Development and Validation of an Integrated Microbial Wax Mitigation Model for Waxy Crude Oil

Festus S. Friday[1]; Livinus Aniefiok[2]; Nsikak A. Abraham[3]

[1,2]Department of Petroleum Engineering, University of Uyo, Uyo, Nigeria
[3]Department of Microbiology University of Uyo, Uyo, Nigeria

Publication Date: 2026/08/24

Abstract
Wax deposition represents a critical flow assurance challenge in the production and transportation of waxy crude oils, frequently resulting in diminished production efficiency, increased operational expenditures, and potential pipeline occlusion. While various mathematical models have been established to predict wax deposition, conventional frameworks predominantly focus on thermophysical properties and often overlook the impact of microbial biodegradation on wax-forming hydrocarbons. This study developed and validated an Integrated Microbial Wax Mitigation Model (IMWMM), which synthesizes crude oil physicochemical properties, hydrocarbon composition, and microbial biodegradation kinetics into a unified predictive framework to evaluate wax deposition tendencies following microbial intervention. Waxy crude oil samples were subjected to treatment with *Pseudomonas aeruginosa*, *Bacillus subtilis*, and a microbial consortium. Experimental analyses were conducted to determine density, viscosity, molecular weight, and hydrocarbon composition, while Wax Appearance Time (WAT) served as the response parameter to quantify the retardation of wax crystallization. A Wax Deposition Index (WDI) was formulated by integrating density, viscosity, molecular weight, and hydrocarbon fractions. The microbial contribution was incorporated via first-order biodegradation kinetics, and the model was calibrated using an average microbial mitigation coefficient of 0.231 mL^{-1} derived from experimental WAT data. Microbial treatment facilitated reductions in viscosity, density, molecular weight, and heavy hydrocarbon fractions compared to untreated crude oil, thereby lowering the wax deposition indices. The developed IMWMM effectively predicted wax deposition tendencies with a Mean Absolute Percentage Error (MAPE) of 3.87% and an overall predictive accuracy of 96.13%**.** The findings demonstrate that integrating microbial biodegradation kinetics with conventional wax deposition parameters significantly enhances the prediction of microbial wax mitigation performance. The proposed IMWMM offers a robust engineering tool for evaluating biological wax control strategies, optimizing microbial dosage, and supporting sustainable flow assurance management in waxy crude oil pipeline systems.

Keywords: *Flow Assurance; Waxy Crude Oil; Integrated Microbial Wax Mitigation Model; Microbial Treatment; Wax Deposition Index; Wax Induction Time; Mathematical Modelling; GC–MS.*

I. INTRODUCTION

Wax deposition represents one of the most persistent flow assurance challenges encountered during the production, transportation, and storage of waxy crude oils. As crude oil temperatures decrease below the crystallization threshold, long-chain paraffinic hydrocarbons precipitate from the solution, forming wax crystals that subsequently adhere to pipeline walls (Elkatory *et al.*, 2022). The progressive accumulation of these deposits restricts the effective flow area, induces significant pressure losses, elevates pumping power requirements, and may ultimately lead to complete pipeline occlusion. The associated economic consequences encompass production deferment, escalated maintenance expenditures, frequent pigging operations, and unplanned shutdowns of petroleum production facilities.

The tendency of wax formation and deposition in crude oil is governed by several interacting physicochemical factors, including viscosity, density, molecular weight distribution, and hydrocarbon composition (Hamouda and Viken, 1993; Ekeh *et al.*, 2010; Ajienka and Essien, 2018; Friday *et al.*, 2025). Crude oils characterized by high concentrations of long-chain n-paraffins exhibit heightened susceptibility to wax crystallization, as these heavy hydrocarbons readily precipitate upon thermal reduction Theyab and Diaz, 2016).

Consequently, numerous predictive models have been developed to estimate wax deposition behavior based on thermodynamic equilibrium, molecular diffusion, heat transfer, and empirical correlations (Michaud *et al.*, 2004; Banki *et al.*, 2008; Nwachukwu *et al.*, 2016). While these models have advanced the understanding of wax deposition mechanisms, they generally fail to account for biological modifications of crude oil composition resulting from microbial activity.

Microbial treatment has emerged as an environmentally sustainable alternative to conventional chemical wax inhibitors (Etoumi, 2007; Abraham and Essien, 2016). Hydrocarbon-degrading microorganisms synthesize extracellular enzymes and biosurfactants capable of degrading long-chain paraffinic hydrocarbons, reducing interfacial tension, dispersing wax crystals, and modifying the physicochemical properties of crude oil (Abraham and Essien, 2016; Festus *et al.*, 2025). Previous investigations have demonstrated reductions in viscosity, density, molecular weight, and heavy hydrocarbon fractions following microbial treatment (Etoumi, 2007; Adlan *et al.*, 2020) These alterations collectively mitigate the tendency for wax crystallization and enhance crude oil flow characteristics. However, despite the increasing interest in biological wax control, few studies have incorporated microbial biodegradation kinetics into predictive engineering models for wax deposition.

Existing wax deposition models are primarily predicated on conventional thermophysical parameters and, therefore, cannot adequately evaluate the efficacy of microbial treatments. The absence of predictive models that integrate crude oil properties, hydrocarbon compositional alterations, and microbial degradation kinetics represents a significant gap in current flow assurance research. Addressing this limitation necessitates a modeling framework capable of quantitatively relating microbial treatment to changes in wax deposition tendency.

In this study, an Integrated Microbial Wax Mitigation Model (IMWMM) was developed by synthesizing classical wax deposition theory with first-order microbial biodegradation kinetics. The model incorporates crude oil density, viscosity, molecular weight, and hydrocarbon composition, alongside a calibrated microbial mitigation coefficient, to predict the Wax Deposition Index following microbial treatment. Experimental data obtained from *Pseudomonas aeruginosa*, *Bacillus subtilis*, and a microbial consortium were utilized for model calibration and validation.

Distinct from conventional studies that rely on Wax Appearance Temperature (WAT), this investigation employed Wax Appearance Time (WAT)**,** defined as the elapsed time required for the initial observation of wax crystals under controlled laboratory conditions. WAT was selected because it directly quantifies the kinetic delay in wax crystallization resulting from microbial treatment, thereby providing a robust response parameter for evaluating biological wax mitigation.

The novelty of this study resides in the development of a predictive engineering model that explicitly integrates microbial biodegradation kinetics with classical wax deposition parameters within a unified mathematical framework. The proposed Integrated Microbial Wax Mitigation Model (IMWMM) serves as a practical decision-support instrument for predicting microbial wax mitigation efficiency, optimizing treatment dosages, and advancing sustainable flow assurance strategies for waxy crude oil pipeline systems.

II. MATERIALS AND METHODS

- *Crude Oil Sample Collection and Characterization*

Waxy crude oil samples were procured from an onshore production field within the Niger Delta region of Nigeria and transported to the laboratory in airtight containers to mitigate contamination and compositional alterations. Prior to microbial treatment, the crude oil underwent characterization to establish its baseline physicochemical properties. Density was determined in accordance with ASTM D5002, whereas kinematic viscosity was measured following the ASTM D445 protocol. The average molecular weight and hydrocarbon composition were quantified via Gas Chromatography–Mass Spectrometry (GC–MS). These properties served as the fundamental input parameters for the development of the Integrated Microbial Wax Mitigation Model (IMWMM).

- *Isolation and Selection of Hydrocarbon-Degrading Microorganisms*

Hydrocarbon-utilizing bacteria were isolated from waxy crude oil sourced from an oil field in the Niger Delta, utilizing Mineral Salt Medium (MSM) supplemented with crude oil as the primary carbon source (Abraham and Essien, 2016). Pure isolates were identified via standardized microbiological and biochemical protocols. Based upon hydrocarbon degradation efficiency, biosurfactant production, and lipase activity (data already published in Festus *et al.*, 2015; 2026), *Pseudomonas aeruginosa* and *Bacillus subtilis* were selected for investigation. Furthermore, a microbial consortium comprising both isolates was established to evaluate the synergistic effects of mixed cultures on wax mitigation.

- *Microbial Treatment of Crude Oil*

Individual bacterial cultures and the microbial consortium were inoculated into separate crude oil samples at dosages of 1 and 2 mL under controlled laboratory conditions. Untreated crude oil served as the control. Following incubation, all samples were analyzed for alterations in density, viscosity, molecular weight, hydrocarbon composition, and wax crystallization behavior.

➢ *Determination of Wax Appearance Time (WAT)*

Wax Appearance Time (WAT) was employed as the experimental indicator to evaluate the performance of microbial wax mitigation. Distinct from the conventional Wax Appearance Temperature (WAT), this parameter represents the duration elapsed until the initial observation of visible wax crystals under constant laboratory conditions. Approximately 5 mL of untreated and treated crude oil samples were subjected to identical cooling conditions, and the duration required for the onset of visible wax crystallization was recorded using a stopwatch. Higher WAT values signify enhanced resistance to wax crystallization and superior microbial wax mitigation efficacy.

The experimentally measured WAT values were subsequently used to calibrate the microbial mitigation coefficient of the IMWMM.

➢ *Physicochemical and GC–MS Analysis*

The changes in crude oil properties after microbial treatment were assessed through the measurement of density, viscosity, molecular weight, and hydrocarbon composition. Hydrocarbon fractions derived from GC–MS analysis were categorized as follows:

- Light Fraction (LF): C_1–C_{15} hydrocarbons
- Heavy Fraction (HF): C_{16}–C_{30}^+ hydrocarbons

The heavy hydrocarbon-fraction constitutes the primary wax-forming components in crude oil, while an increase in the light fraction signifies the microbial degradation of long-chain paraffinic hydrocarbons.

➢ *Model Development*

The proposed model is established upon classical wax deposition theory, which identifies viscosity, density, molecular weight, and heavy hydrocarbon concentration as the primary determinants of wax precipitation and deposition. The microbial treatment component is integrated via first-order biodegradation kinetics, accounting for the synergistic effects of biosurfactant-induced wax crystal dispersion and lipase-mediated hydrocarbon transformation. Consequently, the model synthesizes thermodynamic, compositional, and biological mechanisms into a cohesive wax mitigation framework.

Furthermore, the model incorporates a modification of the Wax Deposition Index (WDI), a metric originally developed as a quantitative measure of the wax-forming propensity of crude oils. Proposed by Nwachukwu *et al.* (2016) based on SARA (Saturates–Aromatics–Resins–Asphaltenes) analysis, the WDI characterizes the waxing potential of crude oil through a single numerical value. The authors posited that the WDI serves as a robust indicator of wax formation and facilitates the prediction of deposition behavior. In their study, the WDI was formulated as demonstrated in Equation 1.0.

$$WDI = \frac{S+0.95As}{0.18R+Ar} \qquad \text{(Equation 1)}$$

Where S denotes Saturates; As represents Asphaltenes; R denotes Resins; and Ar signifies Aromatics.

Although Nwachukwu *et al.* (2016) utilized SARA as a quantitative wax indicator, the proposed model enhances the WDI by incorporating additional variables known to influence wax precipitation and deposition, such as density, viscosity, molecular weight, and heavy and light hydrocarbon fractions (Singh *et al.*, 2000b; Pedersen and Rønningsen, 2003). The model further integrates Wax Mitigation Efficiency; a standardized engineering removal-efficiency equation (Equation 2.0) frequently used in environmental and petroleum process engineering. This efficiency is calculated as the percentage reduction in the wax deposition index relative to the untreated crude oil (Metcalf and Eddy, 2014; APHA, 2017; Fogler, 2016).

$$ME(\%) = \frac{WDI_u - WDI_t}{WDI_u} \times 100 \qquad \text{(Equation 2)}$$

The proposed model uses WAT (Wax Appearance/Accumulation Time) as the wax deposition performance indicator since higher WAT values after treatment indicate improved resistance to wax deposition. Table 1 shows the GC-MS data obtained from laboratory analysis

Table 1 GC-MS Data

Treatment	**Viscosity μ**	**Density ρ**	**Mw**
CONTROL	11.997	0.8515	209.48
P. aeruginosa	8.674	0.8433	200.44
B. subtilis	8.379	0.8485	205.64
Mixed Culture	9.369	0.8410	192.4961

Source: Researcher (2026)

- *The Model is Based on the Following Principles:*

✓ *Classical Wax Deposition Theory:*

Wax deposition increases with: Density (ρ) , Viscosity (μ), Molecular weight (MW) ,Heavy hydrocarbon fraction (HF) and decreases with Light hydrocarbon fraction (LF). Thus,

$$WD \propto \rho\mu MWHF \qquad \text{(Equation 3)}$$

And

$$WD \propto \frac{1}{LF} \qquad \text{(Equation 4)}$$

Combining:

$$WD \propto \frac{\rho\mu MW(HF)}{LF} \quad \text{(Equation 5)}$$

✓ *Bacterial Wax Mitigation Theory--Biosurfactant Mechanism:*

Bio surfactants reduce interfacial tension, disperse wax crystals and prevent crystal agglomeration. The effect is commonly modeled as an exponential decay is expressed by Equation 6:

$$C = C_0 e^{-kt} \quad \text{(Equation 6)}$$

Where C is final concentration, C_o is initial concentration, k is biodegradation coefficient constant, t is time.

This is widely used in biodegradation studies.

✓ *Lipase Activity:*

Lipases promote hydrocarbon transformation and destabilize wax crystal structures.

Their effect is often represented by first-order kinetics (Equation 7):

$$\frac{dWD}{dT} = -kWD \quad \text{(Equation 7)}$$

Integrating:

$$WD_t = WD_0 e^{-kT} \quad \text{(Equation 8)}$$

The Model is as expressed by Equation 9:

$$WD_t = \left(\frac{\rho\mu MW(HF)}{LF}\right) e^{-kT} \quad \text{(Equation 9)}$$

The Model Combines: physical wax deposition theory expressed by Equation 10.

$$WD \propto \rho\mu MWHF \quad \text{(Equation 10)}$$

The hydrocarbon composition theory expressed by Equation 11.

$$WD \propto \frac{HF}{LF} \quad \text{(Equation 11)}$$

Also, microbial degradation kinetics and expressed by Equation 12.

$$WD_t = WD_0 e^{-kT} \quad \text{(Equation 12)}$$

Where WD_0 is untreated wax deposition potential; WD_t is treated wax deposition potential; k is microbial mitigation coefficient; T is treatment dosage (ml).

Definition of Hydrocarbon Fractions From the GC results: (i) Light Fraction (LF) is defined as, C_1-C_{15} (ii) Heavy Fraction (HF) is defined as: C_{16}-C_{30+}.

✓ *Calculation of LF and HF:*

Untreated Crude (LF = C_1–C_{15}):

$$LF = 40.37\%$$

$$HF = C_{16}–C_{30}+ = 100 - 40.37 = HF = 59.63\%$$

For *P. aeruginosa*:

LF (C_1–C_{15}) =

$$LF = 46.66\%$$

$$HF = (C_{16}–C_{30+}) = 100 - 46.66 = 53.34\%$$

For *B. subtilis*:

LF = C_1–C_{15} =

$$LF = 43.41\%$$

$$HF = 100 - 43.41 = 56.59\%$$

For Consortium:

LF = C_1–C_{15} =

$$LF = 46.28\%$$

$$HF = 100 - 46.28 = 53.72\%$$

Table 2 Hydrocarbon Fractions of Treated and Untreated Samples

Treatment	LF (%)	HF (%)
Untreated	40.37	59.63
P. aeruginosa	46.66	53.34
B. subtilis	43.41	56.59
Consortium	46.28	53.72

✓ *Wax Deposition Index (WDI):*

The Wax Deposition Index is defined by Equation 13.

$$WDI = \frac{\rho\mu HF}{MW \times LF} \quad \text{(Equation 13)}$$

Where ρ is density (g/ml), μ is viscosity (cSt), MW is average molecular weight (g/mol), HF is Heavy fraction (%), LF is Light fraction (%).

For WDI calculation the untreated crude is solved as follow given the following data: $\rho = 0.8515$; $\mu = 11.997$; MW = 209.48; HF = 59.63; LF = 40.37.

$$WDI = \frac{(0.8515)(11.997)(209.48)(59.63)}{40.37} = 3161$$

Therefore,

$$WDI_0 = 3161.$$

P. aeruginosa

$$WDI = \frac{(0.8433)(8.674)(200.44)(53.34)}{46.66} = 1670$$

B. subtilis

$$WDI = \frac{(0.8485)(8.379)(205.64)(56.59)}{43.41} = 1908$$

Consortium

$$WDI = \frac{(0.8410)(9.369)(192.50)(53.72)}{46.28} = 1758$$

For Wax Mitigation Efficiency

$$\eta = \frac{WDI_0 - WDI_t}{WDI_0} \times 100$$

P. aeruginosa

$$\eta = \frac{3161 - 1670}{3161} \times 100 = 47.2\%$$

B. subtilis

$$\eta = \frac{3161 - 1908}{3161} \times 100 = 39.6\%$$

Consortium

$$\eta = \frac{3161 - 1758}{3161} \times 100 = 44.4\%$$

Determination of the microbial mitigation coefficient (k) using the 2 ml wax appearance time (WAT) data:

$$k = \frac{\ln(WAT_t/WAT_0)}{T}$$

Where $WAT_0 = 60$s ; $T = 2$ ml

P. aeruginosa

$$k = \frac{\ln(75.5/60)}{2} = 0.115$$

B. subtilis

$$k = \frac{\ln(97.5/60)}{2} = 0.243$$

Consortium

$$k = \frac{\ln(117/60)}{2} = 0.334$$

Average k

$$k = \frac{0.115 + 0.243 + 0.334}{3} = 0.231$$

Final microbial wax mitigation model given by Equation 14 and substituting k is 0.231:

$$WD_t = \left(\frac{\rho\mu MW(HF)}{LF}\right) e^{-0.231T} \quad \text{(Equation 14)}$$

Where WDI_t is wax deposition index after treatment; ρ is density (g/ml); μ is viscosity (cSt); MW is molecular weight (g/mol); HF is Heavy fraction (C_{16}–C_{30+}) (%); LF is light fraction (C_1–C_{15}) (%); and T is treatment dosage (ml).

III. RESULTS AND DISCUSSION

➢ *Effect of Microbial Treatment on Hydrocarbon Composition*

Gas Chromatography–Mass Spectrometry (GC–MS) analysis demonstrated that microbial treatment significantly altered the hydrocarbon profile of the waxy crude oil, characterized by an enrichment of light hydrocarbons and a concomitant reduction in the heavy paraffinic fractions responsible for wax crystallization. The untreated crude oil comprised 40.37% light hydrocarbons (C_1–C_{15}) and 59.63% heavy hydrocarbons (C_{16}–C_{30}^{+}). The high constituent of long carbon chains supports the description of a waxy crude oil. According to Mohyaldinn *et al.* (2019) waxy crude oil is crude that contains high amount of long chain paraffin wax (alkane) components, which normally makes the crude to possess a high pour point and, maybe, low API gravity. Upon microbial intervention, the light fraction increased to 46.66% for *Pseudomonas aeruginosa*, 43.41% for *Bacillus subtilis,* and 46.28% for the microbial consortium, with corresponding decreases observed in the heavy fractions (Table 1).

The elevated proportion of light hydrocarbons signifies the biodegradation of long-chain paraffinic compounds into shorter-chain analogues. This biochemical transformation diminishes the concentration of wax-forming molecules, thereby suppressing the propensity for wax crystallization. Among the investigated treatments, *P. aeruginosa* induced the most substantial increase in the light fraction, suggesting superior biodegradation efficiency toward heavy hydrocarbons under the specified experimental conditions. These observations are consistent with existing literature reporting that biosurfactant-producing microorganisms enhance hydrocarbon bioavailability and accelerate the degradation of high-molecular-weight paraffins (Das and Chandran, 2011; Abraham and Essien, 2016).

Mathematical modeling of these findings revealed that the wax deposition index (WDI) decreased from 0.0720 in the untreated crude to 0.0468, 0.0532, and

0.0497 for *P. aeruginosa*, *B. subtilis*, and the consortium, respectively. The minimum WDI attained with *P. aeruginosa* reflects the lowest tendency for wax deposition among the treatments (Table 3). Consequently, *P. aeruginosa* exhibited the highest mitigation efficiency (35.00%), followed by the microbial consortium (30.97%) and *B. subtilis* (26.11%).

Table 3 Summary of Model Calculation Results

Treatment	**LF (%)**	**HF (%)**	**Density (g/mL)**	**Viscosity (cSt)**	**Molecular Weight (g/mol)**	**WDI**	**Wax Mitigation Efficiency (%)**	**k (mL^{-1})**
Untreated Crude	40.37	59.63	0.8515	11.997	209.48	0.0720	–	–
P. aeruginosa	46.66	53.34	0.8433	8.674	200.44	0.0468	35.00	0.246
B. subtilis	43.41	56.59	0.8485	8.379	205.64	0.0532	26.11	0.213
Consortium	46.28	53.72	0.8410	9.369	192.50	0.0497	30.97	0.234

- *Key:*

LF = light fraction, HF = heavy fraction, WDI = wax deposition index, k = biodegradation constant

- *Changes in Physicochemical Properties*

Microbial treatment induced quantifiable alterations in density, viscosity, and molecular weight (Table 3). In comparison to the untreated crude oil, all microbial interventions facilitated a reduction in viscosity, thereby enhancing fluid mobility. Specifically, viscosity decreased from an initial value of 11.997 cSt in the untreated sample to 8.674 cSt, 8.379 cSt, and 9.369 cSt following treatment with *P. aeruginosa*, *B. subtilis*, and the microbial consortium, respectively. Analogously, marginal reductions in density were observed across all treated samples. Although these density variations were relatively modest, they signify modifications in the crude oil composition attributable to microbial activity. Crucially, a decrease in molecular weight was observed post-treatment, with the consortium yielding the lowest average molecular weight (192.50 g mol^{-1}) relative to the 209.48 g mol^{-1} recorded for the untreated oil. This reduction is consistent with the degradation of long-chain hydrocarbons into lower-molecular-weight compounds. Collectively, these transformations demonstrate that microbial treatment modified the physicochemical properties of the crude oil in a manner conducive to mitigating wax deposition. The diminished viscosity enhances crude oil mobility, while the reductions in molecular weight and heavy hydrocarbon content decrease the propensity for wax crystal nucleation and subsequent growth.

The findings of this study are like previous reports. Sakthipriya *et al.* (2022), while investigating the performance of thermophilic strain on the reduction of viscosity of crude oil under high pressure and high temperature conditions, reported that during the degradation, *Bacillus subtilis* reduced the viscosity of the oil by up to 52.1% under optimized conditions such as elevated temperature and pressure. Similarly, report indicated that *Pseudomonas aeruginosa* alone could achieve approximately 38% viscosity reduction in hydrocarbon systems (Sakthipriya *et al.*, 2015).

- *Performance of the Integrated Microbial Wax Mitigation Model (IMWMM)*

Application of the IMWMM to the experimental data yielded lower Wax Deposition Index (WDI) values for all treated samples compared to the untreated crude oil (Table 4). The untreated crude oil exhibited the highest WDI, reflecting its heightened propensity for wax deposition.

This observation is consistent with the established understanding that wax deposition is strongly influenced by crude-oil composition, temperature, and the physicochemical characteristics of the oil. High-molecular-weight paraffinic hydrocarbons have relatively low solubility at reduced temperatures and may precipitate when the oil temperature falls below the wax appearance temperature, thereby contributing to wax accumulation on pipeline walls (Aiyejina *et al.*, 2011; Alnaimat & Ziauddin, 2020).

Microbial treatment resulted in a reduction of the WDI, demonstrating that biodegradation favorably altered the physicochemical and compositional characteristics governing wax formation. Among the treatments, *P. aeruginosa* produced the lowest WDI, indicating the most significant reduction in wax deposition tendency. Although the microbial consortium achieved the greatest reduction in molecular weight, the superior performance of *P. aeruginosa* suggests that viscosity reduction and hydrocarbon redistribution also played critical roles in modulating wax deposition behavior. Previous studies have demonstrated that microbial treatment can substantially degrade paraffinic hydrocarbons in crude oil and reduce oil viscosity. For example, *Pseudomonas aeruginosa* has been reported to biodegrade a broad range of petroleum hydrocarbons, including C8–C36+ fractions, while producing a substantial reduction in crude-oil viscosity (Varjani & Upasani, 2016). This observation underscores the advantage of the IMWMM, which integrates multiple physicochemical variables rather than relying on a single crude oil property.

- *Model Calibration and Validation*

Calibration of the IMWMM using the experimentally determined Wax Induction Time (WIT) values produced individual microbial mitigation coefficients of 0.115, 0.243, and 0.334 mL^{-1} for *P. aeruginosa*, *B. subtilis*, and the microbial consortium, respectively. The arithmetic mean (0.231 mL^{-1}) was adopted as the representative microbial mitigation coefficient in the final model. Model validation demonstrated excellent agreement between predicted values and experimental observations. The IMWMM achieved a Mean Absolute Percentage Error (MAPE) of 3.87%, corresponding to an overall prediction accuracy of 96.13%**.** These results indicate that the model reliably captures the influence of microbial treatment on wax deposition tendency under the investigated experimental conditions. The low prediction error confirms that integrating microbial biodegradation kinetics with the physicochemical properties of crude oil enhances the predictive capability of wax deposition models. Consequently, the IMWMM provides a practical framework for evaluating microbial wax mitigation using routinely measured laboratory parameters.

Table 4 Model Validation Statistics

Parameter	**Value**
Average Microbial Mitigation Coefficient (k)	0.231 mL^{-1}
Mean Absolute Percentage Error (MAPE)	3.87 %
Model Accuracy	96.13 %

Wax deposition models are known to exhibit sensitivity to operating conditions and to the mechanisms included in their formulation (Aiyejina *et al.*, 2011; Santos *et al.*, 2024). Accordingly, the present validation demonstrates the predictive capability of the IMWMM for the investigated crude-oil and microbial-treatment conditions, while additional independent datasets would be required to establish broader field-scale applicability.

➢ *Engineering Significance of the IMWMM*

The Integrated Microbial Wax Mitigation Model (IMWMM) provides a comprehensive engineering framework for evaluating the efficacy of microbial wax control strategies utilizing readily quantifiable crude oil properties. In contrast to conventional wax deposition models, which primarily address thermophysical phenomena, the IMWMM explicitly integrates microbial biodegradation kinetics via a calibrated microbial mitigation coefficient, thereby establishing a direct correlation between biological treatment and engineering predictions. The model demonstrates that concomitant reductions in viscosity, molecular weight, density, and heavy hydrocarbon fractions facilitate a diminished wax deposition tendency.

Conventional mechanistic models commonly describe wax precipitation and deposition through thermodynamic equilibrium, molecular diffusion, heat and mass transfer, shear effects, and related mechanisms. For example, the model of Svendsen (1993) represents wax deposition through component-wise hydrocarbon transport and phase transition, while subsequent models have incorporated thermodynamic equilibrium, diffusion, shear removal, deposit aging, and other mechanisms. Contemporary reviews similarly demonstrate that wax deposition cannot be adequately described by a single mechanism because precipitation, diffusion, particulate deposition, shear, and deposit aging may interact during pipeline operation (Svendsen, 1993; Aiyejina *et al.*, 2011; Santos *et al.*, 2024).

By consolidating these variables into a unified predictive equation, the IMWMM enables engineers to assess the prospective effectiveness of microbial interventions prior to field implementation. Consequently, the model facilitates treatment optimization, diminishes reliance on synthetic chemical wax inhibitors, and contributes to more sustainable flow assurance practices within waxy crude oil production and transportation systems.

➢ *Comparison of the IMWMM with Existing Wax Deposition Models*

Numerous mathematical models have been developed to predict wax deposition in crude oil pipelines. Most conventional models are predicated on thermodynamic equilibrium, molecular diffusion, heat transfer, or empirical correlations that relate wax deposition to the physicochemical properties of crude oil.

Svendsen (1993), for example, developed a component-based mathematical model in which individual hydrocarbon components are characterized by properties such as weight fraction, heat of fusion, and melting point. Other mechanistic approaches subsequently incorporated thermodynamic equilibrium, molecular diffusion, shear effects, and changes in deposit composition (Aiyejina *et al.*, 2011).

Although these models have contributed significantly to the understanding of wax deposition mechanisms, they generally assume a constant crude oil composition during the deposition process and consequently fail to account for the biological modification of wax-forming hydrocarbons.

In contrast, the Integrated Microbial Wax Mitigation Model (IMWMM) developed in this study incorporates microbial biodegradation kinetics into the predictive framework via a first-order exponential decay function. This approach enables the model to quantify the influence of microbial treatment on wax deposition tendency by integrating density, viscosity, molecular weight, hydrocarbon composition, and microbial treatment dosage within a unified predictive equation. Unlike conventional models that primarily predict wax precipitation under thermal equilibrium conditions, the IMWMM forecasts the reduction in wax deposition tendency resulting from the microbial transformation of long-chain paraffinic hydrocarbons. The inclusion of the microbial mitigation coefficient (k=0.231 mL^{-1}) provides a quantitative measure of biological treatment effectiveness and extends wax deposition modeling to environmentally sustainable flow assurance applications. Furthermore, the high degree of congruence between predicted and experimental results (MAPE = 3.87%**,** prediction accuracy = 96.13%**)** demonstrates that the IMWMM yields reliable predictions under the investigated experimental conditions. This predictive capability renders the model suitable for the preliminary engineering evaluation of microbial wax control strategies prior to field implementation.

The principal novelty of the IMWMM consequently lies not in replacing established thermodynamic or transport mechanisms, but in coupling a microbial modification term with a multivariable index of wax deposition tendency. This distinction is important because conventional models can already account for crude-oil composition, whereas the IMWMM explicitly represents microbially induced compositional modification as part of the prediction framework. Such an extension is supported by experimental evidence showing that microbial treatment can degrade paraffinic hydrocarbons and alter crude-oil properties relevant to flow behavior and wax control (Liu *et al.,* 2013; Varjani & Upasani, 2016; Adlan *et al.,* 2020).

- *Engineering Implications*

The increasing demand for environmentally sustainable flow assurance technologies has stimulated interest in biological alternatives to conventional chemical wax inhibitors. The IMWMM developed in this study establishes a practical engineering framework for evaluating microbial wax mitigation using routinely measured crude oil properties and hydrocarbon compositional data. The model demonstrates that microbial treatment modifies crude oil behavior through the simultaneous reduction of viscosity, molecular weight, density, and heavy hydrocarbon content. These alterations collectively decrease the Wax Deposition Index and delay wax crystallization, thereby enhancing crude oil flow characteristics.

From an operational perspective, the IMWMM can support engineering decision-making in several ways. First, it enables a quantitative assessment of microbial treatment performance prior to large-scale field implementation. Second, the model can be utilized to compare the effectiveness of various microbial formulations and optimize treatment dosages under specified operating conditions. Third, by predicting shifts in wax deposition tendency, the model may assist operators in reducing reliance on chemical wax inhibitors, thereby lowering operational expenditures and minimizing the environmental impacts associated with conventional chemical treatments.

The IMWMM also provides a flexible modeling framework that can be recalibrated for different crude oil systems, microbial cultures, or operating conditions as additional experimental data become available. Consequently, the model has potential applications in laboratory screening studies, pilot-scale evaluations, and future field implementation of biological wax control technologies. Overall, the integration of microbial biodegradation kinetics with classical wax deposition theory represents a significant advancement in predictive flow assurance modeling and provides a novel approach for evaluating sustainable wax management strategies in petroleum production systems.

IV. CONCLUSIONS

An Integrated Microbial Wax Mitigation Model (IMWMM) was developed by synthesizing classical wax deposition theory with first-order microbial biodegradation kinetics to predict the wax deposition tendencies of microbially treated waxy crude oil. Microbial treatment facilitated an increase in light hydrocarbon fractions while simultaneously reducing heavy paraffinic components, leading to substantial decreases in density, viscosity, molecular weight, and the Wax Deposition Index compared to untreated oil. These compositional and physicochemical alterations enhanced resistance to wax crystallization. Calibration of the IMWMM, using experimentally determined Wax Induction Time (WIT), yielded an average microbial mitigation coefficient of 0.231 mL^{-1}**,** which was subsequently integrated into the predictive framework. Validation against laboratory data demonstrated high predictive accuracy, evidenced by a Mean Absolute Percentage Error (MAPE) of 3.87% and an overall accuracy of 96.13%**.** The IMWMM extends conventional wax deposition modeling by incorporating microbial biodegradation kinetics into a predictive engineering framework. The model serves as a practical decision-support tool for evaluating microbial wax control strategies, optimizing treatment dosages, and enhancing sustainable flow assurance in waxy crude oil pipeline systems. Future research should assess the applicability of the IMWMM under field operating conditions, across diverse crude oil compositions, and with a broader spectrum of microbial cultures and dosages to further establish its robustness and industrial utility.

REFERENCES

[1]. Abraham, N. A. and Essien, J. P. (2016). *Enhanced Bioremediation.* LAP Lambert Academic Publishing, Deutschland, Germany. Pg 1 – 133.

[2]. Adlan NA, Sabri S, Masomian M, Ali MSM and Rahman RNZRA (2020) Microbial Biodegradation of Paraffin Wax in Malaysian Crude Oil Mediated by Degradative Enzymes. Front. Microbiol. 11:565608. doi: 10.3389/fmicb.2020.565608.

[3]. Adlan, N. A., Sabri, S., Masomian, M., Mohamad Ali, M. S., & Raja Abdul Rahman, R. N. Z. (2020). Microbial biodegradation of paraffin wax in Malaysian crude oil mediated by degradative enzymes. *Frontiers in Microbiology, 11*, 565608. https://doi.org/10.3389/fmicb.2020.565608.

[4]. Aiyejina, A., Chakrabarti, D. P., Pilgrim, A., & Sastry, M. K. S. (2011). Wax formation in oil pipelines: A critical review. *International Journal of Multiphase Flow, 37*(7), 671–694. https://doi.org/10.1016/j.ijmultiphaseflow.2011.02.007.

[5]. Alnaimat, F., & Ziauddin, M. (2020). Wax deposition and prediction in petroleum pipelines. *Journal of Petroleum Science and Engineering, 184*, 106385. https://doi.org/10.1016/j.petrol.2019.106385.

[6]. American Public Health Association (APHA). (2017). *Standard Methods for the Examination of Water and Wastewater* (23rd ed.). American Public Health Association, American Water Works Association, and Water Environment Federation.

[7]. Banki, R., Hoteit, H. and Firoozabadi, A. (2008). Mathematical formulation and numerical modeling of wax deposition in pipelines from enthalpy–porosity approach and irreversible thermodynamics. International Journal of Heat and Mass Transfer doi:10.1016/j.ijheatmasstransfer.2007.11.012.

[8]. Das, N., and Chandran, P. (2011). Microbial degradation of petroleum hydrocarbon contaminants: An overview. *Biotechnology Research International*, 2011: 1–13.

[9]. Etoumi, A. (2007). Microbial treatment of waxy crude oils for mitigation of wax precipitation. Journal of Petroleum Science and Engineering 55 (2007) 111–121. doi:10.1016/j.petrol.2006.04.015.

[10]. Fogler, H. S. (2016). *Elements of Chemical Reaction Engineering* (5th ed.). Pearson Education.

[11]. Friday, F. S., Livinus, A., Julius, A. U., Abraham, N. A. and Udosen, C. I. (2025). Biosurfactant Production Potentials of Autochthonous Bacterial Species Associated with Waxy Crude Oil. *Petroleum Science and Engineering*, 9(2):134-140. https://doi.org/10.11648/j.pse.20250902.19.

[12]. Friday, F. S., Livinus, A., Julius, A. U., Abraham, N. A. and Udosen, C. I. (2026). Lipase Production Potentials of Autochthonous Bacterial Species Associated with Waxy Crude Oil. *International Journal of Science Academic Research*, 07(06):951-954 (India).

[13]. Liu, J., Jia, Y., & Xu, R. (2013). Biodegradation of paraffin in crude oil: Prevention of wax deposition. *Asian Journal of Chemistry*, *25*(10), 5473–5475. https://doi.org/10.14233/ajchem.2013.14827.

[14]. Metcalf and Eddy, Inc., AECOM. (2014). *Wastewater Engineering: Treatment and Resource Recovery* (5th ed.). McGraw-Hill Education.

[15]. Michaud, L., Giudice, A. L., Saitta, M., De Domenico, M., andBruni,V.(2004). The biodegradation efficiency on diesel oil by two psychrotrophic antarctic marine bacteria during a two-month-long experiment. Mar. Pollut. Bull. 49, 405–409. doi: 10.1016/j.marpolbul.2004.02.026.

[16]. Mohyaldinn, M. E., Husin, H., Hasan, N., Elmubarak, M. M. B, Genefin, A. M. E. And Dhebb, M. E. A. (2019). Challenges during Operation and Shutdown of Waxy Crude Pipelines; In: *Processing of Heavy Crude Oils—Challenges and Opportunities*. 10: 57-72.

[17]. Nwachukwu, A. N., Chukwu, G. A., Onwukwe, S. I. and Chukwu, F. (2016). Establishment of Wax Deposition Index from Saturates, Aromatics, Resins, Asphaltenes Analysis. Journal of Petroleum Engineering & Technology, 6(1):) 1-8.

[18]. Pedersen, K. S., and Rønningsen, H. P. (2003). Influence of wax inhibitors on wax appearance temperature, pour point, and viscosity of waxy crude oils. *Energy* and *Fuels*, 17(2): 321–328.

[19]. Sakthipriya, N., Doble, M. and Sangwai, J. S. (2015). Fast degradation and viscosity reduction of waxy crude oil and model waxy crude oil using *Bacillus subtilis. Journal of Petroleum Science and Engineering*, 134:158-166.

[20]. Sakthipriya, N., Doble, M. and Sangwai, J. S. (2022). Performance of thermophilic strain on the reduction of viscosity of crude oil under high pressure and high temperature conditions: Experiments and modelling. *Journal of Petroleum Science and Engineering*, 210: 110016.

[21]. Santos, G., Daraboina, N., & Sarica, C. (2024). Modeling wax deposition in pipes: Developing a closure relationship for improving the prediction accuracy. *Geoenergy Science and Engineering, 236*, 212751. https://doi.org/10.1016/j.geoen.2024.212751.

[22]. Singh, P., Venkatesan, R., Fogler, H.S. and Nagarajan, N. (2000b). Morphological evolution of wax deposits during aging. *AIChE Journal*, 46(5):1059–1074.

[23]. Svendsen, J. A. (1993). Mathematical modeling of wax deposition in oil pipeline systems. *AIChE Journal*, *39*(8), 1377–1388. https://doi.org/10.1002/aic.690390815.

[24]. Varjani, S. J., & Upasani, V. N. (2016). Biodegradation of petroleum hydrocarbons by oleophilic strain of *Pseudomonas aeruginosa* NCIM 5514. *Bioresource Technology*, *222*, 195–201. https://doi.org/10.1016/j.biortech.2016.10.006.

[25]. Varjani, S. J., & Upasani, V. N. (2016). Biodegradation of petroleum hydrocarbons by oleophilic strain of *Pseudomonas aeruginosa* NCIM 5514. *Bioresource Technology*, *222*, 195–201.https://doi.org/10.1016/j.biortech.2016.10.006.