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## Application and Chemistry of Drilling Fluids: A Review

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### ABSTRACT

Drilling fluids, commonly referred to as drilling muds, are indispensable to safe and efficient oil and gas exploration and production operations. This review examines the applications and underlying chemistry of drilling fluids, with emphasis on their functional roles, compositional diversity, and performance in complex subsurface environments. Drilling fluids are primarily applied to cool and lubricate the drill bit, transport drill cuttings to the surface, maintain wellbore stability, control formation pressures, and minimize formation damage. Depending on operational and geological requirements, drilling fluids are broadly classified into water-based, oil-based, and synthetic-based systems. The chemistry of drilling fluids governs their rheological behavior, filtration control, density, lubricity, and chemical stability under high-pressure and high-temperature conditions. The key chemical components include clays (such as bentonite), polymers, weighting agents, emulsifiers, shale inhibitors, and fluid-loss additives. Interactions between these components and formation minerals significantly influence drilling efficiency and environmental compatibility. Recent advances in drilling fluid chemistry have focused on the development of high-performance polymers, nanomaterials, and environmentally benign additives to enhance thermal stability, reduce toxicity, and improve wellbore integrity. This review also highlights emerging trends such as smart drilling fluids, real-time monitoring, and the integration of chemical design with data-driven optimization techniques. Understanding the application and chemistry of drilling fluids is essential for improving drilling performance, reducing operational risks, and ensuring compliance with increasingly stringent environmental regulations. The insights presented provide a comprehensive foundation for researchers and industry professionals seeking to optimize drilling fluid systems for modern oil and gas operations.

**Keywords:** Drilling fluids, wellbore, emulsifiers, rheological behavior, nanomaterials

## 1. Introduction

Drilling fluids, often termed the "lifblood" of the drilling operation, are sophisticated, chemically engineered systems critical for the rotary drilling of oil and gas wells. Far from being simple mixtures, they are complex, multi-phase colloidal dispersions whose properties are meticulously controlled to perform under the extreme conditions of temperature, pressure, and chemical exposure encountered downhole. The primary objective of a drilling fluid is to facilitate the safe, efficient, and cost-effective construction of a wellbore, a function achieved through an intricate interplay of chemistry and physics (Caenn et al., 2017).

At its most fundamental level, a drilling fluid is a system composed of a continuous phase (the base fluid) and a dispersed phase (various additives and solids). The choice of base fluid defines the primary classification of the mud and its core chemical environment. Water-Based Muds (WBMs): These systems use water (fresh, saline, or seawater) as the continuous phase. They represent the largest volume of fluids used globally due to their lower cost and greater environmental acceptability. The chemistry of WBMs revolves around the dispersion of clay particles (e.g., bentonite) and water-soluble polymers, which are stabilized by electrical double-layer repulsion. The challenge lies in managing this stability in the presence of contaminants like salts and divalent cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) and in inhibiting the interaction between the aqueous phase and water-sensitive shale formations (Amanullah & Al-Arfaj, 2021).

Non-Aqueous Fluids (NAFs): This category includes both Oil-Based Muds (OBMs), which use diesel or mineral oil, and Synthetic-Based Muds (SBMs), which use engineered fluids like olefins and esters. The continuous organic phase in NAFs is immiscible with water, which is incorporated as a dispersed phase to form a stable water-in-oil emulsion. This structure provides inherent lubrication, superior shale inhibition (by preventing water contact), and exceptional thermal stability. The chemistry of NAFs is dominated by the selection of emulsifiers and wetting agents that stabilize the emulsion and keep solids oil-wet, ensuring consistent rheology and filtration properties (Mahmoud et al., 2021).

The evolution of drilling fluid chemistry is increasingly focused on nanotechnology and smart materials. The integration of nanomaterials, such as functionalized silica nanoparticles and graphene oxide, has enabled a new generation of multi-functional additives. These materials operate at the molecular level to simultaneously enhance rheology, reduce fluid loss, and improve lubricity, addressing multiple challenges with a single additive (Ali et al., 2022). Furthermore, the concept of "smart" or stimuli-responsive fluids is emerging from laboratory research. These systems are designed with chemical moieties that change their conformation or properties in response to specific downhole triggers, such as pH, temperature, or shear rate. For instance, a fluid could be engineered to remain thin at surface conditions for easy pumping but automatically thicken upon encountering the higher temperature of the wellbore to improve cuttings transport, representing a shift from passive to active fluid systems (Vryzas & Kelessidis, 2024).

In essence, a modern drilling fluid is a dynamically managed chemical plant in a circulating system. Its formulation is a delicate balance of components designed to control density, rheology, filtration, lubrication, and chemical activity, making it one of the most critical and complex technologies in hydrocarbon exploration and production.

## 2. Multifaceted Significance in Modern Hydrocarbon Extraction

The significance of drilling fluids extends far beyond merely lifting cuttings to the surface. Their role is integral to the entire well construction process, impacting safety, economics, and environmental compliance. **Geopressure Management and Well Control:** The most critical safety function is controlling subsurface pore pressures. The fluid's density, or mud weight, is meticulously calculated and maintained using weighting agents like barite to exert a hydrostatic pressure that exceeds the formation pressure. A failure in this primary barrier can lead to a "kick" (influx of formation fluids) and potentially a catastrophic blowout. Recent advances focus on real-time pressure monitoring and the use of automated density control systems to navigate narrow pressure windows in deepwater and HPHT wells, significantly enhancing safety margins (Siddiqi et al., 2023).

**Geomechanical Wellbore Stability:** The wellbore is a mechanically unstable structure. The drilling fluid provides both mechanical and chemical support. Mechanically, the hydrostatic pressure pushes against the rock walls, preventing immediate collapse. Chemically, the fluid interacts with the formation, particularly shales. WBMs can cause shale hydration and swelling, leading to instability, while OBMs/SBMs and advanced inhibitive WBMs are designed to prevent this fluid invasion through osmotic and chemical inhibition mechanisms, as demonstrated by recent studies on ionic liquids and graphene-based inhibitors (Ahmed et al., 2024).

**Maximizing Reservoir Asset Value:** As the drill bit penetrates the hydrocarbon-bearing zone, the fluid must be designed to minimize "formation damage." This involves using specialized fluid loss additives and bridging agents to form an ultra-thin, impermeable filter cake on the wellbore wall. This cake prevents the invasion of fine solids and filtrate into the reservoir rock, which can clog pore throats and severely reduce permeability, thereby safeguarding the well's ultimate productivity and the field's recovery factor (Khalil et al., 2022).

**Enabling Drilling Efficiency and Cost Management:** Efficient drilling requires rapid penetration and minimal downtime. Drilling fluids contribute directly by cooling and lubricating the drill bit and string, reducing torque and drag, especially in deviated and horizontal wells. Furthermore, by preventing wellbore problems such as stuck pipe, hole collapse, and excessive solids build-up, a well-maintained fluid system drastically reduces non-productive time (NPT), which is a major cost driver in drilling operations (Mikhailov et al., 2023).

**Environmental Stewardship and Compliance:** The choice of drilling fluid has profound environmental implications. While OBMs offer technical advantages, their discharge is heavily regulated. This has driven the development of SBMs with lower toxicity and the innovation of high-performance, environmentally benign WBMs that utilize green additives derived from biomass, aligning operational needs with stringent global environmental standards (Singh et al., 2023).

### 3. Evolution and Classification of Drilling Fluids

The evolution of drilling fluids has progressed from simple water-clay mixtures to sophisticated engineered systems designed to meet specific geological challenges. Recent research (2020-2024) has significantly advanced our understanding of fluid composition and performance characteristics across different categories.

### 3.1. Water-Based Muds (WBMs): Technological Advancements in Shale Inhibition and HTHP Applications

Traditional WBMs have been substantially improved through novel chemical formulations. While they remain the most environmentally acceptable option, recent innovations have focused on overcoming their limitations in reactive shale formations and high-temperature environments. Ahmed et al. (2024) demonstrated that amino-functionalized ionic liquids can reduce shale swelling by over 80% compared to conventional potassium chloride systems through multiple inhibition mechanisms including cation exchange, surface adsorption, and pore throat plugging. Furthermore, the development of high-performance water-based muds (HPWBMs) incorporating graphene oxide nanosheets has shown remarkable thermal stability (up to 150°C) and superior shale inhibition capabilities, bridging the performance gap with non-aqueous fluids while maintaining environmental compliance (Zhang & Wang, 2023).

The rheological stability of WBMs under extreme conditions has been enhanced through synthetic polymer technology. Zhou et al. (2023) developed a thermo-associative copolymer that maintains stable viscosity profiles at temperatures exceeding 150°C, addressing the common challenge of thermal degradation in conventional polymers. These copolymers exhibit reversible viscosity changes with temperature fluctuations, providing optimal hydraulics throughout the drilling operation.

### 3.2. Oil-Based Muds (OBMs): Enhanced Performance and Environmental Mitigation Strategies

OBMs continue to be the fluid of choice for technically challenging wells, particularly in high-pressure, high-temperature (HPHT) environments and reactive shale formations. Recent research has focused on optimizing their performance while addressing environmental concerns. Mahmoud et al. (2021) conducted a comprehensive review of advanced remediation techniques, highlighting that thermal desorption units (TDUs) can achieve over 95% recovery of base oil from drill cuttings, significantly reducing environmental impact. Additionally, the development of synthetic-based alternatives to traditional diesel-based fluids has gained momentum, with studies showing that modified vegetable oil-based fluids offer comparable lubricity and shale inhibition with substantially lower toxicity profiles (Johnson & Zhang, 2022).

The emulsion stability of OBMs under extreme downhole conditions has been improved through novel surfactant packages. Recent work by Chen et al. (2023) introduced zwitterionic surfactants that maintain stable water-in-oil emulsions at temperatures up to 200°C and pressures exceeding 25,000 psi, addressing the critical challenge of emulsion breakdown in ultra-HPHT environments.

### 3.3. Synthetic-Based Muds (SBMs): Performance Optimization and Lifecycle Assessment

SBMs represent the current state-of-the-art in balancing technical performance with environmental responsibility. Recent lifecycle assessment studies have quantitatively demonstrated their advantages over traditional OBMs. Pereira et al. (2022) found that ester-based SBMs reduce marine toxicity by 70-80% and exhibit biodegradation rates 3-5 times faster than mineral oil-based systems, validating their preference in environmentally sensitive offshore operations. The thermal stability of synthetic base fluids has been systematically investigated, with findings indicating that linear paraffins and internal olefins maintain stable rheological properties at temperatures exceeding 200°C, making them suitable for

geothermal and ultra-deepwater applications (Thompson & Lee, 2024). Furthermore, the integration of nanoparticle technology in SBM formulations has demonstrated synergistic effects, with silica nanoparticles enhancing both filtration control and emulsion stability while reducing the required chemical additive concentrations by 15-20% (Rodriguez et al., 2023).

#### 4. Emerging Hybrid Systems and Specialty Fluids

The boundaries between traditional fluid classifications are becoming increasingly blurred with the development of hybrid systems. Recent innovations include nano-enhanced drilling fluids that incorporate functionalized nanoparticles to create multi-functional fluid systems. Elochukwu et al. (2022) documented that carbon nanotubes (CNTs) functionalized with hydrophilic groups can simultaneously improve rheological properties, enhance thermal conductivity, and provide superior lubrication, reducing torque and drag by up to 40% in extended-reach drilling applications. Another significant advancement involves the development of "designer" drilling fluids tailored for specific reservoir characteristics. Research by Santos et al. (2024) introduced reservoir-adaptive fluid systems that can modify their wettability characteristics in response to downhole conditions, potentially eliminating the need for separate drill-in fluid systems and reducing formation damage in productive zones.

#### 5. Advanced Chemical Additives: Mechanisms and Innovations

The performance of modern drilling fluids is critically dependent on the sophisticated action of chemical additives. Recent research has moved beyond traditional materials, focusing on understanding nanoscale mechanisms, green chemistry, and creating multi-functional additives that enhance several fluid properties simultaneously.

##### i. Nanomaterials as Multi-Functional Additives: A Paradigm Shift

The integration of nanotechnology represents one of the most significant recent advancements. Nanoparticles are not merely incremental improvements; their high surface area-to-volume ratio and unique surface chemistry allow them to perform multiple roles.

##### ii. Mechanisms of Action: Nanoparticles function through several mechanisms:

**Pore Blocking and Filter Cake Enhancement:** Nano-silica and graphene oxide (GO) sheets are highly effective at plugging the nano-pores in a forming filter cake. Research by Kumar et al. (2021) demonstrated that starch-silica nanocomposites reduced fluid loss by over 50% at high temperatures by creating a denser, less permeable barrier. The nanoparticles fill the interstitial spaces between larger polymer chains and clay particles.

**Lubricity and Friction Reduction:** 2D nanomaterials like graphene and hexagonal boron nitride (h-BN) act as nanoscale ball bearings. Wang et al. (2023) found that functionalized graphene sheets in water-based mud reduced the coefficient of friction by 35-40% by forming a protective, low-shear-strength film on both the drill string and wellbore, which is crucial for extended-reach drilling.

**Rheological Modification:** Cellulose Nanocrystals (CNCs) and carbon nanotubes (CNTs) can form robust networks within the fluid. A study by Zhou et al. (2023) showed that CNCs, derived from biomass,

provide excellent suspension and gel strength in high-salinity environments where traditional polymers like Xanthan Gum degrade, offering a sustainable and high-performance alternative.

### iii. The Rise of High-Performance, Green Additives

Environmental regulations and a push for sustainability have driven the development of high-performance, biodegradable additives from renewable resources.

**Natural Polymer Derivatives:** Modified starches and cellulose remain staples, but recent work focuses on enhancing their thermal stability and efficiency. Singh et al. (2023) reviewed the use of carboxymethylated chitosan and guar gum derivatives as fluid loss controllers, which are not only effective but also non-toxic and readily biodegradable.

**Shale Inhibitors from Biomass:** Traditional salts like KCl are being supplemented or replaced by organic inhibitors. Jain et al. (2024) highlighted the efficacy of tannin extracts and amino-acid-based inhibitors. These work by adsorbing strongly onto clay surfaces through hydrogen bonding and cation exchange, effectively preventing hydration and dispersion without the environmental impact of high chloride concentrations.

**Lubricants from Vegetable Oils:** Epoxidized vegetable oils and their derivatives are emerging as high-performance lubricants. Johnson & Zhang (2022) demonstrated that a modified soybean oil-based lubricant provided superior lubricity to mineral oil in OBMs, with the added benefits of being renewable and having a lower aquatic toxicity profile.

## 6. The Rise of Green and Smart Drilling Fluid Technologies

Sustainability and digitalization are the two dominant themes in recent drilling fluid research.

**Green Chemistry and Circular Economy:** The drive for sustainability has spurred the development of additives from renewable resources and industrial waste. Singh et al. (2023) catalogued numerous examples, including using palm oil fly ash as a fluid loss additive and rice husk-derived silica as a reinforcing agent for filter cakes. This approach not only reduces the environmental impact but also lowers costs and promotes a circular economy. Furthermore, the development of non-toxic, biodegradable lubricants from vegetable oils is replacing traditional mineral-oil-based lubricants.

**Smart and Stimuli-Responsive Fluids:** This emerging field aims to create "intelligent" fluids that autonomously adapt to downhole conditions. Vryzas & Kelessidis (2024) discussed the potential of stimuli-responsive polymers whose viscosity can be triggered by changes in pH, temperature, or salinity. For instance, a fluid could be designed to be thin and pumpable at surface conditions but automatically thicken upon encountering the higher temperature in the wellbore to improve hole cleaning. Another application is in lost circulation, where a fluid containing a monomer could polymerize upon contact with a specific formation fluid, sealing fractures intelligently.

**Digital Integration and Real-Time Monitoring:** The era of "digital mud" is dawning. Advanced sensors now provide real-time data on rheology, density, and chemical composition at the flow line. This data stream, when integrated with AI models, allows for predictive maintenance of the fluid system. Salehi & Kiran (2024) described a machine learning algorithm that can predict fluid property changes hours in

advance, allowing engineers to proactively adjust additive dosing, thus maintaining optimal performance and preventing drilling dysfunctions before they occur.

The sophisticated chemistry of drilling fluids, as reviewed is not an academic exercise; it is directly and pragmatically applied to solve critical challenges during the drilling process. This section details how these chemical systems are functionally deployed to ensure safe, efficient, and productive operations.

**7. Geopressure Management and Wellbore Stabilization: A Chemical and Mechanical Synergy.** The paramount application of drilling fluids is to maintain wellbore integrity and prevent the uncontrolled flow of formation fluids. This is a continuous battle against geological forces, won through precise chemical and mechanical control. Precision Density Control: The primary mechanism is the hydrostatic pressure exerted by the fluid column, a direct function of its density. While barite remains the workhorse weighting agent, recent applications focus on managing "sag"—the settling of weighting material in deviated wells, which can create dangerous density variations. Bageri et al. (2020) demonstrated that using micronized ilmenite significantly improves sag stability compared to conventional barite, providing a more uniform density profile and enhancing safety in critical offshore wells. Furthermore, real-time density monitoring coupled with automated mixing systems now allows for dynamic adjustment of mud weight, enabling operators to navigate narrow pore-pressure/fracture-gradient windows with unprecedented precision (Amanullah & Al-Arfaj, 2021).

Chemical Wellbore Strengthening: Beyond mere mechanical support, advanced fluids are engineered to actively strengthen the wellbore. This involves the use of specially sized and shaped bridging particles (e.g., calcium carbonate, graphite) and additives known as "wellbore strengthening agents." These materials are designed to plug and prop micro-fractures in the wellbore wall as they initiate, effectively increasing the fracture resistance of the formation. This technique allows drilling with a higher mud weight, providing a larger safety margin to control pore pressure without causing losses. The application of nanocomposites for this purpose, as explored by Khalil et al. (2022), shows promise in creating more effective and resilient seals within these fractures.

## **8. Advanced Hydraulics and Cuttings Removal: Engineering Flow for Efficiency**

The efficient removal of drilled cuttings is a complex hydraulic problem directly addressed by the fluid's rheological design. Inadequate hole cleaning leads to a host of issues, including pack-off, stuck pipe, and excessive non-productive time.

Optimized Rheological Profiles: The fluid must possess a high "low-shear-rate viscosity" (LSRV) to suspend cuttings when circulation stops, yet a low "high-shear-rate viscosity" to minimize pump pressure and energy consumption during circulation. The development of advanced polymers, such as the thermo-associative copolymers studied by Zhou et al. (2023), provides this ideal rheological profile automatically, adjusting to downhole temperatures to maintain optimal carrying capacity.

Real-Time Hydraulic Modeling and Cleaning in Complex Wells: In extended-reach (ERD) and horizontal wells, gravity causes cuttings to form stationary beds on the low side of the hole. Modern practice employs sophisticated real-time hydraulic modeling software that integrates rig data (flow rate, RPM, ROP) with fluid properties. As described by Mikhailov et al. (2023), these digital twins of the wellbore can predict the formation of cuttings beds and recommend specific cleaning procedures, such as periodic

"sweeps" (pills of high-viscosity fluid) or adjustments to drill string rotation, to proactively manage hole cleaning and prevent costly incidents.

## 9. Reservoir Drilling and Formation Damage Control: Protecting the Asset

When the drill bit enters the hydrocarbon-bearing zone, the drilling fluid's mission shifts to preserving the natural flow capacity of the reservoir. Formation damage, the reduction in permeability near the wellbore, can severely impact a well's productivity and the field's ultimate recovery.

**The Imperative of a Quality Filter Cake:** The first line of defense is the formation of a thin, tough, and impermeable filter cake. This cake is engineered using a blend of fluid loss additives and bridging agents. The goal is to quickly seal the pore throats of the reservoir rock with a minimal amount of invasion. Recent innovations involve "acid-soluble" and "oil-soluble" bridging materials (e.g., acid-soluble calcium carbonate, oil-soluble resins). These materials effectively block the pores during drilling but can be easily dissolved by acid treatments or produced hydrocarbons during initial production, thereby restoring the reservoir's native permeability (Khalil et al., 2022).

**The Role of Nanotechnology in Ultra-Fine Filtration:** The limitations of conventional additives in sealing nano-darcy scale pores have been addressed by nanotechnology. Kumar et al. (2021) demonstrated that nanocomposites, such as starch-silica, create a much denser and more effective filter cake. The nanoparticles plug the microscopic gaps between larger polymer chains and bridging particles, leading to an order-of-magnitude reduction in filtrate invasion. This "nano-cake" provides superior protection for high-value reservoirs, ensuring that the well delivers closer to its theoretical potential.

## 10. Lubricity and Friction Reduction: Enabling Complex Trajectories

The drilling of directional, horizontal, and extended-reach wells introduces immense friction between the drill string and the wellbore. High torque and drag can exceed the capabilities of surface equipment and make it impossible to reach the target depth.

**Lubricating Additives and Mechanisms:** Drilling fluids are formulated with lubricants to mitigate this friction. These include liquid lubricants (oils, synthetic esters, surfactants) and solid lubricants (graphite, glass beads, thermoplastic polymers). The latest research explores the exceptional lubricity of 2D nanomaterials. Elochukwu et al. (2022) highlighted that graphene, with its extremely low shear strength between layers, can coat metal and rock surfaces, creating a "ball-bearing" effect that dramatically reduces the coefficient of friction. Field applications have shown torque reductions of over 30% in challenging ERD wells using nano-enhanced lubricants, making previously undrillable well paths feasible.

This review has detailed the critical role of drilling fluids as engineered chemical systems that are fundamental to the safety, efficiency, and success of modern hydrocarbon drilling. The key findings can be summarized as follows:

**Foundational Chemistry Dictates Function:** The classification into Water-Based, Oil-Based, and Synthetic-Based Muds establishes distinct chemical environments that dictate additive selection and overall performance. The chemistry is not arbitrary; it is precisely tailored to manage colloidal stability, rheological behavior, and interfacial interactions downhole.

**Multifunctional Applications are Enabled by Additive Innovation:** The primary applications—wellbore stability, cuttings transport, and formation damage control—are directly enabled by specialized chemical

additives. The advancement from simple clays and polymers to nanomaterials and smart composites has dramatically enhanced fluid performance. For instance, nanocomposites provide superior fluid loss control (Kumar et al., 2021), while novel ionic liquids offer eco-friendly shale inhibition (Ahmed et al., 2024).

**Integration of Digital and Real-Time Technologies:** The era of passive fluid management is over. The integration of real-time monitoring, hydraulic modeling, and data analytics allows for proactive optimization of fluid properties, transforming drilling fluids into a dynamic, digitally managed system that prevents problems before they occur (Mikhailov et al., 2023; Salehi & Kiran, 2024).

**Sustainability is a Core Driver of Innovation:** Environmental considerations are no longer an afterthought but a primary driver of research. The development of Synthetic-Based Muds (Pereira et al., 2022), green additives from biomass (Singh et al., 2023), and advanced waste remediation techniques (Mahmoud et al., 2021) reflects the industry's commitment to reducing its environmental footprint while maintaining high performance.

## 11. Conclusion

In conclusion, drilling fluids are far more than simple "mud"; they are a cornerstone of petroleum engineering, representing a complex and essential integration of chemistry, mechanics, and environmental science. The evolution of their formulation—from basic mixtures to sophisticated systems incorporating nanotechnology, smart materials, and digital intelligence—has been pivotal in enabling the industry to access more challenging reservoirs.

The continuous innovation in drilling fluid technology is not merely an academic pursuit but a practical necessity. It directly addresses the dual challenges of escalating technical difficulty in well construction and increasingly stringent environmental regulations. As the industry moves forward, the ongoing research into stimuli-responsive fluids, multi-functional nanomaterials, and AI-driven fluid management promises to unlock new levels of performance and efficiency. Ultimately, the strategic development and application of advanced drilling fluids will remain indispensable for the safe, economical, and environmentally responsible extraction of oil and gas resources in the decades to come.

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