm the presence of bioactive aromatic compounds and metal oxides.

Together, Table 5 and Figure 9 provide complementary insights into the functional groups and chemical constituents of the Moringa Oleifera seed extract, validating its potential application as a bio-based inhibitor in industrial processes. This detailed characterization lays the groundwork for further analysis of its efficacy and performance in practical scenarios.

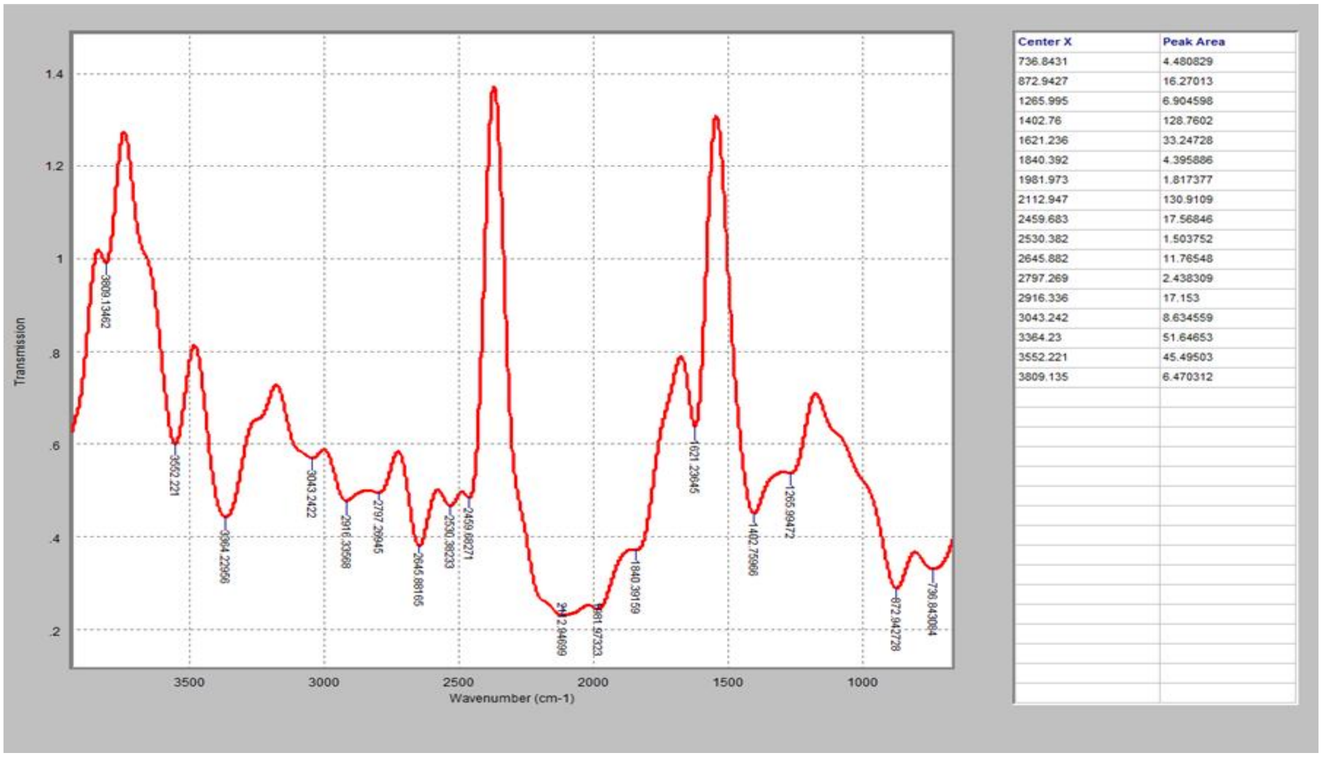


Figure 9—FTIR spectra for Sample B (Moringa Oleifera Seed).

Table 5—FTIR spectra interpretation for Sample B (Moringa Oleifera Seed).

Wavelength	Functional Group	Description
3433 cm^{-1} and 3452 cm^{-1}	–OH stretching vibrations (ester, alcohol, carboxylic acid, ether groups)	These peaks correspond to –OH stretching, indicating the presence of ester, alcohol, carboxylic acid, and ether groups.
1636 cm^{-1}	–OH bending vibration	Attributed to the bending vibration of the hydroxyl group.
1034 cm^{-1}	Aromatic stretching (bioactive compounds and proteins)	Related to the aromatic stretching of bioactive compounds and proteins.
442 cm^{-1} and 438 cm^{-1}	Metal oxide characteristic absorption band (MgO particle)	Assigned to the stretching mode of magnesium oxide (MgO).

Sample C. **Table 6** provides a detailed analysis of the functional groups identified in Sample C, derived from Lemon Extract, using FTIR spectroscopy. Each row in the table lists the wavelength (in cm^{-1}), corresponding bond type, and functional group detected. Key findings include the presence of hydroxyl (-OH) groups associated with alcohols and phenols at 395.31 cm^{-1}, C-H stretches indicating alkanes at 2931.80 cm^{-1} and 2862.36 cm^{-1}, and C≡C stretching vibrations suggesting alkynes at 2222.00 cm^{-1}. Additional functional groups, such as carbonyl (C=O) indicative of α, β-unsaturated esters, and C-N stretches denoting aliphatic amines, were also identified. These results confirm the diverse chemical composition of the lemon extract, which may contribute to its wax inhibition properties.

Table 6—Functional groups present in Sample C (Lemon).

Wavelength (cm⁻¹)	Bond	Functional Group
395.31 (s, sh)	O-H stretch, H-bonded	Alcohols, Phenols
2931.80 (m)	C-H stretch	Alkanes
2862.36 (m)	C-H stretch	Alkanes
2222.00 (w)	C=C stretch	Alkynes
1728.22 (s)	C=O stretch	A, β-unsaturated ester
1319.31 (s)	C-O stretch	Alcohols, carboxylic acid, esters
1242.16 (s)	C-N stretch	Aliphatic amines
1149.57 (m)	C-H wag ($-CH_2X$)	Alkyl halides
1095.57 (m)	C-N stretch	Aliphatic amines
1056.99 (m)	C-N stretch	Aliphatic amines
1026.13 (m)	C-N stretch	Aliphatic amines
804.97 (m)	C-Cl stretch	Alkyl halides
840.98 (m)	C-Cl stretch	Alkyl halides

Figure 10 complements Table 6 by presenting the FTIR spectra for Sample C in graphical form. The spectrum illustrates transmittance as a function of frequency (wavenumber, cm^{-1}), visually depicting the absorbance peaks corresponding to the functional groups detailed in Table 6. Prominent peaks, such as those near 395 cm^{-1}, 2931 cm^{-1}, and 1728 cm^{-1}, align with the chemical bonds identified in the table. The spectrum also highlights minor peaks representing aliphatic amines and alkyl halides, reinforcing the complexity and multi-functionality of the extract.

Both Table 6 and Figure 10 provide a comprehensive chemical profile of the Lemon Extract, emphasizing its potential as a bio-based alternative to traditional wax inhibitors in the petroleum industry. These functional groups indicate a composition rich in organic acids and alcohols, providing both polar and non-polar functionalities that can interact with and inhibit wax crystallization. The FTIR spectra demonstrate that each inhibitor possesses unique functional groups that enable different modes of interaction with wax molecules in crude oil, hence affecting the efficiency of wax inhibition. This characterization serves as a foundation for further exploration of its performance in pipeline flow assurance applications.

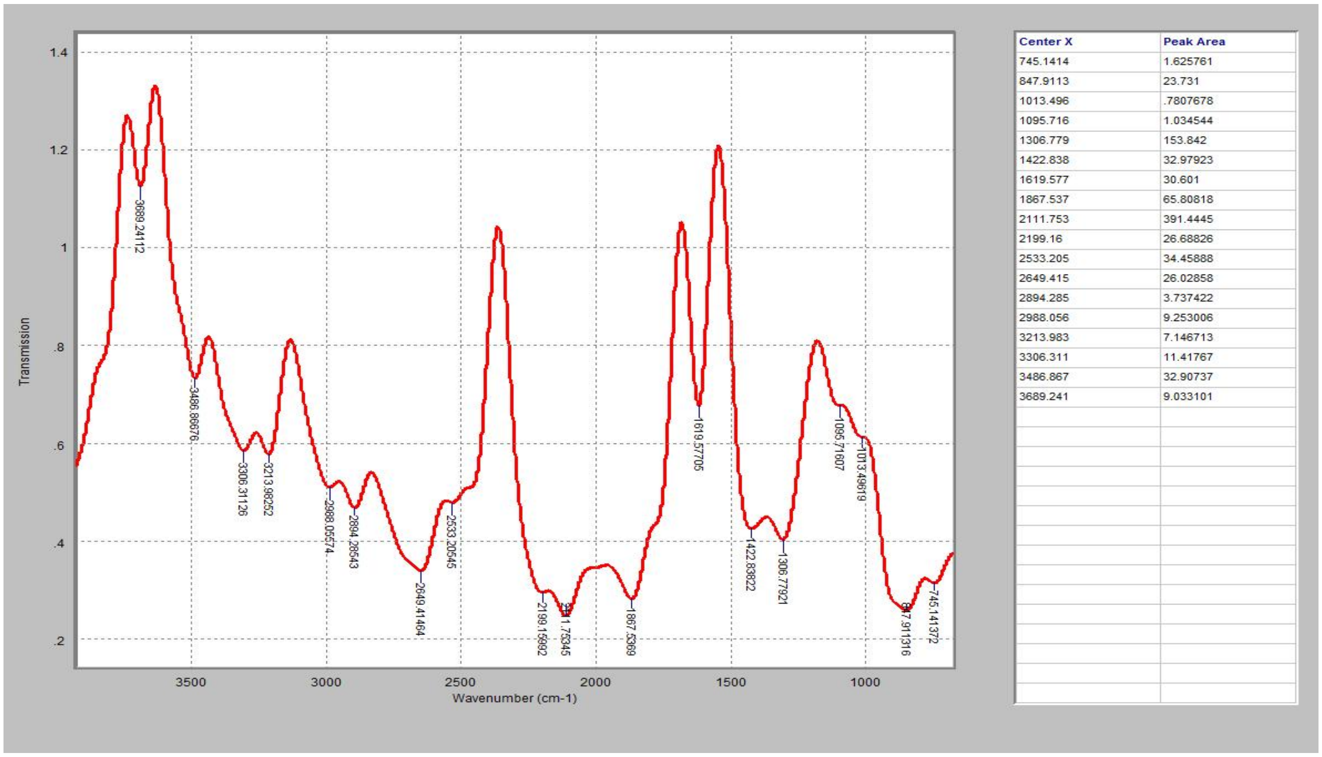


Figure 10—FTIR spectra for Sample C (Lemon).

Properties of the Crude Oil. **Table 7** outlines the specific gravity, API gravity, kinematic viscosity, and dynamic viscosity of the crude oil used in this study. With a specific gravity of 0.860 and API gravity of 33.035, the crude is classified as a light crude oil. Light crude oils typically have lower viscosity and lower wax content, but they are still prone to wax precipitation at low temperatures.

Kinematic viscosity was measured at 8.14 cP, and dynamic viscosity was 7.01 cP. These values indicate that the crude oil has relatively low resistance to flow, consistent with its classification as a light crude. This viscosity data provides a baseline for assessing the performance of wax inhibitors by understanding how much the inhibitors can reduce flow resistance by preventing wax deposition.

Table 7—Physicochemical analysis of the crude oil.

S/N	Specific Gravity	API Gravity	Crude Type	Kinematic Viscosity, cP	Dynamic Viscosity, cP
1	0.860	33.035	Light Crude	8.14	7.01

Pour and Cloud Point. The cloud and pour point data obtained for the control and treated samples with varying concentrations of inhibitors illustrate the temperature-dependent wax inhibition performance. The control sample (no inhibitor) reached the cloud point (CP) at 27°C and the pour point (PP) at 24°C (**Table 8** and **Figure 12**). This indicates the onset of wax precipitation and solidification under cooling conditions, which can lead to pipeline blockages in the absence of inhibitors.

Table 8—Temperature vs time for control.

Time (mins)	Temperature (^oC)
3	30
6	29
9	28
12	27 (CP)
15	26
18	24 (PP)
21	-

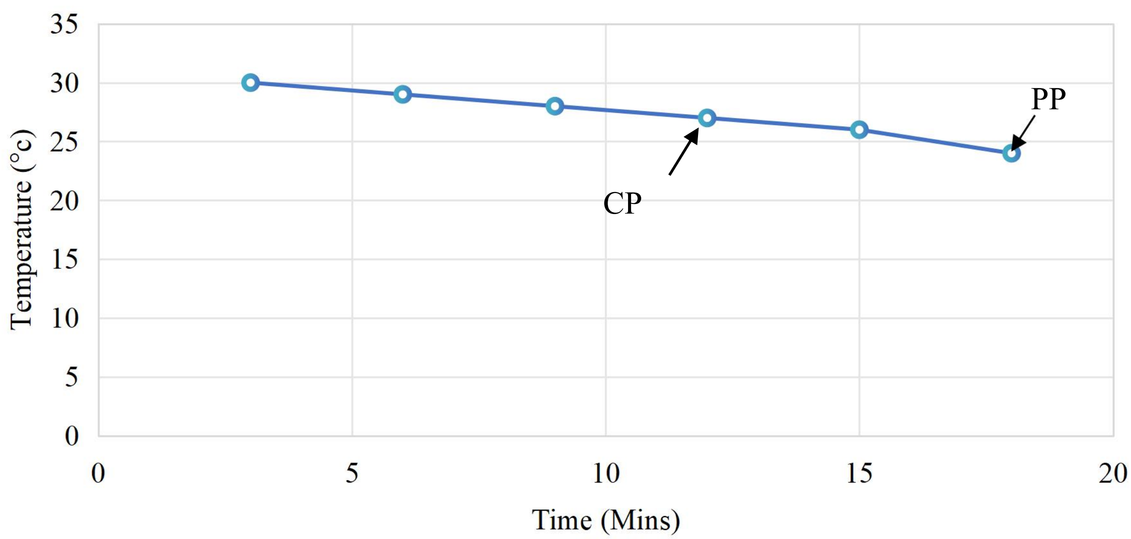


Figure 12—Temperature vs time for control.

Sample A. As shown in **Table 9** and **Figure 13**, Xylene was effective at delaying the cloud and pour points across concentrations. At 1 ml XY, the cloud point was delayed to 26 °C, and the pour point to 23 °C. Higher concentrations of Xylene (5 ml to 9 ml) further delayed the pour point to below 20^{o}C. This demonstrates Xylene's effectiveness as a conventional inhibitor, given its high solvent power, which dissolves wax crystals and reduces wax deposition. However, at higher concentrations, the inhibition effect tends to stabilize, suggesting an optimal concentration beyond which no further benefits are observed.

Table 9—Temperature vs Time for Sample A (XY).

Time	Control	1ml of XY	3ml of XY	5ml of XY	7ml of XY	9ml of XY
3	29	29	29	29	29	29
6	29	29	29	29	29	29
9	28	29	28	29	29	29
12	27 (CP)	28	28	28	29	28
15	26	27	26	27	28	28
18	24 (PP)	26 (CP)	25 (CP)	26	28	28
21	-	24	24 (PP)	24 (CP)	27	27
24	-	23 (PP)	-	21 (PP)	25	25
27	-	-	-	-	23 (CP)	24
30	-	-	-	-	22	22 (CP)
33	-	-	-	-	22	21
36	-	-	-	-	21	20
39	-	-	-	-	20 (PP)	20
42	-	-	-	-	-	19 (PP)
45	-	-	-	-	-	-

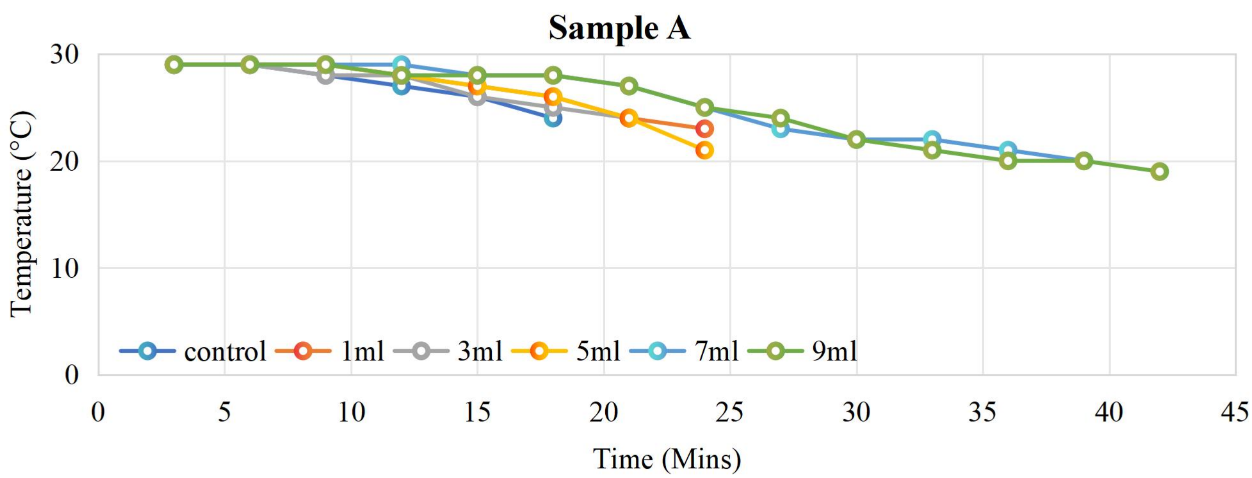


Figure 13—Temperature vs time for Sample A.

Sample B. **Table 10** and **Figure 14** indicate MSE's effectiveness at various concentrations. At 1 ml MSE, the cloud point was reduced to 23°C, with the pour point dropping to 20°C. Higher concentrations (5 ml to 9 ml) further decreased the pour point to around 18°C. The presence of bioactive compounds and proteins in MSE aids in dispersing wax crystals and reducing their tendency to aggregate. MSE's natural composition provides eco-friendly advantages, while its molecular composition effectively inhibits wax formation at higher concentrations.

Table 10—Temperature vs time for Sample B (Moringa Seed Extract).

Time	Control	1ml of MSE	3ml of MSE	5ml of MSE	7ml of MSE	9ml of MSE
3	29	28	28	29	29	29
6	29	28	28	29	29	29
9	28	27	28	28	29	29
12	27 (CP)	27	27	27	28	29
15	26	26	27	27	28	28
18	24 (PP)	25	26	26	27	28
21	-	24	25	25	26	27
24	-	23 (CP)	24	24	26	27
27	-	21	23	23	25	26
30	-	20 (PP)	22 (CP)	22 (CP)	24	25
33	-	-	21	21	23	25
36	-	-	20	20	22	24
39	-	-	19 (PP)	18(PP)	21 (CP)	22
42	-	-	-	-	20	21
45	-	-	-	-	19	20 (CP)
48					18 (PP)	19
51						19
54						18
57						17 (CP)
60						-

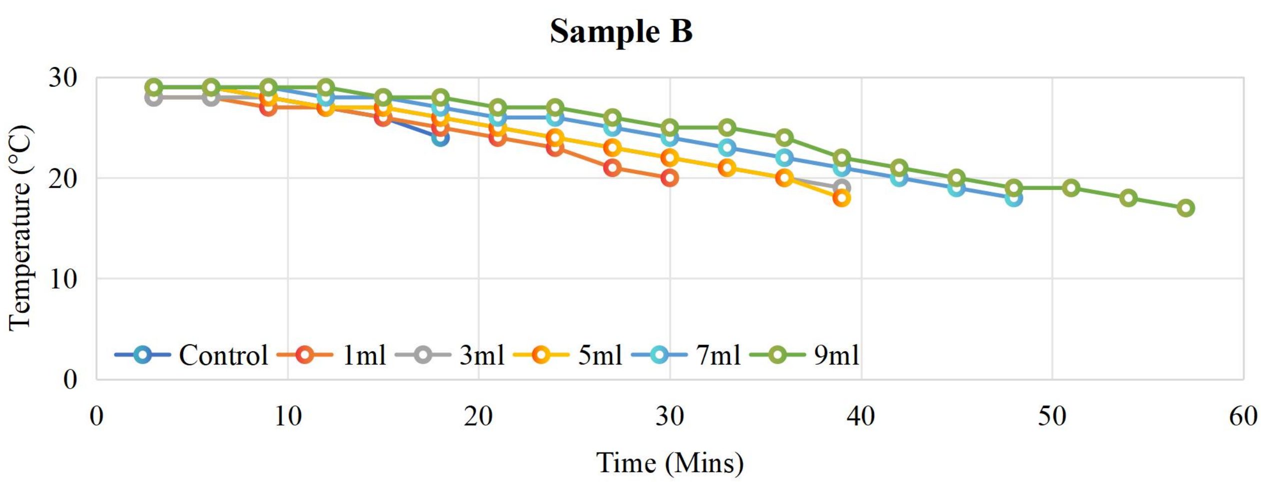


Figure 14—Temperature vs time for Sample B.

Sample C. As seen in **Table 11** and **Figure 15**, Lemon Extract performed similarly to MSE. The cloud point and pour point were significantly reduced with increasing inhibitor concentration. At 3 ml Lemon Extract, the cloud point reached 23°C, with a pour point of 22°C, while 7 ml Lemon Extract reduced the pour point to 18°C. Lemon Extract's organic acids and alcohols interact with wax molecules to disrupt crystallization processes, confirming its potential as an environmentally friendly wax inhibitor.

Table 11—Temperature vs Time for Sample C (Lemon Extract)

Time	Control	1ml of XY	3ml of XY	5ml of XY	7ml of XY	9ml of XY
3	29	28	28	28	28	28
6	29	28	28	28	28	28
9	28	27	27	27	28	28
12	27 (CP)	27	27	27	27	27
15	26	26	27	27	27	27
18	24 (PP)	25	26	26	27	27
21	-	24 (CP)	25	25	26	26
24	-	23 (PP)	24 (CP)	24 (CP)	25	25
27	-	-	23 (PP)	23 (PP)	24	24
30	-	-	-	-	23 (CP)	23 (CP)
33	-	-	-	-	22 (PP)	22 (PP)
36	-	-	-	-	-	-
39	-	-	-	-	-	-
42	-	-	-	-	-	-
45	-	-	-	-	-	-

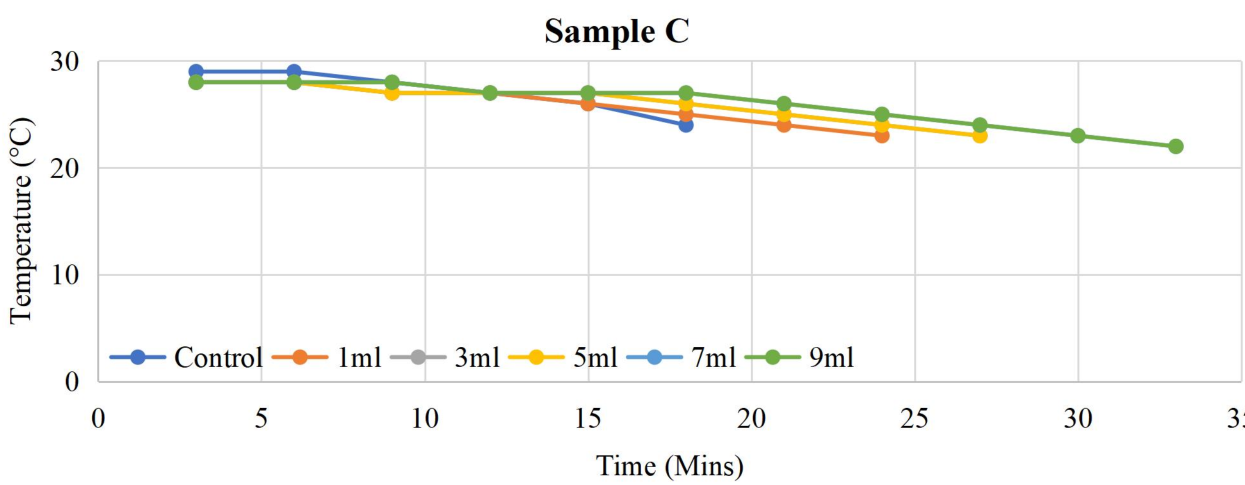


Figure 15—Temperature vs time for Sample C.

Conclusion

This study demonstrates the potential of locally sourced wax inhibitors, such as Moringa Seed Extract and Lemon Extract, in reducing wax deposition in crude oil, with comparable efficacy to conventional inhibitors like Xylene. Both MSE and Lemon Extract offer an environmentally sustainable solution for mitigating wax formation in crude oil, which is essential for operational efficiency in offshore and cold-weather oil production environments. These findings could drive further research into bio-based wax inhibitors, with a focus on optimizing concentrations and improving the environmental profile of crude oil transport and production processes.

Conflicting Interests

The author(s) declare that they have no conflicting interests.

References

Akinyemi, O. P., Udonne, J. D., and Oyedeko, K. F. 2018. Study of Effects of Blend of Plant Seed Oils on Wax Deposition Tendencies of Nigerian Waxy Crude Oil. *J. Pet. Sci. Eng.* **161**(1):551-558.

Akinyemi, O. P., Udonne, J. D., Efeovbokhan, V. E., et al. 201). A Study on the Use of Plant Seed Oils, Triethanolamine and Xylene as Flow Improvers of Nigerian Waxy Crude Oil. *J. Appl. Res. Technol.* **14**(1): 195-205.

Alpandi, A. H., Husin, H., Jeffri, S. I., et al. 2022. Investigation on Wax Deposition Reduction Using Natural Plant-Based Additives for Sustainable Energy Production from Penara Oilfield Malaysia Basin. ACS Omega 7(35): 30730-30745.

Bingfan, L., Gang, L., Xiao, X., et al. 2019. Molecular dynamics simulation of CO2 dissolution in heavy oil resin-asphaltene. *Journal of CO_2 Utilization* **33**(1): 303-310.

Chis, A., Noubissi, P. A., Pop, O. L., et al. 2024. Bioactive Compounds in Moringa oleifera: Mechanisms of Action, Focus on Their Anti-Inflammatory Properties. *Plants* **13**(1): 20-35.

Cruz-Valenzuela, M. R., Tapia-Rodríguez, M. R., Vazquez-Armenta, F. J., et al. 2016. Lime (Citrus aurantifolia) Oils. Essential Oils in Food Preservation. *Flavor and Safety* **16**(2): 531-537.

Deka, B., Sharma, R., and Mahto, V. 2020. Synthesis and Performance Evaluation of Poly (Fatty Esters-Co-Succinic Anhydride) as Pour Point Depressants for Waxy Crude Oils. *J. Pet. Sci. Eng.* **191**(1): 107153.

Yang, F., Zhu, H., Li, C., et al. 2021. Investigation on the Mechanism of Wax Deposition Inhibition Induced by Asphaltenes and Wax Inhibitors. *Journal of Petroleum Science and Engineering* **204**(1): 108723.

Goncalves, S., Castillo, J., Fernández, A., et al. 2004. Absorbance and Fluorescence Spectroscopy on the Aggregation Behavior of Asphaltene–Toluene Solutions. *Fuel* **83**(13):1823-1828.

Haj-Shafiei, S., Serafini, D., and Mehrotra, A. K. 2014. A steady-state heat-transfer model for solids deposition from waxy mixtures in a pipeline. Fuel 137(3): 346-359.

Cao., H., Cao, X., Zhao, X., et al. 2022. Molecular Dynamics Simulation of Wax Molecules Aggregational Crystallization Behavior During Cooling of Crude Oil Mixture. *Case Studies in Thermal Engineering* **37**(1): 102298.

Li, H., Zhang, J., Xu, Q., et al. 2020. Influence of Asphaltene on Wax Deposition: Deposition Inhibition and Sloughing. *Fuel* **266**(1):117047

Kiyingi, W., Guo, J., Xiong, R., et al. 2022. Crude oil wax: A review on formation, experimentation, prediction, and remediation techniques, Petroleum Science 19(5):2343-2357.

Lee, H. 2008. Computational and Rheological Study of Wax Deposition and Gelation in Subsea Pipelines. *Engineering, Environmental Science* **12**(1):125-137.

Olajire, A. 2021. Review of wax deposition in subsea oil pipeline systems and mitigation technologies in the petroleum industry. *Chemical Engineering Journal Advances* **6**(1):100104.

Singh, P., Fogler, H. S., and Nagarajan, N. R. 2000. Prediction of the wax content of the crude oil from the solubility curve. *SPE Production & Facilities* **15**(3): 210-217.

Soedarmo, A. A., Daraboina, N. and Sarica, C. 2017. Validation of Wax Deposition Models with Recent Laboratory Scale Flow Loop Experimental Data. *Journal of Petroleum Science and Engineering* **149**(1): 351-366.

Srivastava, S. P., Tandon, R. S., Verma, P. S., et al. 1992. Crystallization Behavior of n-paraffins in Bombay-High Middle-Distillate Wax/gel. *Fuel* **71**(5):533-537.

Taheri-Shakib, J., Shekarifard, A., and Naderi, H. 2018. Characterization of the Wax Precipitation in Iranian Crude Oil Based on Wax Appearance Temperature (WATt): Part 1. The Influence of Electromagnetic Waves. *Journal of Petroleum Science and Engineering* **161**(1): 530-540.

Tang, X., Duan, W., Xu, K., et al. 2022. Three-dimensional Network Gel Structure and Viscosity Reduction Mechanism of Heavy Oil. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **653**(1):130060.

Liu, Y., Huang, Q., Liu, L., et al. 2022. Experimental and Molecular Dynamics Simulation Investigations of Adhesion in Heavy Oil/Water/Pipeline Wall Systems During Cold Transportation. *Energy* **250**(1):123811.

Lei, Y., Wang, H., Li, S., et al. 2023. Effect of Existence State of Asphaltenes on The Asphaltenes-Wax Interaction in Wax Deposition. *Petroleum Science* **20**(1): 507-514.

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