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Minimizing Environmental Impact in Arctic Drilling Through Specialized Fluids

Oladokun Olawale *

SLB (Schlumberger), Angola.

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Abstract

Objective: This review evaluates how specialized drilling fluids can reduce the environmental impacts of Arctic oil and gas operations. It examines advancements in biodegradable additives, nano-enhanced stabilizers, low-toxicity synthetic esters, and cold-resilient rheology modifiers, assessing their capacity to address the ecological vulnerabilities of Arctic marine and permafrost systems.

Study Design: Structured as a narrative and thematic review, this study integrates engineering, environmental, and regulatory literature to provide a multidisciplinary assessment of drilling-fluid innovation in ultra-low-temperature environments. The review focuses on operational and ecological challenges unique to the Arctic, including extreme cold, slow biodegradation, and limited waste-treatment capacity.

Methodology: A structured search across Scopus, ScienceDirect, Web of Science, ACS Publications, SpringerLink, MDPI, Frontiers, OnePetro, and Google Scholar identified literature published between 2019 and 2025. 25 peer-reviewed studies met the inclusion criteria and were thematically categorized into seven domains: traditional-fluid limitations, low-temperature rheology, eco-friendly additives, nano-biodegradable systems, Arctic ecotoxicology, waste-management strategies, and integration into Arctic risk-assessment frameworks.

Results: Traditional oil-based and synthetic-based muds show persistent toxicity, low biodegradation, and sediment accumulation in cold ecosystems. Specialized fluids, such as biodegradable water-based systems, nano-enhanced additives, and ester-based formulations, demonstrate improved cold-temperature stability, lower ecotoxicity, and reduced environmental persistence. Waste-management strategies such as cuttings, reinjection and low-impact thermal desorption further mitigate ecological burden. However, regulatory frameworks across Arctic jurisdictions remain inconsistent, and cold-condition ecotoxicity testing is limited.

Conclusions: Specialized drilling fluids offer a viable pathway to reducing Arctic drilling impacts, but broader protection requires harmonized regulations, mandatory low-temperature toxicity testing, and investment in sustainable waste-management. Integrating these innovations into updated Arctic environmental-risk models is essential for safer, more responsible polar operations.

Keywords: Arctic Drilling Fluids; Environmental Impact; Low-Temperature Rheology; Biodegradable Additives; Nano-Biodegradable Systems; Ecotoxicology; Permafrost Stability; Waste-Management**.**

* Corresponding author: **Oladokun Olawale**

1. Introduction

Arctic oil and gas exploration has expanded in recent years due to increasing global energy demand and the strategic importance of offshore hydrocarbon reserves in polar regions. However, the Arctic remains one of the most ecologically fragile environments on the planet, characterized by extreme temperatures, highly sensitive marine ecosystems, and slow biodegradation rates that intensify the long-term consequences of industrial activity. The harsh climate and unique geophysical conditions mean that disturbances caused by drilling fluids, whether through discharge, leakage, or cuttings deposition can persist for decades, making the environmental management of drilling operations a central concern in Arctic resource development [1].

Drilling fluids play a crucial role in Arctic operations by ensuring wellbore stability, facilitating cuttings transport, preventing hydrate formation, and maintaining flow under sub-zero temperatures. Traditional drilling fluids, including oil-based muds (OBMs) and earlier generations of synthetic-based muds (SBMs), exhibit high performance but are associated with toxicity, poor biodegradability, and bioaccumulation risks, especially in cold waters where microbial breakdown is slow. Studies demonstrate that discharge of conventional OBMs into Arctic marine systems leads to benthic smothering, persistent contamination, and inhibited recolonization of affected substrates [2] These environmental challenges underscore the need for alternative drilling fluid systems specifically engineered to minimize ecological harm.

In response, recent research has focused on the development of specialized drilling fluids that maintain operational performance at ultra-low temperatures while reducing environmental risks. Innovations in this domain include biodegradable water-based drilling fluids (WBDFs), nano-enhanced eco-fluids, low-toxicity synthetic esters, and biopolymer additives derived from renewable sources. For example, advancements in environmentally friendly drilling lubricants have demonstrated improved rheology and lubricity without relying on petroleum-derived compounds, marking a shift toward sustainable fluid chemistry [3] Similarly, studies on nano-biodegradable additives, such as zinc-based nanorods and plant-derived polymers, highlight significant gains in environmental performance with minimal compromise to drilling efficiency [4].

The Arctic introduces additional complexities not encountered in temperate environments. Permafrost layers are highly sensitive to thermal disturbance, making fluid temperature and thermal conductivity essential factors in maintaining geomechanical stability. High-temperature fluids can accelerate thawing, potentially triggering ground subsidence or well integrity issues. Research on drilling fluids formulated for permafrost and ultra-low-temperature operations reveals that tailored rheological control agents, anti-freeze polymers, and nano-stabilizers are required to maintain fluid flowability and prevent gelation at sub-zero temperatures [5]. These developments demonstrate the necessity of engineering drilling fluids that not only meet technical performance standards but also minimize thermal and chemical impacts on Arctic geological formations.

Furthermore, the environmental implications of drilling fluid waste in the Arctic are substantial and long-lasting. A life-cycle assessment of drilling operations in Western Siberia revealed that waste generated from conventional drilling fluids contributes significantly to ecological degradation, especially in permafrost regions where natural attenuation is severely limited [6] Additional studies emphasize that thermal desorption, cuttings re-injection, and biodegradable formulations are critical elements in reducing the environmental footprint of drilling activities across polar basins [7]

The combination of extreme weather, unlimited biological activity, ice-covered waters, and constrained waste-treatment infrastructure means that Arctic drilling demands a higher standard of environmental protection than operations in other regions. While regulatory bodies such as the Arctic Council, Canadian Energy Regulator, and Norwegian Petroleum Directorate have advanced guidelines for low-toxicity drilling discharges, scientific literature continues to demonstrate the need for improved integration of environmentally specialized fluids into Arctic risk assessment frameworks [8]

Given these challenges, this review examines the modern landscape of specialized Arctic drilling fluids, focusing on environmentally conscious formulations, low-temperature performance mechanisms, ecotoxicity considerations, climate-driven modulators, and emerging risk-modeling approaches. By synthesizing recent experimental findings, engineering innovations, and environmental assessments, this study provides an updated evaluation of how specialized fluids can minimize ecological impact while supporting safe and efficient Arctic resource development.

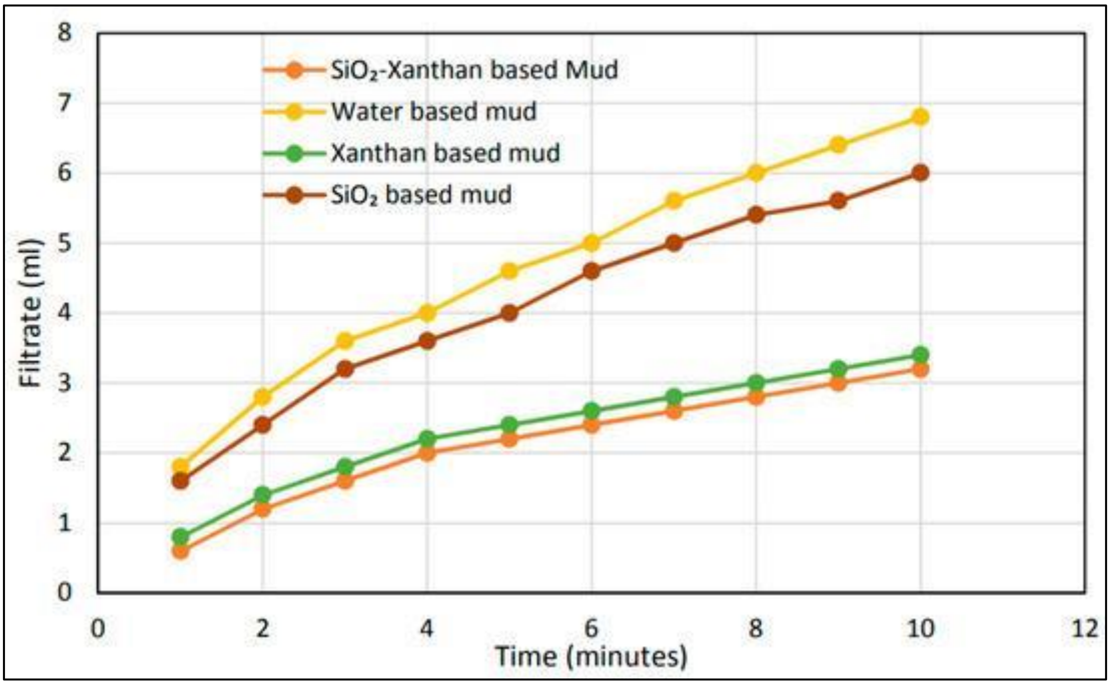

Figure 1 Sample drilling fluid filtrates [13]

2. Methodology

This review evaluates the advancements, environmental implications, and performance characteristics of specialized drilling fluids used in Arctic and ultra-low-temperature petroleum operations. A systematic qualitative review was undertaken to examine peer-reviewed studies published between 2019 and 2025 that address drilling fluid chemistry, cold-region rheology, environmental toxicity, drilling waste management, and Arctic operational considerations. The review relied on thematic categorization and comparative analysis to identify patterns in the development and application of environmentally conscious drilling fluids. This included the integration of experimental data, rheological modeling studies, life cycle assessments, and ecotoxicological evaluations [9]. Literature was collected from major scientific and engineering databases, including Scopus, Web of Science, ScienceDirect, ACS Publications, RSC Advances, SpringerLink, MDPI, Frontiers, OnePetro, and Google Scholar. The search strategy employed Boolean combinations aligned with the topic's technical and environmental dimensions. Key expressions included: "Arctic drilling fluid" AND "environmental impact" "Ultra-low temperature drilling fluid" AND "rheology" "Biodegradable drilling fluid additives" AND "ecotoxicity", "Nano-biodegradable drilling fluids" AND "cold-region operations""Drilling waste management" AND "permafrost""Synthetic ester drilling fluids" AND "biodegradation"

These queries ensured the inclusion of studies relevant to specialized formulations such as cold-resistant water-based systems [1], bio-derived additives [10], and advanced eco-lubricants [3].To ensure relevance and analytical clarity, the following inclusion criteria were applied: Studies published between 2019–2025, relevance to topic, studies must examine drilling fluids or drilling-waste systems in relation to Arctic, polar, or low-temperature environments, peer-reviewed articles, government/industry reports informing Arctic environmental practices, experimental studies, or modeling analyses, environmental components including biodegradation, toxicity, waste-management, or environmental risk assessment data [2], and studies must discuss rheology, fluid chemistry, thermal performance, or operational behavior under low-temperature conditions [5]

The review excluded studies published before 2019, unless cited within newer papers for historical context. Articles focused solely on drilling mechanics without discussing fluid chemistry or environment. Papers centered on mid-latitude operations without relevance to cold-region environments. Non-technical or non-peer-reviewed sources (blogs, newsletters, conference posters without full papers).

Using a multi-stage screening process, titles and abstracts were first reviewed to eliminate non-relevant items. Full-text reviews followed to confirm the inclusion of environmental or low-temperature performance data. The initial search yielded a substantial number of articles. After removing duplicates and screening abstracts for relevance to the topic. Subsequently, full-text articles were assessed against the inclusion and exclusion criteria. This process resulted in a final selection of 25 studies that met all criteria and were included in the final review. Information extracted from each study included:Fluid composition and additive categories, rheological behavior at sub-zero or near-freezing temperatures, environmental toxicity and biodegradation data, performance in permafrost or ice-affected formations, waste-management strategies and LCA outcomes, operational constraints or performance enhancements, and regulatory or policy implications in Arctic jurisdictions

For example, cold-region rheology data were extracted from studies examining viscosity, gel strength, and flow stability in permafrost conditions, while ecotoxicological information was derived from recent analyses on drilling fluid impacts on Arctic sediments and benthic organisms [4].

Waste-related environmental metrics were obtained from LCA-oriented papers [6] [7]

It is important to note that, while the approach used ensured a thorough and high-quality examination of the current literature, there were certain limitations, such as the reliance on only English-language sources, which may have excluded relevant research published in other languages, and the relatively low number of studies included in the final evaluation, which restricts the inclusivity of the findings. Also, some of the most important studies may be paywalled or not available in publicly accessible databases and several structural limitations such as;

Restricted Arctic field testing, much of the experimental work is performed in simulated laboratory environments rather than operational Arctic rigs. Oilfield service companies often withhold chemical specifics of specialized fluids, limiting full transparency. Many environmental studies are performed during Arctic summers when access is easier, limiting winter-condition datasets. Localized environmental data: Results from Canadian, Norwegian, Alaskan, and Russian Arctic regions may not be uniformly generalizable due to geological variability [8]. However, despite these limitations, the methodological structure provides a comprehensive foundation for the subsequent analysis of drilling-fluid innovations and their environmental implications in Arctic operations.

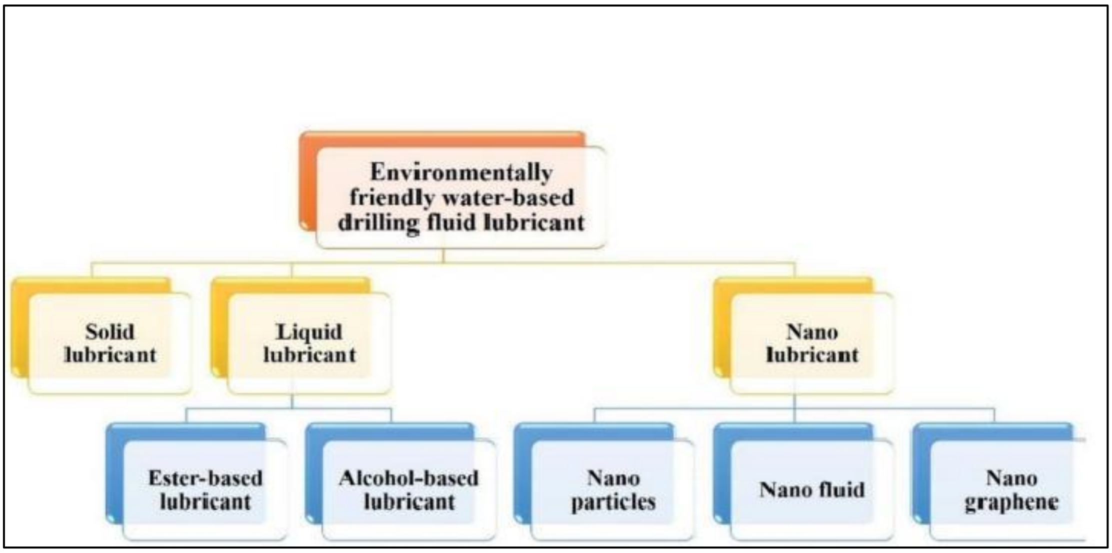

Figure 2 Types of environmentally friendly water-based drilling fluid lubricant. [15]

3. Results and discussion

3.1. Overview of Traditional Drilling Fluid Challenges in Arctic Settings

Arctic drilling operations continue to rely heavily on traditional drilling fluids, particularly synthetic-based muds (SBMs) and oil-based muds (OBMs), despite their known environmental hazards. SBMs, though designed for performance, can persist in cold sediments, showing bioaccumulative behavior due to minimal microbial degradation in permafrost and sub-zero marine environments [2.] OBMs exhibit even greater persistence; their hydrocarbon components degrade extremely slowly under cold Arctic conditions, leading to long-term sediment contamination [1].

Thermal challenges further complicate the use of conventional fluids. In permafrost formations, warmer circulating drilling fluids can transfer heat, risking thaw and disruption of frozen ground structure [11] Moreover, cuttings decorated in fluid often settle in low-dilution Arctic waters, forming persistent benthic blankets of contamination (Pereira et al., review). These settled cuttings can become long-term reservoirs for toxic constituents. Accidental spills pose another severe risk: once OBMs or SBMs enter Arctic waters, their breakdown is extremely slow, resulting in persistent ecological exposure [2]

Table 1 Summary of traditional drilling fluid lubricants [15]

Traditional Lubricants	Shortcomings
Inert solid particles	Not degradable and prone to damage to the formations
Crude oil, diesel	Deterioration of performance of water-based drilling fluid, environmental pollution, and high disposal cost of drilling fluid after mixing with the oil
Zinc dialkyl dithiophosphate (ZDDP)	The decomposition of ZDDP produces toxic compounds containing S/P, causing environmental pollution
Mineral oil-based lubricant	Aromatics contain fluorescence, which affects logging work

3.2. Low-Temperature Performance of Specialized Fluids

To address these issues, researchers have developed specialized drilling fluids optimized for ultra-cold conditions. These formulations integrate advanced rheology stabilizers, nano-additives, anti-freeze polymers, and ice-inhibiting agents to maintain performance under freezing stress.

Role of Rheology Stabilizers Under Freezing Conditions;

- Cold-resistant polymers such as organoclay or amide-based additives significantly improve the rheological properties of fluids at low temperatures. Huang, Lv, and Sun (2023) found that organoclay forms a weak gel network, preserving yield stress and suspension capacity even at very low temperatures [5] expanded on this by developing a hybrid amide-organoclay system (“HAS”) that remains stable down to −55 °C, maintaining strong colloid stability and yield behavior [5]
- Stability of borehole walls is critical in permafrost drilling. Li (2020) demonstrated through simulations that using sub-zero temperature drilling fluids helps limit plastic deformation in permafrost strata, minimizing thaw-induced instability [12]
- Nano-Stabilizers for Preventing Gelation Nanomaterials, including silica and alumina nanoparticles, are increasingly used to prevent gelation and improve structural integrity in cold fluids. Nano-additives enable lower dosages while enhancing strength and reducing filtrate loss [13]. Broad reviews of nanoparticles in drilling fluids also highlight their application for stability, thermal conductivity, and rheological control [14]
- Anti-freeze copolymers (e.g., ethylene–propylene-based) maintain flexibility at very low temperatures, minimizing viscosity spikes and avoiding circulation issues. These systems have been identified in low-temperature fluid reviews as essential for Arctic drilling operations [15]
- Specialized ice inhibitors can suppress ice nucleation and crystal growth within drilling fluids, reducing the risk of blockage and gel network formation. These additives, derived from materials science and glaciology, improve flowability under conditions just below freezing. Their feasibility in polar drilling has been outlined in recent reviews [8]

3.3. Environmentally Friendly Additives

3.3.1. Biopolymers & Plant-Based Additives

Biodegradable polymers like starch derivatives, xanthan gum, and cellulose offer ecological advantages without compromising rheology. For example, plant-based viscosifiers reduce toxicity and are compatible with cold-environment microbial communities [3]. Natural materials such as Aloe vera have demonstrated excellent fluid-loss control and biodegradability when used in drilling muds [16]

Adding to this, reviews of biodegradable lubricants identify extracts from wild jujube, okra, and henna as promising fluid additives that reduce environmental footprint while maintaining lubricity [17]

3.3.2. Nano-Biodegradable Solutions

Nano-biodegradable additives offer dual performance and environmental benefits. Zinc nanorods, synthesized from waste seed materials like gundelia, have shown excellent rheological performance and improved environmental compatibility [4]

Additionally, graphene and bio-graphene nanosheets have been successfully integrated into water-based muds, improving strength, lubrication, and stability while being more biodegradable than conventional synthetics [4]

Table 2 Nanomaterials specifications [25]

Nanoparticles	**TiO_2**	**Al_2O_3**	**SiO_2**
Purity	99.9%	99.5%	99.5%
Type	Anatase	-	S-type
Shape	-	Near spherical	Near spherical particles
Colour	White	White	White
Nanoparticles average size (APS)	18nm	27-43nm	30-50nm
Specific surface area (SSA)	200-240m^2/g	35m^2/g	30-80m^2/g
Relative density	4.23g/cm^3	3.5-3.9g/cm^3	2.4g/cm^3
Manufacturing method	High temperature combustion	-	High temperature combustion

3.3.3. Synthetic-Acid Esters & Low-Toxicity Base Fluids

Synthetic ester-based fluids remain a leading choice for low-toxicity, cold-region drilling. These fluids degrade faster in aquatic environments and reduce bioaccumulation risk. Zhao et al. (2020) showed that some synthetic fluids maintain low toxicity even with microbial challenge [18]. Studies of hydrogenated base fluids also emphasize their low environmental footprint and robust cold-performance.

3.4. Environmental Impact Assessment (Ecotoxicology)

3.4.1. Toxicity to Marine Ecosystems

Cold ecosystems are especially vulnerable to persistent fluid contamination: traditional OBMs and SBMs distribute into sediment and remain bioavailable due to slow biodegradation, affecting benthic species over long periods [2]. Biodegradable formulations, such as esters and nano-biopolymers, show markedly less acute toxicity and lower risk of bioaccumulation [3] [4]

3.4.2. Soil and Permafrost Interaction

Rheologically stabilized fluids (e.g., organoclay gels, amide hybrids) reduce filtrate invasion in permafrost, lowering the risk of thawing and structural damage [5] [19] Nanomaterials further help manage filtration and potentially lower the thermal footprint of fluids [13]

3.4.3. Water Column & Sediment Behavior

Ice-inhibiting additives and nano-enhanced formulations can reduce aggregation, minimizing particulate settling in stratified Arctic waters [8] Biodegradable base fluids like esters also lessen the long-term chemical load in sediments by breaking down more readily [18]

3.5. Drilling Waste Management in Arctic Environments

3.5.1. Cuttings Re-Injection Systems (CRI)

Life cycle assessment (LCA) data from Siberian operations demonstrate that CRI significantly lowers surface discharge and long-term contamination when combined with water-based or biodegradable drilling fluid systems [6]

3.5.2. Low-Impact Thermal Desorption

Thermally desorbing cuttings reduces their active hydrocarbon content, making them safer for reinjection or disposal. LCA scenarios highlight that, despite energy use, the environmental burden is lower compared to untreated discharge, especially in cold regions where natural remediation is slow [7]

3.5.3. Bioremediation & Bioaugmentation

Psychrophilic (cold-adapted) microbial communities paired with biodegradable fluid systems (esters, plant-based polymers) provide a route for long-term remediation. Recent laboratory work suggests they can meaningfully degrade residual fluid components under low-temperature conditions [4]

3.6. Hydrogeological, Climatic & Seasonal Modulators

Hydrogeological features (such as permafrost, sediment type, and salinity gradients) play critical roles in fluid transport and fate. For instance, ice cover reduces mixing, leading to greater stratification and sedimentation of fluid residues [1]. The thermal behavior of fluids also interacts with climate-seasonal dynamics: warming trends may alter salinity and freeze-thaw cycles, affecting crystallization and dispersal of discharged fluids [8]. Sediment grain size further influences contaminant retention, with finer particles binding more strongly to fluid residues.

3.7. Integration of Specialized Fluids into Arctic Environmental Risk Models

3.7.1. Updated Risk Assessment Frameworks

Given the marked differences in degradation, toxicity, and fluid behavior in cold environments, risk-assessment models require recalibration. Biodegradation rates of esters, nanomaterials, and organoclay gels must be integrated into exposure and fate models to replace temperate-based assumptions [2].

3.7.2. Advances in Modeling Techniques

Modern risk assessment can leverage LCA [6], CFD modeling under ice cover [8], and GIS-based mapping of sedimentation and contamination zones. These tools allow for more precise prediction of ecological risk, helping regulators and operators make informed decisions on fluid selection, containment, and management.

3.8. Public Health and Policy Implications

Arctic drilling brings not only technical and environmental challenges but also clear public-health and governance implications: persistent contamination in cold ecosystems, long recovery times for affected communities and food webs, and uneven regulatory frameworks across Arctic jurisdictions create gaps that must be filled through better standards, monitoring, and industry practice. [22]

3.8.1. Regulatory Landscape (Canada, Norway, Alaska, Arctic Council)

Across Arctic jurisdictions regulators have moved toward limiting environmental harm from drilling discharges, but approaches and strictness vary.

Canada requires operators to demonstrate that drilling-fluid systems and monitoring equipment are designed, installed, operated, and maintained to prevent pollution and to submit Environmental Protection Plans as part of authorization for offshore activities (Canada Oil and Gas Drilling and Production Regulations). [21]

Norway has transitioned from prescriptive controls to a more risk-based regulatory system that still explicitly restricts offshore discharges of oil-based fluids; the Norwegian Environment Agency may permit discharge of cuttings with small amounts of synthetic base fluids under strict conditions, but discharge of untreated OBMs is effectively disallowed and environmental monitoring is mandated (OffshoreNO R E guidelines; Activities Regulations). This risk-based pathway grew from decades of institutional development and industry-government interaction. Knol-Kauffman et al. analyze this regulatory evolution in detail [20]

In the United States (Alaska and federal offshore waters), the EPA’s effluent guidelines and standards for offshore oil and gas extraction set limits and monitoring expectations for discharges and require the best available technology where appropriate; historic EPA guidance and rulemaking documents remain foundational to discharge control and toxicity testing requirements.

At the multilateral level the Arctic Council and associated fora provide guidance and best-practice recommendations for offshore operations, promoting stringent environmental monitoring and preventive measures given the Arctic's sensitivity. While the Arctic Council's guidelines are not a binding code; they inform national standards and emergency response arrangements across member states.

Taken together, these jurisdictional documents show an increasing restriction on high-toxicity fluids and discharges, a movement toward risk-based management, and growing expectations for mandatory environmental monitoring and testing prior to and during operations. Knol-Kauffman's analysis [20] is useful for understanding how Norway implemented a workable risk-based approach that other Arctic states study and adapt.

3.8.2. Industry Practices and Compliance

Industry has responded by adopting lower-toxicity alternatives and improving waste handling, though uptake varies by operator and region.

Operators are increasingly using synthetic esters, modern low-toxicity SBMs, and biodegradable water-based systems to reduce persistence and ecotoxicity in cold waters. Reviews of environmentally friendly lubricants and green additives document both the technological trajectory and laboratory/field evidence for reduced harm [3] [4]. These materials improve biodegradation profiles and lower acute toxicity to benthic organisms relative to legacy OBMs.

Practically, industry compliance commonly combines three levers: (a) use of lower-toxicity fluids where permitted; (b) engineered waste management (cuttings reinjection, thermal desorption) to limit surface discharges; and (c) enhanced environmental monitoring programs embedded in Environmental Protection Plans submitted to regulators (Canada) or annual reporting requirements (Norway). The life-cycle assessments showing environmental gains from these practices [6] [7] give regulators and operators quantitative evidence that investment in eco-fluids and waste treatment lowers net environmental burden.

Certification and verification schemes for "environmental fluids" are emerging: independent testing of biodegradation, acute/chronic ecotoxicity, and bioaccumulation potential is increasingly used to demonstrate that a fluid meets the jurisdictional or operator-level acceptance criteria (see regulatory guidelines and industry reporting referenced above). Norway's practice of permitting only treated cuttings or limited synthetic-fluid residue discharges is an example of a conditional acceptance model where certification and monitoring are required.

3.9. Recommendations

Based on the scientific evidence and the regulatory trends above, four practical, evidence-backed policy actions are recommended:

- Mandatory ecotoxicity testing pre-approval. Regulators should require standardized ecotoxicity testing (acute and chronic endpoints) at low Arctic-relevant temperatures for any drilling-fluid formulation proposed for use or discharge. Studies show conventional toxicity testing at temperate temperatures underestimates persistence and organism sensitivity in cold waters; mandating cold-condition tests will improve risk estimates [2].
- Adoption of biodegradable and low-toxicity fluids as the default where operationally feasible. Where possible, national regulators should create a presumption in favor of biodegradable WBDFs and low-toxicity SBMs (esters) for offshore Arctic operations, with OBMs allowed only under exceptional, justified circumstances and with rigorous containment/waste-treatment measures. The chemical and LCA evidence supports marked environmental improvements from modern green additives and ester-based systems [3] [6]
- Alignment with Arctic Council ecosystem protections and coordinated regional standards. Given differing national rules, Arctic stakeholders should harmonize minimum standards for fluid toxicity, discharge limits, monitoring, and contingency planning so cross-border impacts are minimized. The Arctic Council's guidance documents and regional comparative analyses underscore the value of harmonized environmental monitoring standards across Arctic states.
- Incentivize R&D for specialized cold-weather formulations and waste-treatment technologies. Public funding, tax credits, or procurement preferences can accelerate development of ultra-low-temperature biodegradable fluids, nano-biodegradable additives, and energy-efficient treatment technologies (thermal desorption with waste heat integration, improved CRI designs). LCA analyses show these investments reduce long-term environmental burden even when they entail higher upfront costs [6] [7]

The public-health stakes of Arctic drilling are unique: slow ecological recovery, reliance of some Indigenous communities on marine resources, and limited emergency response windows mean that prevention through better fluids, mandatory cold-relevant ecotoxicity testing, and strict waste-management is the most effective health-protective policy. The combination of regulatory direction (Canada, Norway, U.S. guidelines), industry practice change (green fluids, CRI, thermal treatment), and targeted incentives for R&D creates a pragmatic, evidence-based pathway for reducing Arctic drilling's environmental and public-health footprint.

4. Conclusion

This review has underscored the critical role of specialized drilling fluids in reducing environmental risks associated with Arctic drilling. Conventional fluids such as oil-based muds (OBMs) and older synthetic-based muds pose significant long-term ecological threats in cold environments due to their persistence, bioaccumulation potential, and poor biodegradation under Arctic conditions. In contrast, advanced fluid technologies, particularly synthetic low-toxicity base fluids, nano-additives, and biodegradable lubricants, can substantially mitigate these risks.

One promising approach is the development of synthetic-based fluids (NSF) with ultra-low impurity levels, as demonstrated by Sun et al., who reported a hydrocarbon fluid with very low aromatic and sulfur contents, extremely low acute toxicity (LC50 > 1,000,000 mg/L), and good degradation potential. [23].

Additionally, nano-additives deliver a dual benefit: enhancing rheological stability under extreme conditions while reducing ecological footprint. Asad et al. highlighted how nanoparticles improve fluid mechanics and performance with lower additive load and environmental toxicity. [13]. Moreover, eco-lubricants for water-based drilling fluids have seen significant advancement. Reviews of ester-based and nano-lubricants show they can match or surpass performance of conventional lubricants with dramatically lower environmental cost. [15]

On the waste-management front, sustainable strategies such as thermal desorption of cuttings are essential. Thorough life-cycle assessments reveal that, despite the energy demand, thermal treatment of cuttings minimizes environmental burdens more effectively than unrestricted discharge, particularly in cold ecosystems. [23] (Thermal Desorption).

Complementing this, broader evaluations of the drilling life cycle, from fluid production to disposal, identify emission hotspots and guide sustainability interventions. For example, Jambol et al. provide a comprehensive LCA of drilling technologies, highlighting where environmental gains can be made.[24]

Finally, this review highlights that the regulatory, technical, and environmental landscapes must evolve in tandem. Given the fragility of Arctic ecosystems, it's imperative to require cold-condition ecotoxicity testing of new fluid formulations, incentivize the use of low-toxicity and biodegradable fluids, and adopt stricter waste-management protocols. Such measures, aligned with recent life-cycle and nano-material research, can provide a pragmatic but ambitious roadmap for more environmentally responsible Arctic drilling.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Y. Zhang, Z. Qiu, X. Zhao, H. Zhong, W. Huang, and J. Mu, "Experimental study on ultra-low temperature drilling fluid in Arctic permafrost," Polar Science, vol. 28, p. 100645, Feb. 2021, doi: 10.1016/j.polar.2021.100645.

[2] M. Antia, A. N. Ezejiofor, C. N. Obasi, and O. E. Orisakwe, "Environmental and public health effects of spent drilling fluid: An updated systematic review," Journal of Hazardous Materials Advances, vol. 7, p. 100120, Jul. 2022, doi: 10.1016/j.hazadv.2022.100120.

[3] S. Yang, X. Wang, Y. Pan, Q. Zhan, and L. E. Yvan, "Environmentally Friendly Drilling Fluid Lubricant: A review," Industrial & Engineering Chemistry Research, vol. 62, no. 21, pp. 8146–8162, May 2023, doi: 10.1021/acs.iecr.3c00767.

[4] J. A. Ali et al., "Performance evaluation of the nano-biodegradable drilling fluid using the greenly synthesized zinc nanorods and gundelia seed waste," Environmental Science and Pollution Research, vol. 31, no. 39, pp. 51381–51400, Aug. 2024, doi: 10.1007/s11356-024-34561-7.

[5] N. Huang, K. Lv, J. Sun, J. Liu, J. Wang, and Z. Wang, “Study on the Low-Temperature Rheology of Polar drilling Fluid and its regulation Method,” Gels, vol. 9, no. 2, p. 168, Feb. 2023, doi: 10.3390/gels9020168.

[6] G. Ilinykh, J. Fellner, N. Sliusar, and V. Korotaev, “A life cycle assessment of drilling waste management: a case study of oil and gas condensate field in the north of western Siberia, Russia,” Sustainable Environment Research, vol. 33, no. 1, Mar. 2023, doi: 10.1186/s42834-023-00171-0.

[7] Y. H. Song, G. Y. Kim, D. Y. Kim, and Y. W. Hwang, “Life cycle Assessment of Crude Oil-Contaminated soil treated by Low-Temperature thermal Desorption and its beneficial Reuse for Soil Amendment,” Sustainability, vol. 16, no. 24, p. 10900, Dec. 2024, doi: 10.3390/su162410900.

[8] N. Wei et al., “A state-of-the-art review and prospect of gas hydrate reservoir drilling techniques,” Frontiers in Earth Science, vol. 10, Sep. 2022, doi: 10.3389/feart.2022.997337.

[9] H. Mahmoud, A. a. A. Mohammed, Mustafa. S. Nasser, I. A. Hussein, and M. H. El-Naas, “Green drilling fluid additives for a sustainable hole-cleaning performance: a comprehensive review,” Emergent Materials, vol. 7, no. 2, pp. 387–402, Jul. 2023, doi: 10.1007/s42247-023-00524-w.

[10] N. A. Ghazali, S. Naganawa, and Y. Masuda, “The effect of high-temperature environment on the rheology and filtration properties of Rhizophora spp. tannin-lignosulfonate as bio-based additive in water-based drilling fluid,” Journal of Petroleum Exploration and Production Technology, vol. 14, no. 3, pp. 727–743, Jan. 2024, doi: 10.1007/s13202-023-01740-0.

[11] E. Leusheva and V. Morenov, “Effect of temperature conditions in Arctic offshore oil fields on the rheological properties of various based drilling muds,” Energies, vol. 15, no. 15, p. 5750, Aug. 2022, doi: 10.3390/en15155750.

[12] J. Shi, Y. Li, C. Yan, and M. Xue, “Stability Analysis of Borehole Walls When Drilling with Normal-Temperature Drilling Fluids in Permafrost Strata,” Processes, vol. 12, no. 9, p. 1819, Aug. 2024, doi: 10.3390/pr12091819.

[13] M. S. Asad et al., “Sustainable Drilling Fluids: A Review of Nano-Additives for Improved Performance and Reduced Environmental impact,” Processes, vol. 12, no. 10, p. 2180, Oct. 2024, doi: 10.3390/pr12102180.

[14] V. Gokapai, P. Pothana, and K. Ling, “Nanoparticles in Drilling Fluids: A review of types, mechanisms, applications, and future prospects,” *Eng—Advances in Engineering*, vol. 5, no. 4, pp. 2462–2495, Oct. 2024, doi: 10.3390/eng5040129.

[15] X. Zhao, D. Li, H. Zhu, J. Ma, and Y. An, “Advanced developments in environmentally friendly lubricants for water-based drilling fluid: a review,” *RSC Advances*, vol. 12, no. 35, pp. 22853–22868, Jan. 2022, doi: 10.1039/d2ra03888a.

[16] M. Bagum, J. M. Ahammad, T. Husain, and M. E. Hossain, “An experimental study to develop an environmental friendly mud additive of drilling fluid using Aloe Vera,” Journal of Petroleum Science and Engineering, vol. 211, p. 110135, Jan. 2022, doi: 10.1016/j.petrol.2022.110135.

[17] K. Popi, Md. S. Alam, K. Popi, and Md. S. Alam, “Biodegradable materials for lubricity Enhancement of drilling fluids: a review,” SciEn Conference Series Engineering, vol. 3, pp. 37–42, Nov. 2025, doi: 10.38032/scse.2025.3.10.

[18] Y. Sun, X. Zhu, J. Zhao, and D. Sui, “Study on a new environmentally friendly synthetic fluid for preparing Synthetic-Based Drilling Fluid,” Frontiers in Chemistry, vol. 8, p. 539690, Dec. 2020, doi: 10.3389/fchem.2020.539690.

[19] N. Huang et al., “Enhancing rheology and wettability of drilling fluids at Ultra-Low temperatures using a novel amide material,” Gels, vol. 11, no. 9, p. 687, Aug. 2025, doi: 10.3390/gels11090687.

[20] M. Knol-Kauffman, A.-M. Solås, and P. Arbo, “Government-industry dynamics in the development of offshore waste management in Norway: from prescriptive to risk-based regulation,” Journal of Environmental Planning and Management, vol. 64, no. 4, pp. 649–670, Aug. 2020, doi: 10.1080/09640568.2020.1779676.

[21] N. S. Daisy, M. H. Hafezi, L. Liu, and K. Lee, “A Comprehensive Review of Canadian Marine Oil Spill Response System through the Lens of Decanting Regulations and Practices,” Journal of Marine Science and Engineering, vol. 10, no. 9, p. 1310, Sep. 2022, doi: 10.3390/jmse10091310.

[22] L. B. Pereira, C. M. S. Sad, E. V. R. Castro, P. R. Filgueiras, and V. Lacerda, “Environmental impacts related to drilling fluid waste and treatment methods: A critical review,” Fuel, vol. 310, p. 122301, Oct. 2021, doi: 10.1016/j.fuel.2021.122301.

[23] K. Ghasemi, A. Akbari, S. Jahani, and Y. Kazemzadeh, "A critical review of life cycle assessment and environmental impact of the well drilling process," The Canadian Journal of Chemical Engineering, vol. 103, no. 6, pp. 2499–2526, Nov. 2024, doi: 10.1002/cjce.25539.

[24] N. D. D. Jambol, N. O. A. Babayeju, and N. A. E. Esiri, "Lifecycle assessment of drilling technologies with a focus on environmental sustainability," GSC Advanced Research and Reviews, vol. 19, no. 3, pp. 102–111, Jun. 2024, doi: 10.30574/gscarr.2024.19.3.0206.

[25] M. Rashidi *et al.*, "Simulation of wellbore drilling energy saving of nanofluids using an experimental Taylor–Couette flow system," *Journal of Petroleum Exploration and Production Technology*, vol. 11, no. 7, pp. 2963–2979, Jul. 2021, doi: 10.1007/s13202-021-01227-w.