

**ASSESSMENT OF WAX DEPOSITION PREVENTION AND
MITIGATION METHODS IN CRUDE OIL PIPELINES: A
REVIEW**



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**A PROJECT SUBMITTED TO THE
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NOVEMBER 2025

CERTIFICATION

This is to certify that this project was carried out by **AWOLERE OLUWADAMILARE VICTOR** of the Department of Petroleum Engineering with matriculation number **ENG2002601** in partial fulfillment of the requirements for the Award of the Degree, Bachelor of Engineering (B.ENG)

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DEDICATION

This project is dedicated to the Almighty God, whose grace and guidance made this journey possible. I also dedicate this project to my beloved parents for their unwavering love, prayers, and support throughout this endeavor.

To my siblings, you all are the driving force and motivation that kept me going on the journey. Thank you for your unwavering supports and prayers.

ACKNOWLEDGEMENT

First and foremost, I give thanks to the almighty God for his guidance, strength, and grace throughout the course of this project.

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ABSTRACT

Wax deposition remains a major flow assurance challenge in crude oil pipeline systems and is particularly severe in regions such as the Niger Delta where waxy crude oils and fluctuating operating conditions promote rapid cooling and crystallisation of paraffinic hydrocarbons. This study provides an assessment of wax deposition prevention and mitigation technologies through a systematic review of peer-reviewed literature published from 2022 to date. The Preferred Reporting Items for Systematic Reviews and Meta-Analysis framework was adopted to identify, screen and analyse relevant publications. The review examines chemical, thermal and mechanical approaches with emphasis on their mechanisms, effectiveness, limitations and suitability for wax-prone crude oils. Across the collected studies, chemical methods emerged as the most extensively researched and adaptable strategy for prevention. Polymeric pour point depressants, crystal modifiers, solvent blends and plant-based inhibitors demonstrated strong capabilities in reducing Wax Appearance Temperature, altering crystal morphology and improving crude oil flowability. Several authors reported that natural inhibitors derived from jatropha oil, palm kernel oil, palm oil and other agricultural sources produced inhibition efficiencies comparable to synthetic formulations while offering environmental and economic advantages. Nanoparticle enhanced additives also showed improved thermal stability and dispersive behaviour. Thermal methods such as insulation, active heating and temperature maintenance remained effective for keeping crude oil above its crystallisation point although their energy requirements limit continuous use. Mechanical techniques such as pigging continue to dominate remedial operations whenever deposition has already occurred despite operational challenges such as pig sticking and unpredictable wax breaking forces. The findings show that no single method provides a universal solution. Effective management requires combining preventive strategies with periodic remediation while accounting for the crude oil composition, operating conditions and pipeline characteristics. The review highlights the growing potential of plant based additives, nano enhanced inhibitors as environmentally responsible and economically viable alternatives. The study therefore contributes to improving flow assurance practices and supports the development of sustainable wax management strategies within the Niger Delta and other regions producing waxy crude oils.

CHAPTER 1

1.0 INTRODUCTION

1.1. Background of the Study

After crude oil has been produced from the reservoir to the wellhead, it does not stop there. It must be transported through flow lines, pipelines and processing facilities before it can be treated, stored or exported. This transportation phase exposes the crude oil to new thermal and hydrodynamic environments that are very different from the conditions in the reservoir. As the produced oil travels through long subsea or surface pipelines, it begins to cool toward the surrounding temperature, and this cooling is the primary trigger for one of the most persistent flow assurance challenges in the oil and gas industry: wax deposition (Hemmati-Sarapardeh et al., 2022). Crude oil contains a natural fraction of long-chain paraffinic hydrocarbons, commonly referred to as waxes. At high temperatures these wax molecules remain dissolved within the liquid phase. However, once the temperature of the flowing crude drops to the Wax Appearance Temperature, they begin to crystallize out of solution. As the temperature continues to decline, more crystals are formed, and they start to grow, interlock and adhere to the pipe wall. This mechanism gradually forms a solid wax layer which narrows the internal diameter of the pipeline and restricts flow. In some cases, this deposition can progress to the point of complete blockage, creating significant operational and economic consequences for operators (Aiyejina et al., 2010).

Several factors influence the rate and severity of wax deposition. The composition of the crude oil plays a major role, especially the concentration and distribution of paraffinic components. Oils with higher saturate content and heavier paraffins tend to have higher Wax Appearance Temperatures and are more prone to deposition. Temperature gradients between the bulk oil and the pipe wall also strongly affect the process. A larger gradient accelerates crystallization and increases the tendency for wax to accumulate along the pipeline wall. Flow velocity is another important factor. At low velocities, wax crystals have more time to

settle and adhere, whereas higher velocities create sufficient shear to reduce deposition. Pressure conditions, oil viscosity, presence of asphaltenes, the surface properties of the pipeline and even pipeline geometry such as bends or inclines can influence the type and severity of deposition (Huang et al., 2015).

Wax deposition is particularly challenging in regions like the Niger Delta where waxy crude oils are common, and long transportation distances expose the oil to extended cooling periods. Inadequate insulation, frequent shutdowns, vandalism-related downtime and fluctuating operational conditions further worsen the tendency for wax buildup in pipelines. When deposition increases, operators face rising pressure losses, higher pumping costs, reduced production rates and in extreme cases the abandonment of flow lines. These challenges highlight why continuous assessment and improvement of prevention and mitigation technologies remain essential for safe and cost-effective crude oil transportation.

Over the years, several strategies have been developed to manage wax deposition. Prevention remains the preferred approach because it avoids interruptions to production. Chemical additives such as pour point depressants, wax crystal modifiers and drag-reducing agents have been widely studied and used to alter wax crystallization behaviour and reduce viscosity. Thermal strategies such as insulation, active heating and temperature maintenance are also effective in keeping crude oil above its Wax Appearance Temperature. Mechanical solutions, including pigging and scraping, remain the primary remediation techniques when deposition has already occurred. Recent research has expanded into greener alternatives such as plant-based inhibitors, nano-enhanced additives and microbial wax degradation. The evolving nature of these technologies makes it important to continually assess their performance, limitations and economic feasibility, especially within the context of the Niger Delta where pipeline integrity and flow assurance remain critical concerns.

This study therefore reviews recent prevention and mitigation technologies for wax deposition, evaluates their effectiveness as reported in contemporary literature and identifies opportunities for improved application and innovation within wax-prone crude oil systems.

1.2. Problem Statement

Wax deposition has remained a persistent operational challenge in crude oil transportation especially in the Niger Delta where paraffinic crudes are common. As oil flows from wellheads through long distance pipelines or poorly insulated systems, the temperature drop below the Wax Appearance Temperature. When this happens, paraffin molecules begin to crystallize and stick to the inner walls of the pipelines, a process primarily driven by molecular diffusion. Over time, this build up thicken, reduce the inner diameter of the pipe, increase pressure loss and in severe cases restrict or completely stopping oil flow. These disruptions reduce production efficiency, some rely on imported chemicals which can be environmentally unfriendly and ultimately result in costly intervention.

This study therefore reviews recent literatures to analyse and explore latest research trends and economically viable proposed tested options to address the issue of wax deposition.

1.3. Aims and Objectives of the study

- To conduct a systematic review and selection of existing publications on wax prevention and remediation in oil and gas production systems using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework.
- To critically analyze selected literature using the PRISMA approach in order to identify trends, limitations, and technological research progress in wax management.
- To source and establish from selected literature feasible procedures for wax prevention and remediation applicable to Niger Delta Oil and Gas field operations.

- To recommend based on selected literature, a feasible process for wax prevention and remediation in oil and gas pipelines within the Niger Delta.

1.4. Scope of the Study

This research focuses on documented wax deposition prevention and mitigation technologies as presented in peer-reviewed literature published from 2022 to date. The scope covers crude oil pipelines rather than gas pipelines or other hydrocarbon transport systems. Prevention technologies assessed include thermal insulation and heating methods, chemical inhibitors such as pour point depressants and nano-formulated additives, and mechanical prevention options like magnetic field applications and surface modification. Mitigation techniques such as pigging and mechanical cleaning are also examined. The study does not involve experimental work but relies entirely on systematic review using the PRISMA approach, comparison and analysis of findings from multiple authors. Although global studies are considered, particular emphasis is placed on insights relevant to waxy crude oils typical of the Niger Delta.

1.5. Significance of the Study

Understanding wax deposition and the performance of various prevention and mitigation technologies is vital for ensuring safe, reliable and economically sustainable crude oil transportation. The Niger Delta remains a major hub for Nigeria's petroleum production, yet wax-related flow issues continue to cause shutdowns, increased operating costs and environmental risks when pipelines become stressed or damaged. This study provides an integrated review of modern technological advancements, highlights the strengths and limitations of existing methods and identifies promising areas for innovation such as plant-based inhibitors and microbial approaches. By consolidating findings from recent publications, the research provides a practical reference for engineers, researchers and

operators seeking cost-effective, environmentally responsible and operationally efficient solutions to wax deposition challenges. Ultimately, the study contributes to improved flow assurance practices and supports the long-term productivity of crude oil assets in the Niger Delta.

1.6. Limitations of the Study

- The study is entirely based on secondary data from published literatures which means no experimental validation was done to confirm the performance of the reviewed technologies
- Only publications not earlier than 2022 were used for the review which may have led to the omission of earlier but still valuable foundational studies on the topic
- Access to certain relevant publications was restricted due to paywalls, potentially limiting the scope and depth of this review.
- Variations in experimental conditions, crude oil properties and testing methodologies across different studies made direct comparisons difficult and sometimes limited the ability to generalize conclusions
- The environmental and economic evaluations presented depend on the assumption and reporting accuracy of the reviewed authors as the study did not perform its own cost and environmental assessment.
- Only publications that were written in English were used leading to the exclusion of relevant findings reported in other languages.

CHAPTER 2

2.0 LITERATURE REVIEW

Wax deposition continues to present one of the most persistent challenges in crude oil production and transportation. The problem has been widely documented across different crude types and operating environments, with the Niger Delta repeatedly cited as a region where the combination of waxy crude compositions, aging infrastructure, and fluctuating operating conditions intensify the frequency of wax-induced flow disruptions. Researchers consistently agree that the onset of wax crystallization begins when temperatures fall below the wax appearance temperature and that the interaction between thermal gradients, molecular diffusion and flow hydrodynamics collectively determine how quickly crystals migrate to and adhere to pipeline walls. The growing complexity of flow systems has therefore led researchers to explore a wide range of prevention and mitigation methods whose performance varies significantly depending on crude composition, operating temperature and the underlying mechanism of wax formation itself.

Across the reviewed literature, one of the strongest themes is the consistent effort to optimise chemical prevention because of its adaptability to different crude types and operating environments. Several authors found that polymeric pour point depressants, crystal modifiers and solvent-based inhibitors can significantly delay the formation of wax lattices, reduce viscosity and disrupt the growth of large interlocking crystals responsible for plugging. Many experiments, particularly those involving plant-based inhibitors such as orange peel oil, jatropha oil, palm kernel oil and coconut husk extracts (Amni Haslinda Alpandi et al., 2022), demonstrated that locally sourced materials can be just as effective as imported synthetic chemicals. These studies show that minor changes in WAT, even by a few degrees, can dramatically reduce the rate at which wax settles on pipe walls. For example, formulations such as orange peel oil and toluene depressed the WAT by up to thirteen degrees Fahrenheit

(Udoh N.A., 2024), while palm oil derivatives and jatropha blends consistently improved paraffin inhibition efficiency across temperatures that would normally support rapid crystallisation. These findings align with earlier research that established the importance of additives capable of modifying crystal morphology and reducing inter-molecular bonding within the wax network (Soni et al., 2021; Yi & Zhang, 2011).

The broad consensus across the reviewed studies is that the performance of wax inhibitors is strongly concentration-dependent. Low concentrations often achieve limited inhibition, while excessively high concentrations can produce reverse effects by acting as additional sites for agglomeration. This behaviour was clearly demonstrated in experiments involving EVA-based inhibitors, where the pour point depressant performed well at very low concentration but became counterproductive when dosages exceeded one percent. The deterioration in performance at higher concentration illustrates the delicate balance required between chemical structure, crude oil composition and concentration. At optimal concentrations, however, many inhibitors achieved paraffin inhibition efficiencies between sixty and ninety percent, with natural plant-based inhibitors in some cases outperforming or matching synthetic standards such as triethanolamine and xylene (Thevaruban Ragunathan et al., 2021). Such results reinforce the emerging trend in flow assurance research toward environmentally friendly, low-toxicity materials that can deliver competitive performance without posing environmental risks associated with conventional polymers and solvents. A crucial observation from the reviewed works is that crude oil composition significantly influences the performance of chemical inhibitors. Crudes with higher paraffin content naturally demand more potent crystal modifiers, whereas crudes containing larger proportions of aromatics and resins tend to respond more readily to dispersant-type chemicals. Studies comparing Bonny Medium Blend, Bonny Light and other high-wax Nigerian crudes showed that inhibitors display varying levels of effectiveness depending on the molecular distribution of paraffins in the crude (O.P Akinyemi et al., 2017). For instance, coconut husk based inhibitors were more

effective on crudes with higher wax content, where the straight hydrocarbon chains aligned more easily with the inhibitor molecules. This supports earlier findings that wax inhibition performance is linked to molecular compatibility and the ability of additives to interact with key paraffinic structures responsible for crystal growth (Chen et al., 2013; Honse et al., 2012).

Beyond chemical prevention, other authors explored viscosity reduction strategies involving dilution and drag-reducing agents. These studies emphasise the dual benefit of lowering viscosity while simultaneously suppressing turbulence-induced friction, which in turn reduces energy demand in pipeline transport (A.B Ehinmowo et al., 2024). The addition of drag reducing agents coupled with crude dilution showed significant improvements in flow efficiency, with field cases reporting financial savings exceeding one million dollars due to reduced energy consumption. Researchers also noted that molecular structure plays an essential role in the performance of drag reducers, with high-molecular-weight polymers providing the most pronounced drag-reducing behaviour. The importance of optimising temperature, concentration and flow rate was also highlighted, as these variables collectively dictate the extent of turbulence suppression and viscosity reduction.

Nanotechnology emerged as one of the most active research areas among the reviewed publications. Both silicon-based and carbon-based nanomaterials demonstrated remarkable improvements in pour point reduction, shear resistance, and crystal habit modification. Nanohybrid PPDs consistently outperformed conventional EVA (Erxiu Shi, Jiawei Li et al., 2024). They produced significant decreases in pour point, cold filter plugging point and apparent viscosity, often at doses as low as one hundred parts per million. Studies involving nano modified montmorillonite, silica nanoparticles and carbon nanotubes further support this trend. Carbon nanotubes in particular produced strong interactions with asphaltenes and paraffinic molecules, which altered the crystallisation landscape and prevented the formation of interlocking three-dimensional wax crystal networks. These findings have been reinforced

by complementary research where nanoparticles served as nucleation templates that promoted smaller, more dispersed crystals instead of large aggregates (Li et al., 2022).

A number of experiments combined laboratory measurements with molecular dynamics simulations to better explain the inhibition mechanisms within crude oil systems. These simulations provided detailed insight into how additives interact with wax molecules at the atomic level. For example, oleic acid was shown to inhibit wax formation through strong van der Waals interactions with hydrogen atoms in eicosane, increasing molecular spacing and reducing the likelihood of crystalline bonding. The simulations also demonstrated that molecular structure dictates how inhibitors interact with paraffin molecules, supporting the argument that the effectiveness of many plant-based inhibitors arises from their high content of monounsaturated fatty acids. These computational findings were consistent with cold finger tests, where palm-based oils and triethanolamine demonstrated high paraffin inhibition efficiency at optimal concentrations. The agreement between simulation and laboratory results strengthens the reliability of molecular dynamics as a screening tool for future inhibitor development.

The use of blended inhibitors emerged as another significant observation from the reviewed studies. In several cases, mixtures containing polyethylene, xylene, acrylate ester copolymers and alkyl sulphonates outperformed individual chemicals, achieving inhibition efficiencies above sixty percent. This demonstrates the potential of synergistic mechanisms where crystal modification, dispersion and solvation effects occur simultaneously. Optimal mixtures not only reduced wax layer thicknesses to minimal levels but also operated effectively across varying crude compositions. These results highlight the importance of formulation engineering, as crude types rarely respond uniformly to single-component additives. Some crudes require more aggressive solvents, while others respond to long-chain polymers or surfactants capable of disrupting intermolecular forces within the wax phase.

While prevention remains the primary focus in the reviewed literature, several papers also provided insight into remediation strategies that become necessary once wax has already adhered to pipeline surfaces. Mechanical pigging continues to be the most widely adopted remediation method due to its simplicity, adaptability to different pipeline diameters and ability to physically dislodge wax build-up. Studies showed that pigging efficiency is influenced by pig type, pipeline geometry, flow conditions and wax hardness (Davidson Chukwudi O. et al.' 2022). In flow systems with heavy deposition, pigging becomes a regular operational requirement, and the frequency of pigging schedules is closely tied to the thermal and hydraulic conditions along the pipeline.

Thermal remediation is another widely used approach, especially hot oiling and hot water circulation. However, several authors highlighted limitations associated with these techniques. Hot fluids may disperse wax rather than dissolve it completely, and repeated thermal cycling can accelerate deposition in some circumstances. Additionally, thermal methods require substantial energy, making them costly and less sustainable over long operational periods. This is consistent with field experiences reported in the Niger Delta, where frequent hot-oiling campaigns increase operational expenditure and may provide only temporary relief due to rapid cooling of injected hot fluids.

Magnetic treatment of crude oil has emerged as an unconventional but growing area of interest. A number of studies theorise that magnetic fields can influence the alignment and agglomeration behaviour of paraffin molecules. Simulations and experimental tests show that magnetically treated crude oil may form weaker deposits, with crystals appearing smaller and more dispersed (Nikolay Cheremisin et al., 2022). Researchers argue that magnetic exposure modifies intermolecular interactions and reduces the tendency of crystals to form strong networks on metal surfaces. Although intriguing, this technique is still in early development

and requires substantial field-scale verification, especially under the complex multiphase flow conditions typical of Niger Delta pipelines.

Mechanical surface modification is another noteworthy development. Several authors explored coatings and internal surface treatments designed to reduce the adhesion of wax to pipeline walls. Coatings can function individually and collectively as anti-corrosion, drag reducing and thermal insulation materials when applied on pipelines (Lihui et al., 2025). Hydrophobic and low-energy coatings, including polymeric and composite materials, showed potential for delaying deposition onset by altering surface wettability. These studies confirm that surface roughness and chemical affinity strongly influence the rate of wax attachment to steel surfaces. Although still emerging, surface treatment approaches present an opportunity for longer-term, passive wax mitigation without the need for continuous chemical injection.

When comparing prevention and remediation methods across all reviewed literature, it becomes evident that chemical inhibitors remain the most adaptable and cost-effective strategy for continuous wax control. They are easily deployed, require minimal infrastructure changes and are compatible with conventional operational practices. Nanotechnology and plant-based inhibitors represent the most promising areas for future advancement due to their environmental compatibility and performance at low concentrations. Remediation techniques such as pigging and hot oiling remain necessary but are often reactive rather than preventive and may introduce additional operational and economic burdens. Thermal and mechanical methods are highly situational and depend heavily on pipeline geometry, flow regime and the consistency of crude composition.

The reviewed publications consistently demonstrate that no single method can be considered universally effective. Wax deposition is a complex interplay of thermal, chemical and mechanical factors, and its mitigation requires an integrated approach that aligns with the specific characteristics of the crude oil, the surrounding environment and the infrastructure in

use. For the Niger Delta, where waxy crudes, security challenges and aging pipelines intersect, the most realistic pathway involves a mix of optimized chemical prevention, improved monitoring and strategically scheduled remediation. The increasing availability of locally sourced inhibitors presents a viable alternative to costly imported chemicals, while innovations in nanotechnology and use of locally sourced plant-based inhibitors provide promising directions for future research.

CHAPTER 3

METHODOLOGY

The systematic review methodology used in this study is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles, which consists of a 27-item checklist and a four-phase flow diagram (Moher et al., 2009). The following section will introduce the systematic review procedures.

3.1 Database search

In order to locate the relevant articles, the systematic search was conducted on the following electronic databases: web of science, Scopus, Google Scholar, Scribd, OnePetro, research gate, and research rabbit. I selected these databases since they were considered as legally compliant major publisher databases. Filters were limited to the time period from 2022 till the time of publishing and were applied to the peer-reviewed and empirical research articles written in English in order to ensure the quality of the review articles. All downloaded citations were imported into Zotero for duplicate removal and organization.

3.2 Search terms

A structured search strategy was used for various bibliographic databases with keywords used according to each databases' specific requirements. In both the electronic and manual searches, keywords related to "wax deposition in crude oil pipelines", "wax precipitation in Niger Delta oilfields", "waxy crude oil flow assurance", "wax prevention in oil and gas", "wax remediation in oil pipelines", "flow assurance Niger Delta", "thermal insulation for wax prevention", "wet insulation subsea pipeline", "dry insulation pipeline", "subsea pipeline burial wax control", "active heating wax control", "direct electrical heating pipeline wax", "hot water circulation wax prevention", "thermal management waxy crude oil", "pour point depressant crude oil", "chemical wax inhibitors crude oil", "nano pour point depressant silica", "nano wax inhibitor", "carbon-based nano wax inhibitor", "drag reducing agents wax

prevention", "palm oil-based wax inhibitor", "mechanical wax prevention pipeline", "magnetic field wax deposition", "pipeline internal coating wax prevention", "surface treatment anti-wax coating", "pigging for wax removal", "wax appearance temperature", "cloud point wax crude oil", "pour point wax crude oil", "nucleation wax crystals", "heat transfer coefficient wax detection" , "Niger Delta wax deposition case study", "Nigerian crude oil paraffin content" were used to search for related publications. Besides electronic searches, backward and forward citation tracking was conducted in Google Scholar to identify additional studies not captured by database algorithms.

3.3 Inclusion and Exclusion criteria

To ensure the systematic review remains focused and transparent, a defined set of inclusion and exclusion criteria was developed. These criteria guided the selection of relevant literature on wax prevention and remediation in oil and gas pipelines. The search criteria were designed to locate publications that focused on the wax prevention and remediation. In terms of the research questions, a set of inclusion and exclusion criteria that were adopted are shown in the table below

INCLUSION CRITERIA	EXCLUSION CRITERIA
Studies published from 2022 till the time this project was published	Studies published before the cut off year
Research must be from peer reviewed journal articles, conference papers, thesis	Blog posts, non-scientific articles
Research must discuss thermal, chemical and mechanical methods of wax prevention and remediation	Studies focused on arctic, gas-only pipelines or non-petroleum industries without relevance
Research must contain lab experiments, simulations or field case studies	Purely theoretical studies with no application
Research must be written in English	Research written in non-English language
Research with available full text (open or institutional access)	Research with abstract only or inaccessible papers

Figure 3-1: Table of inclusion and exclusion criteria used in the study

Studies published from 2022 onward were selected to reflect the most recent technological advancements in wax prevention and remediation, as earlier studies may not include emerging techniques.

3.4 The screening process

The screening process involved the following steps:

- Removing duplicated articles
- Removing articles that did not meet the inclusion criteria based on the titles and abstracts.
- Removing articles that were published before 2022
- Removing articles that do not have open access

The search produced 271 articles from the previously-used search terms before duplicates were removed. The next screening whose criteria was by filtering out materials published before 2022, the materials reduced to 71. The last screening involved filtering out publications that didn't allow full access to the article after which the materials reduced to 30 which were eventually used as the base papers for this review. The screening process was conducted in accordance with the PRISMA 4-stage model: identification, screening, eligibility, and inclusion. Full texts were accessed through institutional subscriptions and open-access platforms.

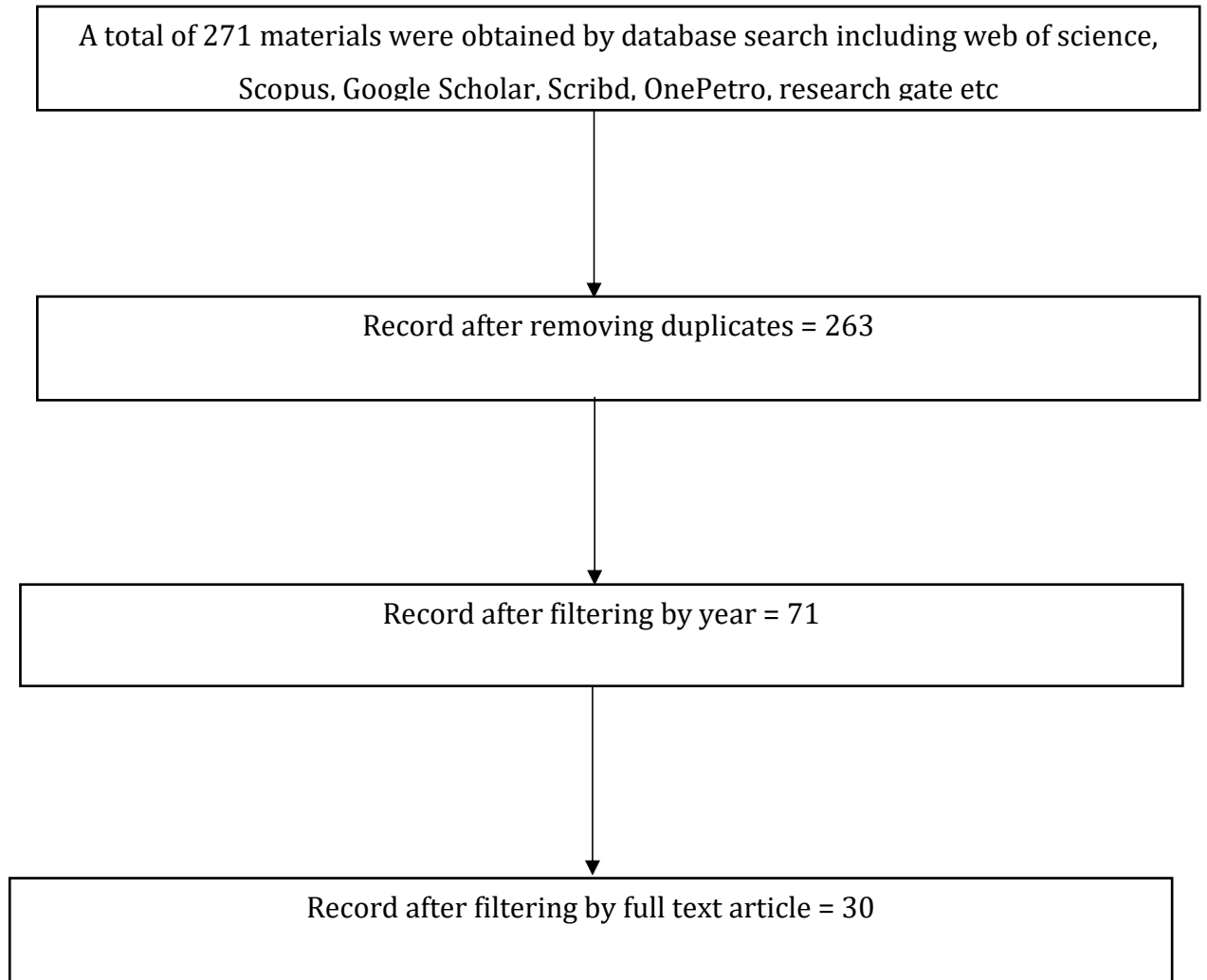


Figure 3-2: Chart of the records during screening process

3.5 Analysis

After the final selection of 30 relevant studies, a structured analytical approach was adopted to extract, categorize, and synthesize data in alignment with the research objectives of this review. The analysis focused on identifying trends, evaluating the effectiveness of wax prevention and remediation techniques, and determining research gaps specific to oil and gas pipelines, particularly in the Niger Delta.

3.5.1 Data Extraction Strategy.

A standardized data extraction table was developed to ensure consistency and minimize bias. For each study, the following information was recorded: Authors (year, and country of study), Research objective and study type (experimental, numerical simulation, or field case study), Crude oil characteristics, Technique discussed (thermal, chemical, mechanical, or hybrid method), Study context, Key findings, performance outcomes, and limitations. Only information directly relevant to wax prevention and remediation was extracted to maintain focus.

3.5.2 Method of Evaluation and Synthesis

The selected studies were analyzed using qualitative thematic analysis and comparative synthesis, structured into the following stages:

- **Categorization by Prevention Method:** Articles were grouped under thermal, chemical, and mechanical prevention strategies. Studies addressing hybrid or integrated approaches were categorized separately.
- **Effectiveness Comparison:** Each technique was assessed based on reduction of wax thickness, energy consumption, cost-effectiveness, operational feasibility, and environmental impact.
- **Contextual Evaluation for Niger Delta Pipelines:** Studies relevant to tropical climates, onshore/offshore systems, low-pressure pipelines, and paraffinic Nigerian crude were highlighted and compared to global studies.
- **Identification of Trends and Innovations:** The analysis tracked emerging technologies (e.g. nanotechnology-based inhibitors, intelligent pigging, and direct electrical heating) and compared them with conventional techniques.

- **Gap and Limitation Assessment:** The strengths and weaknesses of each study were documented, such as limited field validation, lack of long-term performance data, or unrealistic laboratory conditions.

3.5.3 Analytical Tools and Approach.

Although no numerical meta-analysis was performed due to differences in experimental design, crude oil properties, and measurement techniques across studies, narrative synthesis and comparative tables were used to clearly present the findings. Where possible, quantitative data such as wax thickness reduction percentages, pour point depression values, pressure drop improvements, and cost impact were compared across studies.

3.5.4 Analysis Questions

- What are the aims of the studies?
- Were the studies an experiment, simulation, field trial or a review paper?
- What prevention/remediation/mitigation methods were studied?
- What were the major results/findings for prevention/remediation/mitigation in the study?
- What materials were used/proposed for the prevention/remediation/mitigation?
- How should/were the method applied for prevention/remediation/mitigation in the study?
- Were there any limitation, challenges or side effects documented in the studies?
- Is the method more cost effective, environmentally friendly or field applicable compared to other conventional methods?
- Did the authors document any research gaps or recommendations for future work?

3.5.5 Outcome of the Analysis

The analytical process enabled the identification of:

- The most frequently studied prevention and remediation techniques from 2022 to date
- The research trends and categories in wax deposition prevention and remediation
- Technologies with proven field performance in similar environments to the Niger Delta
- Limitations in current research that justify further investigation
- A foundation for developing a proposed integrated wax prevention and remediation framework in Chapter 4

CHAPTER 4

4.0 RESULT

4.1. WHAT ARE THE AIMS OF THE STUDIES?

4.1.1 Chemical Methods of preventing Wax:

Most of the study focused on developing organic local inhibitors which serve as either wax crystal inhibitors, pour point depressants, nano-pour point depressants and drag reducers while the rest are chemicals that served the same purpose.

4.1.2 Chemical Methods of remediating/mitigating Wax:

The studies primarily focused on using chemicals that either serves as dispersants and solvents used to remove deposited wax on the pipeline walls

4.1.3 Thermal Methods of preventing Wax:

Experimental studies and reviews were on active heating and pipeline insulation

4.1.4 Thermal Methods of remediating/mitigating Wax:

Studies were aimed at reviewing the effect of hot oil and steam/water to remediate wax issues

4.1.5 Mechanical Methods of preventing Wax:

Studies and reviews were on magnetic application and application of coatings on pipelines

4.1.6 Mechanical Methods of remediating/mitigating Wax:

Conventional pigs and foam pigs were reviewed and studied

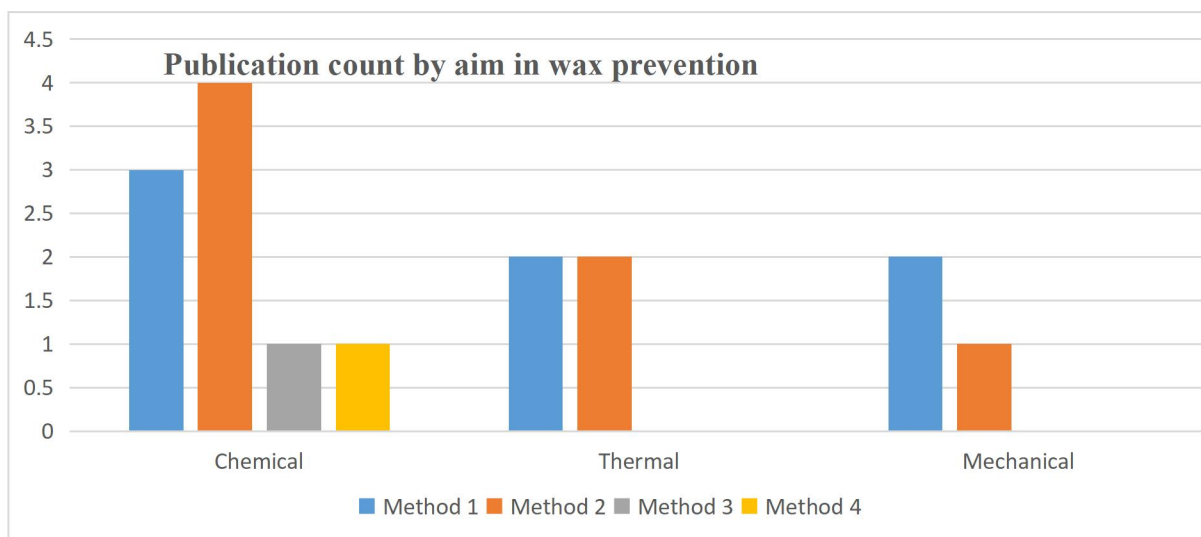


Figure 4-1: Publication count by aim in for wax deposition prevention

Prevention data	Method 1	Method 2	Method 3	Method 4
Chemical	Wax crystal modifiers	Pour point depressants	Nano pour point depressant	Drag reducer
Thermal	Active heating	Pipeline Insulation	-	-
Mechanical	Coating	Magnetic Application	-	-

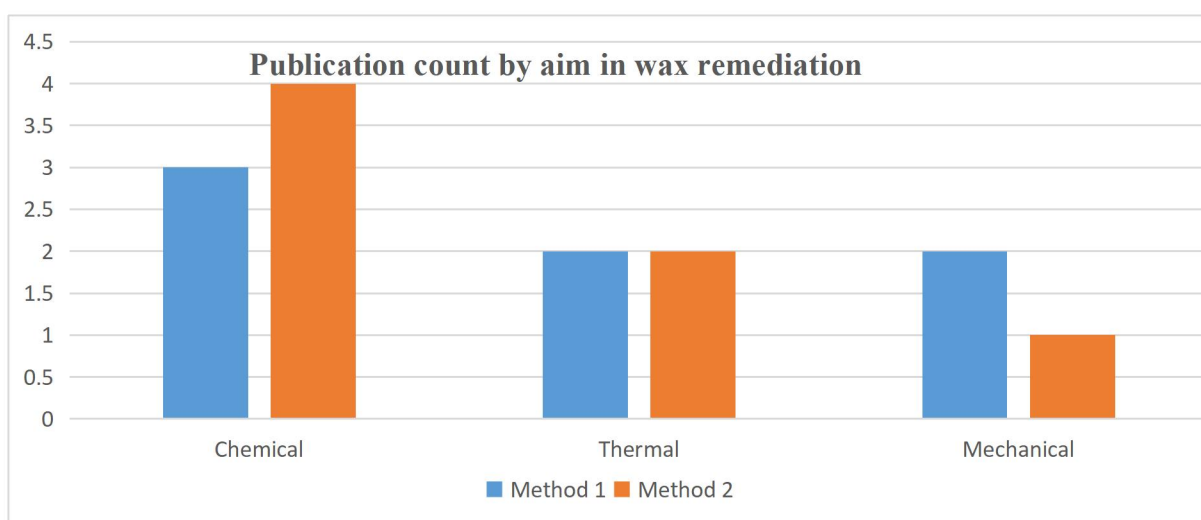


Figure 4-2: Publication count by aim in for wax deposition remediation

Remediation data	Method 1	Method 2
Chemical	Dispersants	Solvents
Thermal	Hot Oil	Hot Steam
Mechanical	Conventional pigging	Foam pigging

4.2. WERE THE STUDIES AN EXPERIMENT, SIMULATION, FIELD TRIAL OR A REVIEW PAPER?

For Chemical Methods of wax prevention and remediation, the publications used for the study has a combined count of 8 experiments, 5 review papers and 1 simulation publications

For Thermal Methods of wax prevention and remediation, the publications used for the study has a combined count of 1 experiment, 6 review papers, 1 field trial and 1 simulation publications

For Mechanical Methods of wax prevention and remediation, the publications used for the study has a combined count of 2 experiments and 2 review papers.

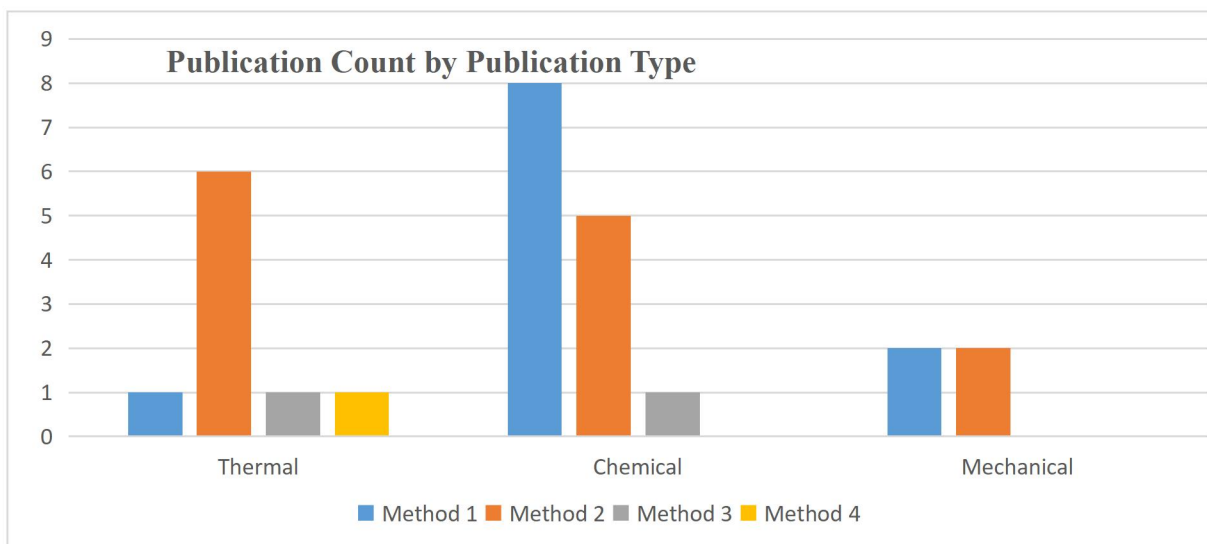


Figure 4-3: Publication count by publication type

Publication Type	Method 1	Method 2	Method 3	Method 4
Chemical	Experiment	Review	Simulation	-

Thermal	Experiment	Review	Simulation	Field Trial
Mechanical	Experiment	Review	-	-

4.3. WHAT PREVENTION/REMEDICATION/MITIGATION METHODS WERE STUDIED?

Chemical, Thermal and Mechanical methods of wax prevention and remediation technologies and techniques were studied in the review

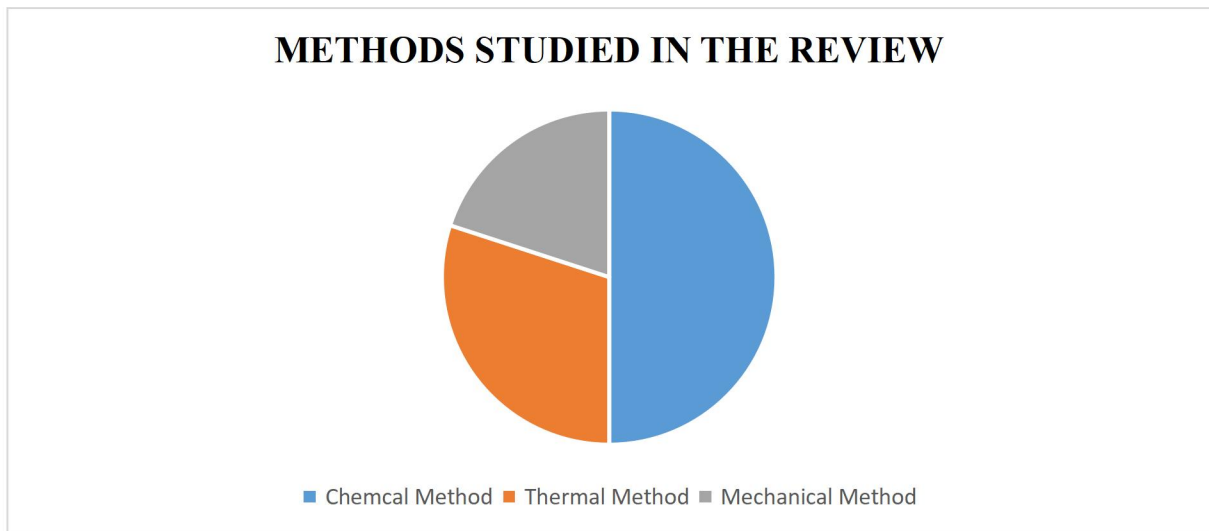


Figure 4-4: Publication count by methods studied in the review

4.4. WHAT WERE THE MAJOR RESULTS/FINDINGS FOR PREVENTION/REMEDICATION/MITIGATION IN THE STUDY?

4.4.1 Chemical Methods of preventing Wax:

1. Objective of Chemical Inhibitors

They reduce Wax Appearance Temperature (WAT) and pour point. They also lower viscosity and yield stress and prevent wax crystal agglomeration and formation of rigid crystalline lattices.

2. Conventional Inhibitors

- Pour Point Depressants (PPDs) and wax crystal modifiers:
- Disrupt wax crystal structures, creating smaller, less cohesive crystals.

- Effectiveness depends on dosage; optimum concentration yields maximum performance.
- Bio-based inhibitors: orange peel oil, coconut husk derivatives, locally sourced natural compounds.
- Cost-effective and environmentally friendly alternatives to synthetic chemicals.

3. Composite and Synergistic Formulations

- Mixtures of polyethylene, acrylate ester polymers, alkyl sulphonates, and xylene show enhanced inhibition (>60%).
- Drag reducing agents (DRAs) and dilution methods reduce turbulence, pressure losses, and energy costs.

4. Nanotechnology-Based Inhibitors (NPPDs)

Nanohybrids combining silica, montmorillonite, carbon nanostructures, and polymers like EVA has high stability and shear resistance, can lower pour point by up to 14 °C and viscosity by approximately 87% and promote multiple nucleation centers for better wax dispersion. Carbon nanotube and graphene oxide composites reduce WAT and gelation points via strong π - π interactions, hindering asphaltene aggregation.

5. Plant-Based and Biodegradable Inhibitors

Examples: Jatropha Seed Oil (JSO), Crude Palm Oil (CPO), Crude Palm Kernel Oil (CPKO) are rich in oleic acid, they disrupt wax crystal formation and maintain flow properties even below WAT.

Performance:

5% JSO had a Paraffin Inhibition Efficiency (PIE) of approximately 86.3%

CPO had a PIE of approximately 58.8% while CPKO had PIE of approximately 54.8%

Blends (e.g., castor + Jatropha oil) further enhance inhibition and flow stability.

4.4.2 Chemical Methods of remediating/mitigating Wax:

Chemical methods for remediating or mitigating wax mainly involve the use of dispersants, crystal modifiers, and solvent-based treatments. Dispersants, also called surfactants, prevent wax crystal agglomeration by keeping crystals suspended and reducing crude oil viscosity. Their low pour points make them effective in cold environments, and their performance improves with additives such as fatty amine ethoxylates, alkyl sulfonates, and alkoxyated compounds that enhance surface activity.

Comparative studies on dispersant D500 and crystal modifier CM500 show that both mitigate wax deposition effectively, though performance depends on brine content, flow rate, and chemical concentration. The dispersant performed best in the presence of 4% brine, while the crystal modifier was more effective without brine. Optimal additive concentration was around 500 ppm, as higher doses caused molecular self-association and reduced efficiency. Both additives performed better at higher flow rates, with CM500 showing a greater response than D500. Brine improved dispersant performance through hydrogen bonding that stabilized smaller wax particles. Longer flow paths and surface interactions reduced efficiency, and while dispersants altered surface wettability to aid wax removal, combining both additives produced no synergy.

Solvent-based remediation remains one of the most reliable wax removal techniques. Aromatic solvents like xylene and toluene dissolve wax and asphaltene effectively, with xylene achieving up to 99% wax dissolution within 150 minutes. Mixing aromatic and aliphatic solvents, such as a 70:30 xylene-to-kerosene blend, balances cost and performance. Green solvents like terpene also show strong solvency with lower toxicity and better biodegradability. Adding surfactants to solvent systems further enhances dispersion and wax breakup during cleanup.

4.4.3 Thermal Methods of preventing Wax:

Studies consistently show that preventing wax deposition in crude oil pipelines depends largely on maintaining the flow temperature above the Wax Appearance Temperature through effective thermal management and insulation. Field applications confirm that the Pipe-in-Pipe system with circulating heat media performs efficiently, maintaining stable hydraulic and thermal conditions even during long shutdowns. The use of a 30 wt% ethylene glycol solution as the heating fluid provided chemical stability, corrosion resistance, and consistent temperature control.

Direct Electrical Heating has emerged as one of the most effective long-term solutions. It works by passing alternating current through the pipeline wall to generate heat that keeps the fluid above the WAT. Variants such as open-loop, end-fed, and center-fed configurations differ in efficiency, with the latter two offering better insulation and reduced heat loss. Complementary systems like Induction Heating and Heat Tracing also perform well, using electromagnetic or resistive heat to prevent wax buildup. These technologies are especially suitable for deep water operations where reliable temperature control is essential.

The success of heating systems depends heavily on insulation quality. While wet insulation systems are common, dry insulation offers better durability and thermal efficiency. Advanced plastic materials such as polyurethane, isocyanurate, and ETFE are preferred for their strength, resistance, and cost-effectiveness in preventing temperature drops that trigger wax crystallization.

Recent innovations in insulation highlight silica aerogel blankets as exceptional materials for wax prevention. Aerogels have ultra-low thermal conductivity, high thermal stability, and fast temperature equilibration. Their nanoscale porous structure allows superior insulation even near high heat sources. Experimental and simulation results confirm their accuracy and efficiency, making them ideal for use in subsea and cold environments.

4.4.4 Thermal Methods of remediating/mitigating Wax:

Hot oiling has long been recognized as one of the most common methods for mitigating wax deposition in crude oil pipelines and production wells. The process involves heating oil to a high temperature sufficient to melt the wax crystals before pumping it into the well tubing or flowline. As the hot oil flows through the system, it transfers heat to the wax deposits, melting and dislodging them from the pipe walls. This procedure is sometimes complemented with the addition of wax dispersants to ensure that the melted waxes remain suspended in the crude oil, preventing their redeposition downstream. While hot oiling is widely applied in onshore and short-distance transportation systems, its application in subsea conditions is generally limited. This limitation arises from its high operational costs and the potential risk of permeability damage, particularly when melted waxes penetrate the reservoir formation. Consequently, hot oiling is best suited for land-based or nearshore operations where accessibility and cost considerations are more manageable.

Another thermal approach commonly employed in wax remediation is the use of hot water or steam treatment. This technique operates on a similar principle of heat transfer, but with notable advantages over hot oiling. Hot water or steam possesses a higher specific heat capacity, allowing it to retain more heat energy as it travels to the wax deposition site. This ensures that it arrives at the target location with a higher temperature, thereby improving wax melting efficiency. Additionally, water is generally more accessible and less costly than crude oil, making the process economically favorable. Since water contains minimal impurities compared to oil, it also reduces the likelihood of introducing contaminants into the pipeline system. However, the effectiveness of hot water treatment can be enhanced by adding surfactants to improve wax dispersion and minimize redeposition. Despite these advantages, the method presents some challenges, including the potential for corrosion and emulsion formation due to water–oil interactions, which can complicate downstream separation processes.

4.4.5 Mechanical Methods of preventing Wax:

Recent research highlights several innovative methods for preventing or mitigating wax deposition in crude oil pipelines. Magnetic treatment has shown strong potential as a non-chemical approach by using electromagnetic fields to alter the structure and polarity of paraffinic molecules. When crude oil flows through a non-uniform magnetic field, an electric field of about 10^3 V/m is induced, disrupting molecular aggregation and reducing wax crystallization on pipeline surfaces. This method is energy-efficient and environmentally friendly, offering a promising complement to traditional chemical and thermal techniques, though it is still in the early stages of field application.

Coating technology has also gained significant attention as an effective and versatile solution. Coatings form a protective barrier between crude oil and pipeline surfaces, preventing corrosion, minimizing friction, and improving thermal insulation. They enhance transportation efficiency, extend pipeline lifespan, and lower maintenance costs while improving safety through better impact and wear resistance.

Depending on function, coatings are classified as anti-corrosion, thermal insulation, or drag-reducing. Anti-corrosion coatings block oxygen and moisture or use zinc-rich layers for sacrificial protection. Some include corrosion inhibitors or self-healing microcapsules that release repair agents upon damage. Thermal insulation coatings use materials like polyurethane foam, rock wool, and aluminum silicate to minimize heat loss, while drag-reducing coatings smooth internal surfaces or use surfactant-based additives to reduce friction and surface tension.

The durability of coating systems depends on material properties such as adhesion, hardness, and flexibility, as well as application quality and operating conditions. High temperature, pressure, and humidity can accelerate degradation, highlighting the importance of regular inspection and maintenance.

Future coating innovations are proposed to focus on multifunctional, intelligent, and eco-friendly designs. Research is advancing toward coatings with self-diagnosing and self-repairing abilities, improved mechanical strength, and environmentally sustainable, water-based formulations. Integrated multifunctional coatings that combine anti-corrosion, insulation, and drag-reduction properties are expected to dominate future pipeline systems, offering cost efficiency and long-term performance in crude oil transport.

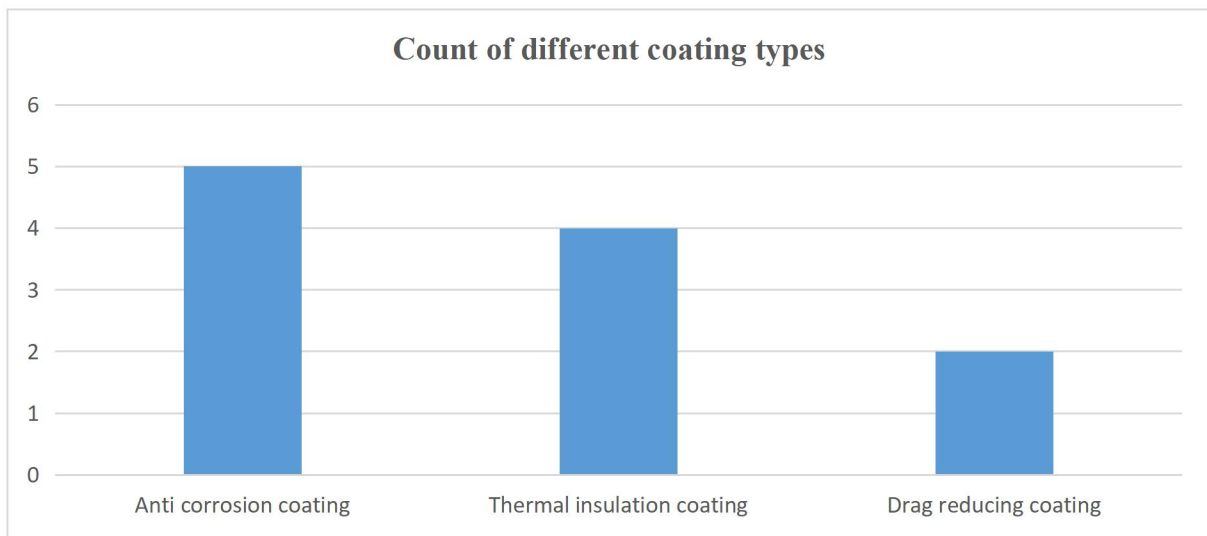


Figure 4-5: Publication count of different types coating

Coating type					
Anti-corrosion coating	Epoxy Coatings	Polyurethane Coatings	Polyolefin Coatings	Polyurea Coatings	Specialized/Composite Materials
Thermal insulation coating	Polyurethane Foam	Rockwool	Aluminum Silicate	Reflective Materials	-
Drag reducing coating	Internal Drag-Reducing Coatings	External Drag-Reducing Coatings	-	-	-

4.4.6 Mechanical Methods of remediating/mitigating Wax:

Mechanical pigging is one of the most effective methods for removing wax deposits from crude oil pipelines. It uses pipe inspection gauges, known as pigs, which scrape wax from the inner walls of the pipeline as they are pushed by the pressure of flowing crude oil. This process restores flow efficiency and is especially common in offshore and long-distance operations because of its reliability. In some wells, pigs are attached to sucker rods or wirelines to clean production tubing, and many pipelines are built with dual flowlines to make pigging easier and reduce downtime.

However, mechanical pigging faces challenges. Its efficiency depends on accurately predicting wax deposition rates and layer thickness. Excessive wax can cause downstream blockages or even trap the pig inside the pipeline, leading to costly shutdowns. To reduce these risks, bypass pigs were developed, allowing controlled fluid flow around the pig body to improve stability and wax-breaking force.

Recent studies introduced low-density foam pigs, which revealed a five-phase wax removal process build-up, pre-plug, damping, plug, and production differing from the traditional four-phase model. Foam pigs can deform elastically and absorb energy, improving interaction with wax deposits. Two main forces influence pigging: the initial wax breaking force, which is higher and poses the risk of pig sticking, and the steady wax breaking force, which maintains consistent wax removal once the layer is breached.

Foam pig density, wax layer thickness, and wax yield stress also affect performance. For softer wax, increasing pig density improves cleaning efficiency, while for stronger wax, the relationship becomes non-linear due to deformation and contact force effects. Thicker wax layers enhance removal, but higher wax strength increases resistance and lowers efficiency.

Overall, mechanical pigging remains vital for wax remediation. Its effectiveness relies on understanding wax rheology, pig material properties, and flow dynamics. Advances like foam

and bypass pigs continue to make the process safer, more efficient, and better suited for modern pipeline systems.

4.5. WHAT MATERIALS WERE USED\PROPOSED FOR THE PREVENTION/REMEDIATION/MITIGATION?

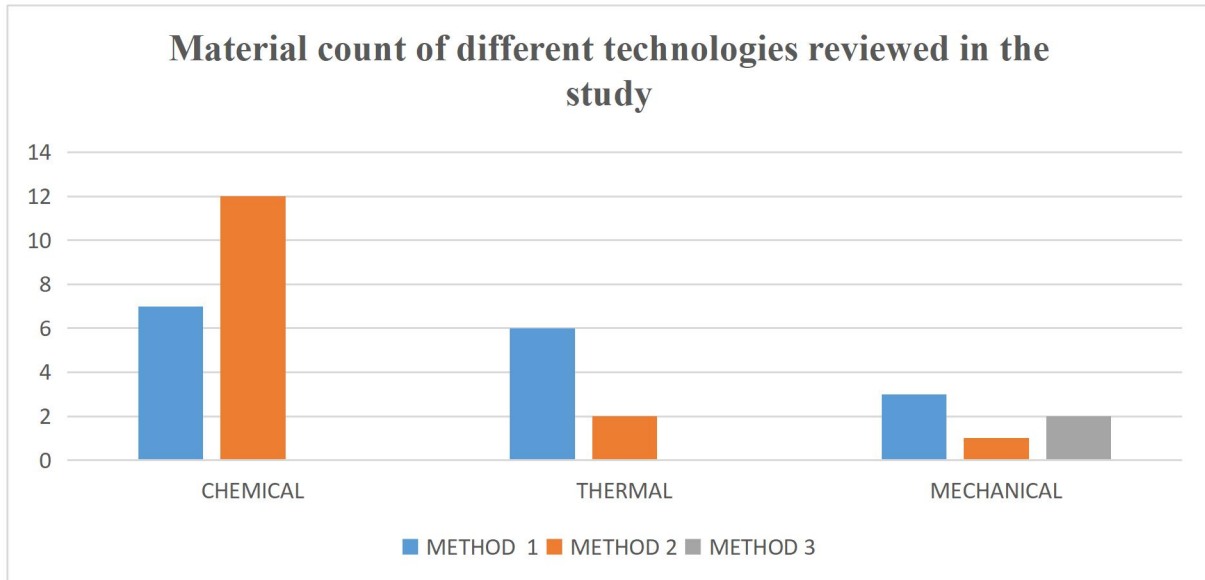


Figure 4-6: Publication count of different types of technologies reviewed

	Method 1	Method 2	Method 3
Chemical	Bio-derived locally sourced inhibitors	Synthetic chemicals	-
Thermal	Heating	Insulation	-
Mechanical	Coating	Magnetic Application	Pigging

4.5.1 Chemical Methods of preventing Wax:

Studies on wax deposition prevention have evolved from using conventional synthetic inhibitors to developing eco-friendly and advanced nanocomposite materials. Natural and plant-based inhibitors such as orange peel oil, soya bean husk oil, and methanol-cellulose from coconut husk have shown strong potential as biodegradable and sustainable alternatives.

Oils like Jatropha seed oil, crude palm oil, and palm kernel oil rich in oleic acid effectively disrupt wax crystallization. Blends of Castor seed and Jatropha seed oils also enhance inhibition through the interaction of unsaturated fatty acids with paraffin molecules.

Polymeric inhibitors like ethylene-vinyl acetate, poly(methyl methacrylate), and polyacrylate polymers act as wax crystal modifiers by co-crystallization and adsorption, altering crystal structure and reducing pour point and viscosity. Customized blends of polyethylene, xylene, acrylate ester polymer, and alkyl sulphonate have shown high inhibition efficiency, while triethanolamine and oleic acid blends further improve performance through van der Waals interactions with wax molecules. Flow improvers such as drag reducing agents, surfactants, nanoparticles, and polymers like polyisobutylene and xanthan gum also help reduce viscosity and friction losses, enhancing crude flow efficiency.

Recent innovations focus on nanohybrid pour point depressants that combine polymer inhibitors with nanoparticles such as nano-SiO₂, graphene oxide, carbon nanotubes, and magnetic ferrite (Fe₃O₄). These materials provide superior adsorption, stability, and thermal resistance by creating multiple nucleation sites that modify wax crystal morphology and prevent aggregation.

4.5.2 Chemical Methods of remediating/mitigating Wax:

1. Dispersants and Surfactants: They prevent wax crystals from aggregating and adhering to pipeline walls. They form a thin protective film, reducing viscosity and aiding wax transport with flowing crude. The common types are fatty amine ethoxylates, alkyl sulfonates, alkoxyated derivatives (cost-effective). Polyalkylated phenol dispersants showed superior performance by adsorbing on wax surfaces, altering wettability, and disrupting crystal networks. The performance enhanced by brine (e.g., 5 wt% NaCl) improves dispersant efficiency in multiphase systems.

2. Solvent Treatments: This directly dissolve deposited wax to restore flow. They are categorized into Aromatic solvents e.g xylene and toluene which are highly effective. Xylene dissolves nearly 99.4% of wax in 150 min, Aliphatic solvents e.g kerosene which dissolves approximately 35.4% but lowers cost and Blends; a 70:30 xylene-to-kerosene mixture balances efficiency and expense.

3. Green Solvents: are environmentally friendly alternatives to toxic aromatic solvents. They are derived from natural sources like pine resin and citrus peels. Examples include alpha-pinene, beta-pinene, d-limonene. Its advantages includes: lower toxicity, reduced flammability, improved biodegradability, and high solvency power.

4.5.3 Thermal Methods of preventing Wax:

1. Active Heating Systems: helps to maintain flow line temperatures above wax and hydrate formation thresholds, providing continuous temperature control. They help to reduce heat loss, minimizes wax formation, and ensures flow assurance during shutdowns or restart operations.

2. Electrical Heating Technologies: Is grouped into (a) direct Electrical Heating (DEH): Applies AC current to the pipeline wall to generate heat via electrical resistance. Its configurations include Open-loop, end-fed (enhances heat generation through skin/proximity effects.), center-fed (distributes heat more evenly along the pipeline.) and PIP DEH systems and (b) Indirect heating: uses conduction tube, induction, or cable heating transmit heat externally. It is less efficient thermally but offer better electrical control and suitable for short-distance applications.

3. Passive Insulation Methods: Is essential for subsea pipelines to reduce heat loss and maintain stable operating temperatures. Materials used includes: Polypropylene, polyurethane, fiberglass, mineral wool, vacuum insulation panels (VIPs), aerogel. The techniques include:

- Wet insulation: Allows limited water ingress; suitable for deep water pipelines.
- Dry insulation: Provides superior thermal retention; sensitive to moisture.
- Flowline burial: Seabed acts as a natural insulator, improving heat retention up to 4× but increases installation cost.

4. Advanced Insulation Innovations: PIP insulation: Inner and outer pipes separated by aerogel or polyurethane foam; low U-values ($\sim 0.5\text{--}1.0\text{ W/m}^2\text{K}$) effectively prevent wax crystallization. Vacuum-insulated tubing (VIT) & multilayer insulation: Further reduce thermal conductivity but are high-cost solutions.

Experimental rubber-based layers: Show promising heat retention but limited durability under freeze–thaw cycles.

4.5.4 Thermal Methods of remediating/mitigating Wax:

Thermal methods such as hot oiling and hot water treatment are widely used to remove wax deposits from production tubing and flowlines by melting and mobilizing solidified paraffins. In hot oiling, crude oil is heated above the wax melting point and pumped down the wellbore, transferring heat to liquefy and dissolve wax layers along the tubing walls. Wax dispersants are often added to prevent re-solidification as the fluid cools. The process's efficiency depends on maintaining sufficient temperature and oil volume to reach all wax-prone zones. However, if not properly managed, melted wax can migrate into the formation and cause permeability damage, and the method is unsafe for low-flash-point crude oils. Though effective for onshore systems, hot oiling is rarely used in subsea operations due to high cost and technical challenges.

Hot water treatment, on the other hand, circulates heated water or steam through the tubing or flowline to melt paraffin deposits. Because water has a higher specific heat capacity than oil, it delivers greater thermal energy and is more economical. However, water lacks solvency, so surfactants are added to improve wax dispersion by suspending melted particles at the water–

oil interface. Despite its cost advantage, hot water treatment can cause corrosion and promote emulsion formation, requiring corrosion inhibitors and demulsifiers to reduce risks.

4.5.5 Mechanical Methods of preventing Wax:

Induced electric and magnetic field treatments offer an innovative non-chemical method for controlling wax deposition. When crude oil flows through a non-uniform magnetic field, a high-intensity electric field forms, altering the solubility of paraffinic wax molecules. This effect promotes controlled wax crystallization in the bulk flow and reduces adhesion on pipeline walls, improving flow and reducing blockages. The method is energy-efficient and non-invasive, though large-scale application is still being studied.

Complementing this approach are coating technologies that act as passive barriers against wax adhesion, corrosion, and heat loss. Coatings are mainly categorized as anti-corrosion, thermal insulation, and drag-reducing types. Anti-corrosion coatings, such as epoxy-based systems, polyurethane, and polyolefin layers, protect pipelines from chemical and environmental damage while improving durability and adhesion. Advanced materials like zinc-rich coatings, polyaniline-modified epoxy, Ni-Fe-SiC nanocomposites, and graphene-modified organosilicon coatings offer enhanced conductivity, wear resistance, and thermal stability. Self-healing coatings with embedded microcapsules further extend protection by repairing microcracks automatically. Thermal insulation coatings, including polyurethane foam, rockwool, and aluminum silicate fiber fabric, help maintain crude temperature above the wax appearance point. Reflective materials such as aluminum foil are used in multi-layer systems to reduce heat loss, especially in long-distance or subsea pipelines. Drag-reducing coatings like PTFE, epoxy resin, and polyurethane minimize friction and pumping energy by creating smooth internal surfaces. Externally, polyurea and polyurethane layers also protect pipelines from abrasion and environmental effects. Emerging research focuses on multifunctional and eco-friendly coatings that combine anti-corrosion, insulation, and drag-

reducing properties. Intelligent self-repairing and biodegradable coatings are also being developed to improve durability, energy efficiency, and environmental performance in modern oil and gas transport systems.

4.5.6 Mechanical Methods of remediating/mitigating Wax:

The mechanical or pigging method remains one of the most extensively utilized and effective techniques for wax removal in crude oil pipelines. This approach employs pipe inspection gauges (commonly known as pigs) to scrape off precipitated wax deposits that accumulate along the internal walls of pipelines. In this method, a pig whose diameter is slightly smaller than that of the pipeline is launched from a pig launcher and propelled by the pressure of the flowing oil. As it travels through the line, the pig dislodges and removes wax buildup from the pipe wall, thus restoring flow efficiency (Aiyejina et al., 2011).

Foam pigs, have gained prominence in field operations because of their operational safety and adaptability. They are less likely to get stuck within the pipeline, making them ideal for continuous pigging operations. In experimental investigations, foam pigs fabricated from polyurethane were employed at varying densities typically 80, 120, and 180 kg/m³ to study the influence of material properties on wax removal efficiency. The variation in foam density allows for an optimized balance between flexibility and the mechanical force required to dislodge wax deposits, with denser pigs exhibiting higher cleaning efficiency but greater frictional resistance (Aiyejina et al., 2011).

While the pigging process is highly effective in removing accumulated wax, its success depends largely on accurate prediction of deposition rates and pipeline flow characteristics. Excessive wax buildup can sometimes hinder pig movement, causing pressure drops and potential system shutdowns if the pig becomes lodged. Furthermore, large chunks of dislodged wax may accumulate downstream, leading to partial or complete blockage of the line. To mitigate such operational risks, bypass pigs were developed, featuring a central

channel that allows fluid flow through the pig. This flow generates turbulence ahead of the pig, improving wax breakup and reducing the likelihood of pressure buildup or pig entrapment. Studies have shown that the wax-breaking force of bypass pigs increases as the oil content in the deposited layer decreases and as the thickness of the wax layer increases, further enhancing their cleaning performance (Aiyejina et al., 2011).

4.6. HOW SHOULD/WERE THE METHOD APPLIED FOR PREVENTION/REMEDICATION/MITIGATION IN THE STUDY?

4.6.1 Chemical Methods of preventing Wax:

Prevention of wax deposition in crude oil pipelines is primarily achieved through chemical treatment, involving the formulation and application of natural, polymeric, or synthetic inhibitors under controlled conditions. These additives function by altering the physicochemical behavior of crude oil, preventing wax agglomeration, crystal coalescence, and pipeline blockages.

Locally sourced, plant-based inhibitors, such as orange-peel oil, soya bean husk oil, and methanol–cellulose (WI-MC) derived from coconut husk, have demonstrated notable effectiveness. Extraction typically involved Soxhlet apparatus treatments with n-hexane or methanol, followed by purification via rotary evaporation. The inhibitors were dosed into crude oil samples (e.g., 2100 ppm) and assessed for Wax Appearance Temperature (WAT) and viscosity changes. Experimental results confirmed significant reductions in WAT and viscosity, highlighting their ability to hinder wax crystal growth and aggregation (Aiyejina et al., 2011; Okoye et al., 2021).

Synthetic and polymeric inhibitors, including alkyl sulphonates, polyethylene, acrylate ester copolymers, ethylene–vinyl acetate (EVA), and triethanolamine (TEA), have also been widely studied. These compounds act as wax dispersants or crystal modifiers, altering wax morphology, reducing adhesion, and improving flowability. Optimized formulations

combining multiple inhibitors achieved up to 62% reduction in wax deposition relative to untreated samples (Aiyejina et al., 2011).

Natural oils such as crude palm oil (CPO), crude palm kernel oil (CPKO), and Malaysian *Jatropha* seed oil (JSO) exhibit inhibition primarily through steric hindrance and co-crystallization. Oleic, linoleic, and ricinoleic acids within these oils interact with paraffin chains, preventing the formation of interlocking wax networks. Cold finger deposition tests and rheological analyses confirmed their efficacy under simulated subsea temperature gradients (bulk: 60 °C; probe: 45 °C) (Abdullah et al., 2020).

Molecular dynamics simulations and laboratory validation further elucidated the microscopic mechanisms. Simulations using COMPASS force fields revealed that inhibitors, including oleic acid, EVA, and TEA, prevent wax aggregation via van der Waals interactions and surface adsorption, disrupting crystal nucleation and growth. Cold finger experiments confirmed reductions in wax deposition across inhibitor concentrations ranging from 0.1 to 10 wt% (Idowu et al., 2022).

Blends of plant-based oils have shown synergistic effects. For instance, a mixture of 40% JSO in Castor seed oil (CSO) significantly improved pour point and inhibited wax formation, comparable to a TEA–xylene chemical blend at equivalent dosage (0.1% v/v). The performance was attributed to the polar functional groups of unsaturated fatty acids interacting with paraffin molecules, preventing network formation (Oboh et al., 2021).

Experimental setups typically simulated field-relevant conditions, with temperature ranges of 30–60 °C for viscosity and WAT measurements, cold finger gradients of 45–60 °C, and flow loop rates of ~45 L/min. Inhibitor dosages varied between 0.1 wt% and 2100 ppm, optimized for both efficiency and environmental compatibility.

4.6.2 Chemical Methods of mitigating/remediating Wax:

The removal of paraffin wax using chemical additives was evaluated through a controlled flow test designed to replicate wax blockage under laminar flow conditions. Two oil-soluble additives a dispersant and a crystal modifier were selected from an initial screening of nine candidates based on their potential to modify wax crystal behavior and improve crude oil flow performance.

Additive Preparation and Pre-Heating: Each additive was pre-heated and homogenized to prevent premature wax precipitation. The additive shale oil mixtures were loaded into 60 mL syringes and maintained at 55 °C in a convection oven prior to injection. This temperature, above the crude oil's Wax Appearance Temperature (WAT approx.. 40 °C), ensured uniform dispersion of the additives before entering the flow system.

Flow Test Setup: The experimental apparatus comprised a simple open-flow system, where the additive–oil mixture was injected into horizontal stainless-steel capillary tubes (1 ft and 2 ft in length) using a precision syringe pump. The system was maintained at room temperature (25 °C), deliberately below the WAT to promote wax precipitation and simulate blockage formation. This setup minimized fluid handling and allowed precise observation of deposition behavior under controlled small-scale conditions.

Additive Concentration: Concentrations ranged from 100 to 800 ppm. Optimal performance was observed at ~500 ppm, beyond which efficiency decreased due to potential over-saturation or incompatibility with wax. Laminar flow rates of 0.75, 1.5, 3, and 6 mL/h were tested. Higher flow rates improved remediation efficiency, likely due to enhanced mixing and reduced wax adhesion time. Tests included co-injection of a 5 wt% NaCl solution at Water-to-Oil Ratios (WORs) of 2% and 4% via a union-tee fitting. This simulated multiphase flow and evaluated the synergistic or adverse effects of brine on additive performance.

Performance Evaluation: Remediation efficiency was quantified by the total pore volume (PV_b) or fluid volume (V_b) that passed through the tube before blockage occurred. Blockage

was defined by an inlet pressure exceeding 15 psig (5 psig for certain CM tests). Improvements were indicated by increased PVb or Vb relative to untreated oil or oil–brine controls.

Mechanisms of Action: The two additives operated through complementary mechanisms:

Crystal Modifier: Co-crystallized with paraffin wax molecules, altering lattice structures to produce smaller, less cohesive crystals. This inhibited formation of continuous wax networks that cause deposition and blockage.

Dispersant: Acted as a surfactant adsorbing on wax particle surfaces and the pipe wall, changing wettability from hydrophobic to hydrophilic. This reduced adhesion and enhanced suspension of wax particles in the flowing crude.

The presence of brine improved dispersant efficiency through hydrogen bonding between water molecules and hydroxyl groups on the dispersant, stabilizing its activity and inhibiting both bulk-phase and near-wall wax growth. Consequently, the combination of dispersant and brine reduced deposition rates and prolonged flow duration before blockage, demonstrating its potential as an effective chemical remediation strategy for wax management in pipelines.

4.6.3. Thermal Methods of preventing Wax:

Wax deposition in pipelines is primarily prevented by maintaining crude oil above its Wax Appearance Temperature (WAT) using thermal management systems. Passive insulation methods, such as pipe-in-pipe (PIP), foam insulation, and flowline burial, reduce heat loss and delay wax crystallization. PIP systems use an insulating annulus or air gap to sustain temperature above WAT, minimizing solid wax formation (Singh et al., 2000; Aiyejina et al., 2011).

Active heating methods introduce continuous energy to prevent wax precipitation. Key techniques include Direct Electrical Heating, which uses pipeline wall resistive heating, and

Hot Water Circulation, circulating glycol solutions within a PIP annulus to stabilize temperature (Singh et al., 2000; Banki et al., 2008). Active heating reduces the need for pigging and is particularly effective in deepwater operations.

The choice between passive and active systems depends on environmental conditions, flowline length, crude properties, and economics. Combining passive insulation with active heating improves energy efficiency and ensures reliable crude transport while minimizing wax deposition, operational downtime, and extending pipeline life (Aiyejina et al., 2011; Banki et al., 2008; Singh et al., 2000).

4.6.4. Thermal Methods of remediating/mitigating Wax:

Wax removal is commonly achieved via hot oiling and hot water/steam treatments, which melt and mobilize paraffin deposits in flowlines and production tubing. Hot oiling involves heating crude above the wax melting point and circulating it through the well annulus, often with wax dispersants to prevent re-deposition. Its effectiveness depends on wax composition, molecular weight, and temperature profiles, with heavier waxes depositing in hotter zones. Limitations include formation damage, safety risks, and high cost in subsea applications (Becker, 2000; Allen & Roberts, 1982).

Hot water/steam treatments are cost-effective alternatives, leveraging water's high specific heat capacity for heat transfer. Surfactants are added to improve wax dispersion by suspending solid particles at the wax–water interface. Challenges include potential corrosion and emulsion formation, requiring careful process control (Becker, 2000).

4.6.5. Mechanical Methods of preventing Wax:

Wax prevention has been approached via magnetic treatment (MT) and advanced pipeline coatings. MT employs an analytical model to predict wax deposition under flowing oil exposed to a non-uniform magnetic field, generating an induced electric field ($\sim 10^3$ V/m) that

alters wax solubility and crystal orientation. The model incorporates heat/mass transfer, asphaltene content, water cut, and oil viscosity, enabling predictions of wax layer growth, internal diameter reduction, and time between overhauls (TBO). Validation against field data confirmed MT's effectiveness in reducing wax deposition (Allen & Roberts, 1982; Becker, 2000).

Pipeline coatings provide passive protection against wax adhesion, heat loss, corrosion, and friction. Types include:

Anti-corrosion coatings: epoxy (liquid/solid), polyolefins (PE/PP) applied via spraying or extrusion.

Thermal insulation coatings: polyurethane foam, rockwool, aluminum silicate to maintain temperature above WAT.

Drag-reducing coatings: PTFE, epoxy, polyurethane, polyurea to reduce frictional resistance.

4.6.6. Mechanical Methods of remediating/mitigating Wax:

Wax deposition in pipelines is commonly mitigated using mechanical pigging, which removes wax via pipe inspection gauges (PIGs) propelled by oil pressure or wireline/sucker rods. Pigs scrape wax from the pipe wall, restoring flow efficiency. Bypass pigs allow partial fluid passage to prevent pressure buildup while enhancing wax-breaking force, particularly with thicker deposits (Aiyejina et al., 2011).

Experimental studies using foam pigs (densities 80–180 kg/m³) in pipe-in-pipe setups with controlled wax layers (2–6 mm) have elucidated wax removal physics. Tests monitored resistive forces, wax yield stress, and removal efficiency. Analysis revealed a five-phase removal mechanism for low-density foam pigs: build-up, pre-plug, damping, plug, and production phases, showing elastic buckling and energy absorption during deformation.

Effectiveness depends on wax layer properties, pig density, velocity, and pipeline geometry. Combining experimental data and physical modeling enables optimization of pig design and pigging schedules, ensuring minimal downtime and sustained pipeline integrity.

4.7. WAS THERE ANY LIMITATION, CHALLENGES OR SIDE EFFECTS DOCUMENTED IN THE STUDIES?

4.7.1 Chemical Methods of preventing Wax:

PPDs, DRAs, WI-MC, TEA, toluene) face challenges such as viscosity increase, pressure loss, energy consumption, and shear degradation of polymeric DRAs. Effectiveness depends on crude composition, operating conditions, and optimum additive concentration, with overdosing sometimes reducing performance. Environmental and health risks due to toxicity and high cost are additional concerns.

Laboratory experiments often fail to replicate field conditions, with inaccuracies caused by sample depletion, finite flow, and measurement errors (± 0.005 – 0.059 mm). Natural additives (CPO, CPKO, JSO) may lose efficiency at high doses, acting as nucleation sites, and are generally less effective than commercial inhibitors.

Nanocomposite pour point depressants face unresolved mechanistic contradictions, limited thermal stability, poor crude compatibility, and high production costs. Some formulations can increase wax hardness or reduce performance under magnetic fields.

Operational challenges include high wall viscosity, unstable flow regimes, and increased differential pressure at low temperatures, highlighting the need for optimized dosing, chemical stability, and field validation.

4.7.2 Chemical Methods of remediating/mitigating Wax:

Experimental design constraints: Use of capillary tubes instead of closed-loop systems ensured consistent wax content but could not replicate large-scale pipeline flow dynamics. Blockage detection was subjective, and stochastic wax deposition led to variability between runs. Assumptions of Newtonian flow and uniform roughness became less accurate as wax accumulated. Wettability data were incomplete due to missing contact angle measurements.

Mechanistic challenges: Pressure fluctuations were difficult to interpret, reflecting both constriction and shear removal. Particle re-entrainment and random blockage location added uncertainty.

Chemical additive limitations: Both dispersants and crystal modifiers showed optimal performance around 500 ppm, with efficiency declining at higher concentrations due to particle association. At low flow rates, dispersants could promote blockage via surface adsorption; crystal modifiers sometimes generated harder, more adherent wax layers.

Solvent-based remediation: Effective for wax removal (xylene, toluene) but limited by high cost, fire risk, corrosion, and environmental concerns. High molecular weight waxes are less responsive, making large-scale solvent use economically and practically challenging.

4.7.3 Thermal Methods of preventing Wax:

Design and material challenges: Subsea pipelines face flow assurance risks due to wax and hydrate formation. Corrosion is critical when using seawater or freshwater; aqueous glycol was adopted for stable heat transfer and lower corrosion potential. Thermal cycling causes fatigue, expansion, and local bending, mitigated via controlled lateral buckling points.

Operational limitations: Continuous operation is essential; interruptions from storms or leaks reduce system effectiveness. Modified pipe-in-pipe (PIP) design with insulation on the outer layer improved thermal efficiency, corrosion protection, and heat-medium circulation. Direct

Electrical Heating (DEH): Wet-insulated DEH faces electrical losses, limited insulation, EMI, and infrastructure demands. PIP-DEH is costly and complex.

Insulation material challenges: Aging, freeze–thaw cycles, and permafrost degradation reduce long-term performance. Silica aerogels have low mechanical strength and brittleness; repeated cycling degrades thermal conductivity, necessitating composite reinforcement.

Modeling limitations: Discrepancies exist between predicted and measured temperatures due to environmental variations and instrument heat loss, requiring refinement of numerical and experimental models.

4.7.4 Thermal Methods of remediating/mitigating Wax:

Despite its widespread application, hot oiling presents notable limitations that restrict its use, particularly in offshore and subsea operations. The method requires heating oil to temperatures above the wax melting point before circulation through the well or flowline. While effective in dissolving wax, it poses the risk of permeability damage when melted waxes migrate into the formation, potentially reducing reservoir productivity. Additionally, the technique is energy-intensive and costly, especially under subsea conditions where maintaining elevated temperatures over long distances is economically impractical. Hot oiling is therefore best suited for short-distance crude transportation and surface facilities rather than deep water or long tie-back systems. The process also becomes less effective in wells producing crudes with low flash points, as excessive heating can create safety hazards.

Hot water treatment, though more cost-effective due to water's availability and higher specific heat capacity, has its own operational drawbacks. The lack of solvency in water compared to oil limits its ability to dissolve wax completely, necessitating the addition of surfactants to improve dispersion. However, this introduces the risk of emulsion formation, which complicates downstream separation processes. Furthermore, prolonged use of hot

water systems can promote corrosion within pipelines and flowlines, particularly if adequate inhibitors are not applied.

4.7.5 Mechanical Methods of preventing Wax:

Magnetic Treatment (MT): Paraffin hydrocarbons have extremely low magnetic susceptibility; magnetic fields (10^4 – 10^5 A/m) cannot directly prevent wax crystallization. Viscosity effects vary with crude composition dependent on asphaltenes and polar resins leading to unpredictable results. Ineffective for low-viscosity oils (<1% asphaltenes). Model limitations exclude viscosity destruction mechanisms, potentially underestimating viscosity changes by 15–20%. Efficiency decreases with higher viscosity and in multiphase flow when oil is not the continuous phase.

Anti-Wax Coatings: Polymer and fluorinated coatings are prone to mechanical wear, erosion, delamination, and chemical incompatibility under high temperature or reactive crude conditions. Performance declines under turbulent flow, high asphaltene/resin content, or uneven application. Damaged coatings can create localized deposition zones. Coatings have high cost and application complexity, especially in long subsea pipelines, limit scalability.

4.7.6 Mechanical Methods of remediating/mitigating Wax:

Foam pigs have high initial wax-breaking force due to elastic buckling during start-up increases risk of pig sticking. Its efficiency drops against high-strength wax deposits; elastic deformation limits scraping capacity. Low density foam pigs are adaptable but sensitive to wax yield stress and flow conditions.

Disc and cup pigs have rigid structure that leads to higher frictional resistance, especially in pipelines with bends or varying diameters. Bypass flow limitations cause uneven wax removal and potential downstream accumulation. There is a risk of jamming in restricted sections and it is less adaptable than foam pigs for irregular pipelines.

4.8. IS THE METHOD MORE COST EFFECTIVE, ENVIRONMENTALLY FRIENDLY OR FIELD APPLICABLE COMPARED TO OTHER CONVENTIONAL METHODS?

4.8.1 Chemical Methods of preventing Wax:

Chemical inhibitors from local/renewable sources (orange peel, soybean husk, coconut husk, castor/jatropha oils) are economical and perform comparably to solvents like toluene. Nanoparticle-based PPDs and magnetic nanocomposites reduce dosage (≈ 100 ppm) and energy use. Hybrid chemical–DRA strategies improve flow and reduce power costs; solvent blends (xylene–kerosene 70:30) are cheaper than pure xylene compared to thermal methods that are of high-cost due to electricity and operational demands.

Bio-based and biodegradable inhibitors (terpene solvents, plant oils, coconut husk derivatives) lower toxicity and carbon footprint. Conventional thermal and solvent methods pose environmental hazards: low flash point, corrosion, chemical toxicity.

Chemical, hybrid, and nano-modified inhibitors allow direct injection without production shutdowns, providing flexible and reliable operation. DRAs and viscosity-reduction emulsions show operational success in real pipelines.

4.8.2 Chemical Methods of remediating/mitigating Wax:

Dispersants, crystal modifiers, and solvent treatments are more economical than thermal and mechanical methods. Optimal chemical concentration (~ 500 ppm) improves efficiency while reducing waste and costs. Xylene dilution maintains performance at lower expense; dispersants are cheaper due to low dosage requirements. Traditional solvents (benzene, chlorinated hydrocarbons) are toxic. Green alternatives like terpene (from pine resin, orange peel) are biodegradable and eco-friendly.

Open flow system experiments reflect real pipeline conditions via cumulative oil volume before blockage. Crystal modifiers maintain performance during scale-up for long pipelines.

Brine presence enhances dispersant efficiency in multiphase flow, though low flow rates can reduce effectiveness due to pipe adhesion.

4.8.3 Thermal Methods of preventing Wax:

Active Heating (Aqueous Glycol Circulation): is cost-effective and practical for offshore/deepwater pipelines. It maintains flow line temperature above wax/hydrate thresholds, reducing pigging and operational downtime. It has reliable hydraulic and thermal performance which is useful for shutdown and hydrate remediation.

Electrical Heating (DEH & Heat Tracing): reduces or eliminates chemical injection, lowering operational and capital costs. It is environmentally friendly; field-proven in deepwater (>1000 m) and long tiebacks (>200 km). Although Pipe-in-pipe and induction heating are still emerging; DEH is preferred for complex subsea operations.

Thermal Insulation: is economical and field-applicable; prevents permafrost degradation, structural stress, and thaw settlement. Advanced materials like silica aerogel blankets offer low thermal conductivity (approx. 0.015 W/mK), lightweight, flexible, and environmentally sustainable.

4.8.4 Thermal Methods of remediating/mitigating Wax:

Hot oil and hot steam treatment methods are relatively cost-effective and field applicable but have limited environmental advantages compared to more modern techniques. Hot oiling involves circulating heated crude or diesel oil through the pipeline to melt deposited wax. It is practical for short-distance flowlines and onshore systems due to its simplicity and immediate effectiveness. However, repeated use increases operational costs because of frequent reheating and potential heat losses to the surroundings. The process can also reduce crude quality and lead to sludge formation, making it less environmentally friendly.

Hot steam injection, on the other hand, is highly effective for severe wax blockages because it delivers intense localized heat that rapidly restores flow. It is especially useful in land-based systems or wells where mechanical pigging is not feasible. Despite its strong thermal efficiency, the method is energy-intensive, requires significant water supply, and may pose corrosion risks to pipelines. This increases operational cost and limits long-term environmental sustainability.

4.8.5 Mechanical Methods of preventing Wax:

Magnetic Treatment (MT): Enhances Time Between Overhauls (TBO), reducing maintenance frequency and downtime. It improves flowability, particularly in high-viscosity, waxy crude oils. Its efficiency depends on oil composition, viscosity, and flow rate; less effective for low-viscosity oils with low asphaltene content. It has indirect environmental benefit by potentially reducing chemical inhibitor usage.

Coating Technology: has low-cost, efficient, and widely applicable for pipeline protection. It reduces heat/friction losses, prolongs service life, and lowers operational costs. Multifunctional coatings combine anticorrosion, thermal insulation, and drag reduction. It is applicable across onshore, subsea, and variable temperature pipelines. Emerging green coatings use biodegradable, non-toxic, solvent-free materials.

4.8.6 Mechanical Methods of remediating/mitigating Wax:

Mechanical Pigging: Is the most established and reliable method for wax removal in pipelines. Foam pigs are flexible, navigate varying diameters and irregularities; best for light to moderate wax layers. Disc and cup pigs have higher mechanical strength, better for high-strength wax deposits.

From economic consideration perspective foam pigs have low manufacturing cost but risk of sticking due to high initial wax-breaking force. Disc/cup pigs may have higher upfront cost but provide consistent cleaning efficiency and lower long-term blockage risk.

Pigs are safer than chemical treatments as they have no toxic additives or solvents involved.

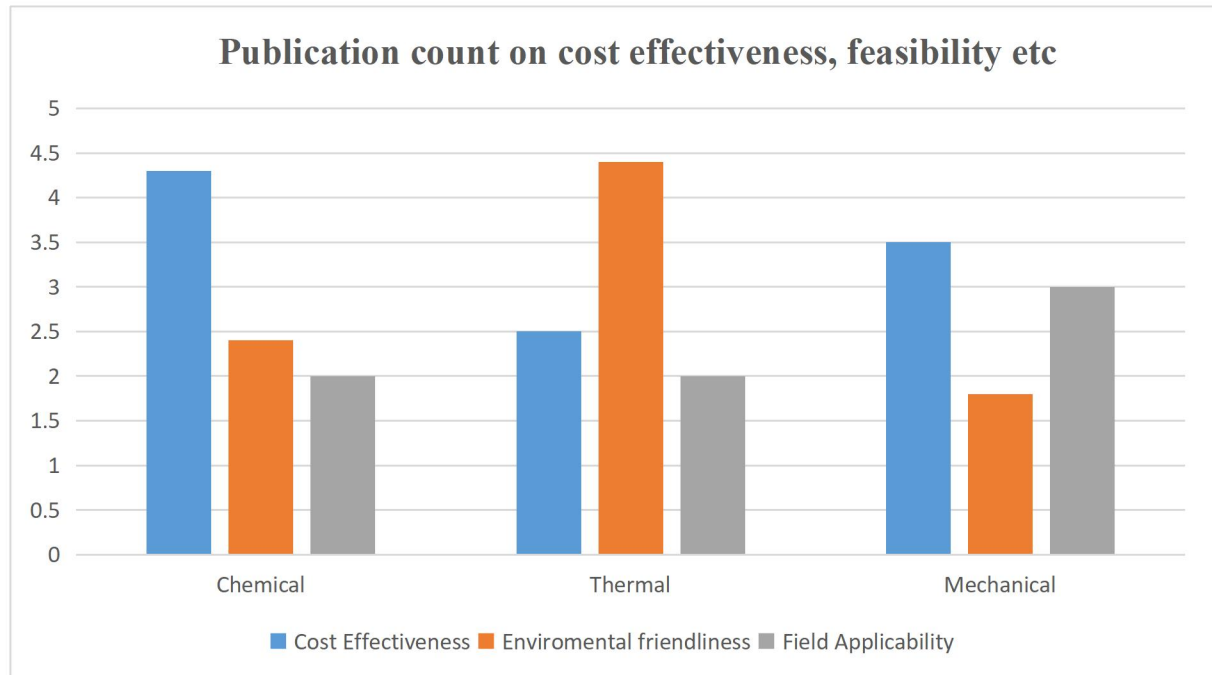


Figure 4-7: Publication count on cost effectiveness, feasibility etc

4.9. DID THE AUTHORS DOCUMENT ANY RESEARCH GAPS OR RECOMMENDATIONS FOR FUTURE WORK?

4.9.1 Chemical Methods of preventing Wax:

Regional Focus: Limited predictive understanding of wax formation in Nigerian oil fields (approx.70% affected), particularly accurate determination of Wax Appearance Temperature (WAT).

Chemical Inhibitors: Need for optimized solvent selection, improved polymeric drag-reducing agents, and biodegradable, non-toxic inhibitors. Future work should validate

laboratory-developed inhibitors (e.g., WI-MC, CSO–JSO blend) under field-scale, dynamic flow conditions.

Mechanistic Understanding: Limited knowledge of nano-pour point depressants (NPPDs); research should clarify mechanisms, optimize synthesis and dosage, and explore magnetic and carbon-based NPPDs.

Integrated Approaches: Recommend combining multiple remediation techniques for reliability; improve modeling based on field-scale data rather than laboratory-only studies.

Characterization and Analysis: Employ DSC, SEM, and SARA analysis to understand wax crystal morphology and inhibitor interactions.

Local Implementation: Promote CSO–JSO blend as a practical inhibitor for Nigerian oilfields based on lab performance at low concentrations.

4.9.2 Chemical Methods of remediating/mitigating Wax:

Research Gaps and Future Directions:

Biological Approaches: Explore microorganisms capable of degrading wax, using wax as a carbon source to reduce pipeline deposition.

Modeling Improvements: Shift from laboratory-scale to field-scale modeling for realistic wax deposition predictions; integrate multi-technique remediation strategies for improved reliability under varying flow and temperature conditions.

Mechanistic Understanding: Investigate surface interactions, contact angle behavior, pressure fluctuations, and synergistic effects of additive combinations (dispersants + crystal modifiers).

Chemical Dispersants: Study self-association of wax crystals, optimize dosage, and develop dispersants effective under low-flow or long-residence-time conditions.

Experimental Design: Refine flow-based testing methods over cold finger tests; continue blockage-based quantification (PVb) to assess wax control efficiency.

Sustainability: Prioritize green solvents (e.g., terpene-based) and microbial treatments as eco-friendly, field-proven solutions.

Time-Scale and Scale-Up: Extend experimental durations and optimize solvent blends (e.g., 70:30 xylene–kerosene) for improved large-scale applicability.

Overall Direction: Integrate biological, green chemistry, and multi-method approaches, refine field-relevant modeling, validate lab-scale successes under operational conditions, and ensure cost-effective, sustainable wax remediation.

4.9.3 Thermal Methods of preventing Wax:

Electrical Heating Systems: Improve reliability and reparability of components; address non-repairable DEH PiP connectors and failure-prone electrical joints; conduct field trials for induction heating and heat-tracing systems to establish operational track records.

Passive Insulation: Optimize materials and configurations to enhance durability under thermal/mechanical stresses; investigate freeze-thaw aging and frost heave deformation in buried pipelines.

Aerogel-Based Insulation: Address thermal instability, brittleness, and low mechanical strength; study thermal cycling effects, cooling stabilization, and enhance mechanical properties via composites.

Thermal Modeling: Improve accuracy and predictive capability; incorporate multi-parameter calibration and extended temperature-range validation, especially for subsea conditions.

Overall Focus: Advance material resilience, reparability, field validation, and predictive modeling to ensure cost-effective, reliable, and sustainable subsea flow assurance.

4.9.4 Thermal Methods of remediating/mitigating Wax:

Although the studies on hot oil and hot steam injection have shown that these thermal methods are effective in melting and dislodging wax deposits, several research gaps remain unaddressed. Most authors noted that the efficiency of these methods largely depends on operating temperature, treatment frequency, and the nature of the crude oil, yet limited research has been conducted on optimizing these parameters for different field conditions. Future studies were therefore recommended to focus on improving thermal efficiency while reducing operational costs, particularly through better heat transfer management and insulation to minimize heat loss along pipelines. Additionally, since both methods require significant energy input and may pose risks of formation damage or corrosion, researchers suggested exploring hybrid thermal-chemical techniques that combine moderate heating with environmentally friendly inhibitors. Further experimental and field-based studies were also encouraged to evaluate long-term performance, especially under deep water and subsea conditions, where temperature and pressure variations can significantly alter wax melting behavior and re-precipitation tendencies.

4.9.5 Mechanical Methods of preventing Wax:

Magnetic Treatment (MT): Integrate viscosity destruction mechanism into models to account for 15–20% viscosity change due to super-molecular structure breakdown. More works should investigate physical mechanisms behind inconsistent field effectiveness, given low magnetic susceptibility of paraffin. Researchers should explore combined modeling of wax deposition and hydrate transport for simultaneous flow assurance challenges.

Pipeline Coatings:

Develop high-performance coatings with enhanced corrosion resistance, adhesion, and abrasion tolerance.

Pursue intelligent coatings with self-diagnosis and self-repair capabilities.

Focus on green/biodegradable materials and multifunctional coatings integrating anticorrosion, insulation, and drag reduction.

Emphasize research and field application for improved efficiency and sustainability.

4.9.6 Mechanical Methods of remediating/mitigating Wax:

Foam Pigs: Mechanistic understanding of wax removal is poorly developed, with very few studies analyzing foam pig performance. Observed phenomena like five-phase removal profiles, elastic buckling, and energy absorption are not captured by current models. Similarly, initial wax-breaking force is significantly higher than steady-state force, increasing the risk of pig-stuck incidents; design and operational strategies to mitigate this are needed. Future work should focus on advanced theoretical models validated under real-field conditions.

Conventional Pigs (Disc, Cup, Poly): Simplified models (compression/shear) fail to fully describe multi-phase wax removal, including plug formation, accumulation, and production.

Existing models struggle to predict breaking force and efficiency for variable wax strength, viscoelastic behavior, pipeline geometry, and pig deformation. Lack of reliable predictive methods for breaking force, removal efficiency, and frictional interactions remains a major challenge.

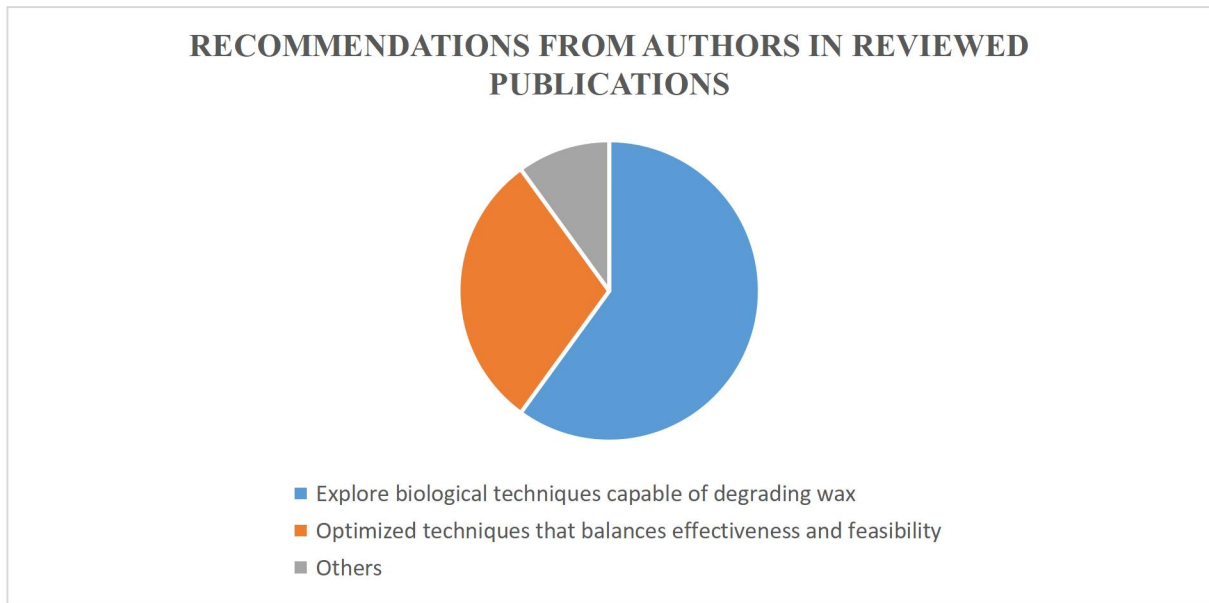


Figure 4-8: Trend of the recommendations from reviewed publications

CHAPTER 5

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This review highlights the complex and persistent nature of wax deposition in crude oil pipelines and emphasizes why it remains one of the most difficult flow assurance problems in the oil and gas industry. Across the collected studies, it is clear that wax formation is not governed by a single factor. Instead, it results from an intricate interplay of crude oil composition, cooling rates, temperature gradients, flow hydrodynamics and operational conditions. The reviewed materials consistently show that prevention remains the most efficient and economically sustainable approach, whereas remediation is often reactive, costly

and disruptive to operations. Chemical methods emerged as the most adaptable and widely researched form of prevention. They demonstrated impressive abilities to depress the wax appearance temperature, modify wax crystal structures, reduce viscosity and disrupt the formation of large crystalline networks. Natural plant-based inhibitors, solvent blends, polymeric modifiers and nanoparticle-enhanced pour point depressants all showed significant potential, especially when tailored to the specific properties of a crude oil sample. Several studies also showed that locally sourced inhibitors can match or even exceed the performance of imported commercial chemicals, offering both economic and environmental advantages.

The literature also revealed the growing relevance of molecular dynamics simulations, which provided deeper insight into the molecular interactions that govern crystal formation and inhibition. These simulations often supported laboratory findings and helped clarify why some inhibitors performed better on certain crude types. Although chemical prevention is the most advanced and widely deployed solution, mechanical and thermal methods remain important whenever deposition cannot be avoided. Pigging continues to serve as the dominant remediation technique, while hot water and hot oil circulation still play supportive roles despite their limitations. Emerging innovations such as magnetic treatment and surface modification through coatings also show potential, although they require further validation under field conditions. The overall conclusion from the reviewed works is that no single technique provides a universal solution. The most practical approach for regions such as the Niger Delta involves combining robust prevention with strategically timed remediation, supported by continuous monitoring and improved understanding of crude oil behaviour. The progressive shift toward greener, safer and more cost-effective inhibitors reinforces the need for continual research and development in wax prevention technologies.

5.2. Recommendations

- Based on the insights gathered from the literature, there is a strong need for continued exploration of plant-based and naturally derived additives. The evidence from several

studies shows that materials such as orange-peel oil, jatropha seed oil, palm kernel oil and coconut husk derivatives can significantly inhibit wax formation while also offering environmental and economic advantages. Further research should examine a wider variety of indigenous plant oils and agricultural by-products, with emphasis on understanding their molecular interactions with paraffinic components. These materials have the potential to provide safer alternatives to synthetic chemicals and can reduce the industry's dependence on expensive imported additives.

- Although research is gradually expanding on the use of micro-organisms for wax control, this area is still at an early stage and requires far more attention. Microbial biodegradation of paraffins holds tremendous promise because the approach can be environmentally friendly, self-sustaining and capable of targeting wax formations directly at the molecular level. More detailed studies are needed to identify strains that thrive under pipeline operating conditions, to understand their enzymatic pathways and to evaluate how they interact with different wax structures. If properly developed, microbial methods could become an important complement to chemical and mechanical strategies.
- There is a need for more field-scale trials to validate laboratory findings. Many inhibitors perform exceptionally under controlled conditions but behave differently once exposed to variable flow rates, pressure fluctuations and complex multiphase interactions in real pipelines. Future research should therefore focus on scaling up promising materials, particularly the nanoparticle-enhanced and blended chemical formulations that have shown superior inhibition efficiencies.
- There is also room to advance the development of predictive models that integrate molecular dynamics, rheological measurements and real-time monitoring data. Such tools would support better decision making and allow operators to adjust prevention strategies proactively rather than reactively.

- More attention should be given to developing solutions that are affordable and accessible for regions such as the Niger Delta. Many of the reviewed studies highlight the high cost of conventional chemicals and the economic burden associated with frequent remediation campaigns. Research efforts should therefore continue to prioritize cost-effective technologies that can be sustained in field operations, alongside environmentally responsible methods that reduce risk to communities and ecosystems. A combination of improved scientific understanding, innovative materials and practical field validation will be essential in advancing wax prevention and mitigation technologies in the years ahead.

5.3. Contribution to Knowledge

The study contributes to existing knowledge by presenting one of the most recent and comprehensive synthesis of wax deposition prevention and mitigation technologies and how these findings can be employed by oil fields in the Niger Delta. By assembling and analyzing the publications from 2022 till date, this work bridges the gap in contemporary literature which often treats prevention and mitigation methods separately. This review brings them together in a unified assessment and demonstrates how thermal, mechanical and chemical methods complements each other.

The research highlights how natural oils such as Jatropha, Palm kernel oil and blended seed oils now demonstrates inhibition efficiencies comparable to synthetic chemicals. These findings deepen scientific understanding of the mechanisms through which oleic rich acid materials disrupted wax crystal growth. It also shifts attention towards sustainable alternatives that are cost effective and environmentally friendly for regions like the Niger Delta where wax issue depends on expensive imported chemicals before it can be solved.

The project further advances knowledge by synthensizing the performance benchmarks of nano enhanced pour point depressants and demonstrated how nanocomposite structures have

transformed operations in recent years. The comparison of silicon based, carbon based and magnetic nanomaterials provides a clearer picture of how nucleation control and changes in wax morphology contributes to improved flow behavior.

This study also offers a context-specific assessment by aligning global findings with the realities of the Niger Delta. This includes the peculiar paraffinic composition of local crudes and conditions that foster rapid cooling during transportation and the infrastructural limitations that make prevention strategies more feasible than continuous mitigation. This emphasis ensures that the insights documented are not merely theoretical but practically relevant for operators in the region.

Finally, by identifying consistencies, contradictions and areas of methodological improvement across the reviewed works, the study provides a clear direction for future research. It shows that although progress has been made, there is still a need for more standardized testing procedures, more field scale validation and deeper exploration of biological techniques. Through this, the project provides a stronger foundation for researchers and field engineers working to improve the reliability and economy of crude oil transportation systems.

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