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Biodegradable drilling fluids: A comprehensive review of formulation, filed applications and future directions

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ABSTRACT: Drilling Fluids are critical to oil and gas exploration, with conventional formulations, particularly Oil-Based Mud (OBMs), posing significant environmental challenges due to their toxicity and non-biodegradable nature. This research explores the development and application of biodegradable Drilling Fluids as sustainable alternatives, focusing on current innovations and future directions. Biodegradable fluids, derived from renewable resources such as natural oils (e.g., coconut, jojoba) and biopolymers (e.g. starch, cellulose derivatives), offer comparable rheological performance to traditional fluids while minimising ecological impacts. Recent advancements include modified starches, cellulose nanocrystals and waste-derived additives like agricultural waste, which enhance fluid properties and align with circular economy principles. Case studies from regions such as the Tarim oilfields, Vietnam, and the Permian Basin demonstrate the practical efficacy of these fluids, with benefits including reduced emissions, cost savings, and improved reservoir protection. However, challenges such as material compatibility, scalability, and cost persist; continued research and collaboration between academia and industry are essential to overcome these barriers and realise the full potential of biodegradable drilling fluids.

Keywords: Biodegradable drilling fluids, biopolymers, environmental sustainability, modified starches, oil-based muds, rheological performance, water-based drilling fluids.

INTRODUCTION

The exploration of oil and gas resources has long been pivotal to global energy supply, yet these processes are not without significant environmental challenges. Among the critical components of drilling operations are drilling fluids, which play a vital role in maintaining wellbore stability, cooling and lubricating the drill bit, and transporting cuttings to the surface. Traditionally, oil-based drilling fluids have been favoured for their superior performance characteristics, such as enhanced lubrication and thermal stability. However, the environmental ramifications of using such fluids, particularly those whose base is diesel, have prompted a shift towards a more sustainable alternative. This transition is underscored by the increasing regulatory pressures and societal demand for environmentally responsible practices in the oil and gas industry. The development and application of biodegradable drilling fluids represent a promising frontier in this endeavour, offering the potential to mitigate environmental impacts while maintaining operational efficacy.

Biodegradable drilling fluids are formulated using renewable resources that can decompose naturally, thereby reducing the ecological footprint of drilling activities. The use of natural oils, such as coconut and shea butter oils, as substitutes for diesel in drilling fluids exemplifies this innovative approach. These oils not only provide comparable rheological properties but also offer significant environmental benefits by minimising the disposal challenges associated with oil-contaminated cuttings. Laboratory studies have demonstrated that coconut oil-based drilling fluids (OBM) exhibit superior viscosity and emulsion stability, although further optimisation is required to address issues such as mud cake thickness (Akintola *et al*., 2024). The integration of biodegradable polymers into drilling fluid formulations further enhances their environmental compatibility. Biodegradable polymers, derived from both synthetic and natural sources, are engineered to decompose into non-toxic substances, thereby alleviating the environmental burden of plastic waste. These polymers have been extensively researched for their applications across various industries, including agriculture, biomedical, and packaging, due to their mechanical strength and eco-friendly properties (Meghana *et al.,* 2022; Čolnik *et al.,* 2020). In the context of drilling fluids, biodegradable polymers can be utilised to improve the mechanical and physical characteristics of the fluids, ensuring that they meet the demanding conditions of drilling operations while remaining environmentally benign.

The development of environmentally friendly additives for water-based drilling fluids is another critical area of innovation. Water-based fluids, while more environmentally acceptable than their oil-based counterparts, often suffer from higher friction coefficients, which can impede drilling efficiency. The incorporation of biodegradable lubricants, such as vegetable oil esters and biodiesel, into these fluids can significantly reduce friction and enhance performance. These lubricants are derived from renewable resources and are designed to degrade naturally, thus aligning with the broader goals of sustainability and environmental stewardship (Kelly, 2022).

OVERVIEW OF DRILLING FLUIDS

Drilling fluids, commonly referred to as drilling muds, are essential components in oil and gas exploration and production. These fluids play a critical role in facilitating the drilling process by performing multiple functions that ensure the efficiency, safety, and environmental integrity of the operation. Drilling fluids are complex mixtures of natural and/or synthetic chemical compounds designed to perform specific tasks during the drilling of oil and gas wells. Their primary functions include:

1. Cooling and Lubrication: Drilling fluids cool the drill bit and lubricate the drill string, reducing friction and preventing overheating (Wypych, 2022).
2. Wellbore Stabilisation: The fluid's density helps stabilise the wellbore, preventing collapse and ensuring structural integrity (Caenn, 2017).
3. Pressure Control: The fluid's weight (density) counteracts formation pressures, preventing blowouts and maintaining well control (Caenn, 2017).
4. Cuttings Transport: The fluid's viscosity and flow rate ensure the efficient transport of drilled cuttings to the surface (Wypych, 2022).
5. Formation Isolation: A filter cake forms on the borehole wall, preventing the invasion of drilling fluid into the formation and protecting the reservoir (Ruqeishi *et al.,* 2018; Dai and Zhao, 2018).

The composition of drilling fluids is tailored to meet the demands of the drilling environment, with properties such as density, viscosity, and fluid loss control being critical to their performance (Caenn, 2017). Table 1 shows a comparison of different types of drilling fluids with regard to their characteristics and usage. Drilling fluids are broadly classified based on the base fluid used in their formulation. The main types include water-based, oil-based, synthetic-based, and pneumatic fluids.

Water-based drilling fluids are the most used type, accounting for approximately 80% of all drilling operations due to their cost-effectiveness and ease of use (Ruqeishi *et al.,* 2018). These fluids use water as the continuous phase and are typically formulated with additives such as clays, polymers, and weighting agents to achieve the desired properties. Recent research has focused on developing novel polymeric additives that improve shale inhibition and reduce swelling, which are common issues in reactive shale formations. For instance, a study demonstrated that a new water-based mud (NWBMs) system significantly reduced shale swelling by 50% compared to traditional WBMs, enhancing wellbore stability and reducing stuck pipe events by 50% in offshore trials (Geri *et al.,* 2024). Additives such as sodium erythorbate, potassium formate, and polyethene glycol have been shown to significantly retard the degradation of biopolymers in WBMs, maintaining viscosity at temperatures up to 232°C, thus addressing the challenge of high-temperature stability(Akpan, 2019). Despite these advancements, WBMs still face challenges in certain geological formations. The reactivity of clays in shale formations can lead to wellbore instability, water influx, and differential sticking, which necessitates continuous innovation in additive formulations (Geri *et al*., 2024). High-temperature environments pose a significant challenge for WBMs, as traditional biopolymers tend to degrade, leading to loss of viscosity and performance. The development of high-temperature stable additives is crucial to overcoming these limitations (Akpan, 2019).

Oil-based drilling fluids use hydrocarbon oils as the continuous phase, often combined with emulsifiers and other additives to achieve the desired viscosity and stability. OBMs typically consist of a base oil, an aqueous phase, emulsifiers, and various additives such as wetting agents, rheology modifiers, and fluid-loss control additives.

Table 1. Comparison of drilling fluid types.

Type of drilling fluid	Key characteristics	Citations
Water-Based (WBM)	Most common, cost-effective, environmentally friendly, but prone to wellbore instability	Ruqeishi *et al*., 2018; Jamrozik *et al*., 2016; Fink, 2012
Oil-Based (OBM)	High thermal stability, excellent wellbore stability, but environmentally hazardous	Jamrozik *et al*., 2016; Fink, 2012; Clark, n.d.
Synthetic-Based (SBM)	Balances performance and environmental impact, widely used in offshore drilling	Veil *et al*., 1995; Ahsan, 2024; Qiu and Zhao, 2013
Pneumatic	Uses compressed air or gas, suitable for shallow wells, minimal fluid loss	Caenn, 2017; Caenn *et al*., 2011

These components work together to provide the desired rheological properties and stability under high-pressure and high-temperature conditions (Mohammed *et al.,* 2020). They exhibit excellent thermal stability, making them suitable for high-temperature and high-pressure drilling operations (Shuhe *et al*., 2016). The lubricating properties of OBMs reduce torque and drag on the drill string, enhancing drilling efficiency and reducing the risk of stuck pipe incidents. However, OBMs are more expensive and pose greater environmental risks compared with WBMs. They are typically used in challenging drilling environments where WBMs are insufficient (Jamrozik *et al.,* 2016).

Synthetic-based drilling fluids are a blend of oil-based and water-based systems, offering a balance between performance and environmental impact. These fluids use synthetic oils, such as polyalphaolefins or esters, as the base fluid. SBMs combine the advantages of OBMs, such as high thermal stability and minimal formation damage, with lower environmental toxicity compared to OBMs (Ahsan, 2024). Synthetic-based fluid ins are typically composed of synthetic hydrocarbons, such as those derived from esters, which are known for their biodegradability and low toxicity. For instance, synthetic ester fluids are recommended for their technical advantages and sustainability, although they face challenges related to thermal and hydrolytic stability at high temperatures and pressures (Johnson *et al.,* 2023).

SBFs are designed to have lower environmental impacts compared to oil-based fluids. They are non-toxic and biodegradable, meeting international standards for environmental safety (Sun *et al.,* 2020; Johnson *et al*., 2023). These fluids maintain stable drilling fluid performance, with high flash points and low fire hazards, making them suitable for high-temperature applications (Sun *et al.,* 2020). SBFs significantly reduce the environmental footprint of drilling operations. They are less toxic and more biodegradable than traditional oil-based fluids, which helps in meeting stringent environmental regulations (Sun *et al*., 2020).

SBFs offer excellent lubricity, thermal stability, and filtration control, which are crucial for efficient drilling operations. They also help in reducing drill pipe sticking and enhancing the rate of penetration (ROP) (Sun *et al.*, 2020; Johnson *et al*., 2023). The use of synthetic esters and other environmentally friendly components allows SBFs to be tailored for specific drilling conditions, including high-pressure and high-temperature environments (Johnson *et al.,* 2023). Despite their advantages, SBFs can face challenges related to stability under extreme conditions. For example, synthetic ester fluids may struggle with maintaining stable borehole conditions and flat rheology in low-temperature climates (Johnson *et al*., 2023).

The production of SBFs can be more costly compared to traditional fluids, and the availability of raw materials can be a limiting factor. However, advancements in refining techniques and the use of sustainable raw materials are addressing these issues (Sun *et al.,* 2020; Johnson *et al.*, 2023). While SBFs are designed to meet environmental standards, ongoing research is necessary to ensure compliance with evolving regulations and to address any potential long-term environmental impacts.

Pneumatic drilling fluids, also known as air or gas-based systems, use compressed air or natural gas as the circulating medium. These fluids are primarily used in shallow, low-pressure wells and are effective in formations where minimal fluid loss is critical. However, they are not suitable for high-pressure environments and are less commonly used compared to other types (Caenn, 2017).

Pneumatic drilling fluids are particularly advantageous in shallow, low-pressure wells where the risk of formation damage is minimised. These fluids help in maintaining wellbore stability and reducing the risk of differential sticking, which is a common issue in low-pressure formations (Huang *et al.,* 2023; Al-Hameedi *et al.,* 2020). Pneumatic fluids are effective in minimising fluid loss, especially in sensitive formations where traditional fluids might cause damage. The use of air and gas-based systems reduces the hydrostatic pressure exerted on the formation, thereby minimising the risk of fluid invasion and formation damage (Rasool *et al*., 2023). One of the significant limitations of pneumatic drilling fluids is their ineffectiveness in high-pressure environments. These fluids lack the density required to counterbalance high formation pressures, which can lead to well control issues

Table 2. Comparative analysis of drilling fluids.

Drilling fluid type	Environmental impact	Performance and regulatory compliance
Water-Based Fluids (WBFs)	Relatively environmentally benign	Lower drilling performance compared to oil-based fluids
Oil-Based Fluids (OBFs)	High environmental impact due to toxicity and persistence	Excellent drilling performance but subject to strict regulations
Synthetic-Based Fluids (SBFs)	Lower environmental impact than OBFs, biodegradable	Comparable performance to OBFs with reduced ecological risks

and increased risk of blowouts (Davoodi *et al.,* 2021; Rasool *et al.,* 2024).

The cooling capacity of pneumatic fluids is also limited, which can lead to overheating of the drill bit and other downhole tools (Yang *et al.,* 2024). Reduced Pneumatic drilling fluids have seen reduced popularity due to several challenges, including cooling and safety concerns. Water-based and synthetic-based fluids offer better cooling properties and are more effective in high-pressure, high-temperature (HPHT) conditions (Rasool and Ahmad, 2023). Safety concerns related to the use of air and gas in drilling operations, such as the risk of fire and explosion, have also contributed to their reduced use (Mahmoud *et al*., 2024).

Table 2 presents a concise evaluation of three primary drilling fluid types—Water-Based Fluids (WBFs), Oil-Based Fluids (OBFs), and Synthetic-Based Fluids (SBFs)—focusing on their environmental impact and performance within regulatory frameworks. WBFs, characterised by their aqueous composition, exhibit minimal ecological harm, making them preferable in environmentally sensitive areas; however, their lubricity and thermal stability are inferior to OBFs, limiting their efficacy in complex drilling operations. OBFs, formulated with petroleum-derived bases, offer superior performance, including enhanced lubricity and stability under high-temperature and high-pressure conditions, but their toxicity and persistence in ecosystems necessitate stringent regulatory oversight, often restricting their use. SBFs, designed with synthetic hydrocarbons, balance high performance with reduced environmental risk due to their biodegradability and lower toxicity, positioning them as a viable alternative to OBFs in compliance with modern environmental regulations.

Nanofluids, a class of drilling fluids enhanced with nanoparticles, have emerged as a promising solution to improve the performance of drilling operations. These fluids leverage the unique properties of nanoparticles to enhance the rheological, thermal, and filtration characteristics of conventional drilling fluids. The incorporation of nanoparticles such as zinc oxide (ZnO), iron oxide (Fe_2O_3), and silicon dioxide (SiO2) into water-based muds (WBMs) has been shown to significantly improve their performance under challenging drilling conditions.

Nanoparticles like Fe2O3 and ZnO have been shown to improve the rheological properties of drilling fluids, which are crucial for maintaining wellbore stability and efficient cuttings transport. For instance, the addition of nano-Fe2O3 to WBMs resulted in a 13.8% reduction in API filtrate volume and a 40% reduction in filter-cake thickness, enhancing the fluid's ability to maintain structural integrity under high-temperature and high-pressure (HTHP) conditions (Mahamadou & Jun, 2024). ZnO nanoparticles, when added to water-based nanofluids, have demonstrated improved viscosity and stability, which are essential for effective drilling operations. The viscosity of ZnO nanofluids can be tailored by adjusting the nanoparticle concentration and size, leading to enhanced fluid performance (Yalçın *et al.,* 2023).

The inclusion of nanoparticles in drilling fluids can significantly reduce fluid loss and improve mudcake quality. For example, nano-based drilling fluids have been shown to form a thin and impermeable mudcake, reducing the invasion of drilling fluids into the formation and minimising formation damage (Al-Yasiri *et al.,* 2019).

The use of Multi-Walled Carbon Nanotube (MWCNTs) in nano-water-based drilling fluids (NWBDFs) has been found to decrease the filtration rate and improve the stability of the gel structure against temperature variations, further enhancing the fluid's performance (Tian *et al.,* 2023).

Nanoparticles can also enhance the thermal and lubrication properties of drilling fluids, which are critical for operations in extreme environments. The addition of 2D nanolayered structures, such as graphene and MoS2, has been shown to improve the thermal conductivity and lubrication properties of drilling fluids, making them more effective in high-temperature drilling scenarios (Zamora-Ledezma *et al*., 2022).

SiO2 nanoparticles have been reported to reduce friction and power consumption in drilling operations, contributing to more energy-efficient drilling processes (Rashidi *et al*., 2021). The development of environmentally friendly and cost-effective nanofluids is a key focus in the industry. Nanoparticles such as ZnO and SiO2 are not only effective in enhancing fluid performance but also offer the potential for sustainable drilling solutions due to their benign environmental impact(Aftab *et al.,* 2020). Despite the promising benefits, the application of nanofluids in the oil and gas industry is still in its early stages, with ongoing research needed to address challenges such as nanoparticle stability and cost-effectiveness (Vryzas and Kelessidis, 2017).

ENVIRONMENTAL IMPACT OF CONVENTIONAL DRILLING FLUIDS

Drilling operations in the oil and gas industry rely heavily on the use of drilling fluids, which are essential for maintaining wellbore stability, cooling and lubricating the drill bit, and removing cuttings from the well. However, these fluids, which include water-based, oil-based, and synthetic-based muds, pose significant environmental challenges due to their chemical compositions and the large volumes of waste they generate. The environmental impact of these fluids is a growing concern, particularly in sensitive ecosystems such as marine environments, where improper disposal can lead to contamination and long-term ecological damage.

Water-Based Muds (WBMs): These are primarily composed of water and various additives to enhance their properties. They are generally considered less harmful than oil-based muds but can still contain toxic substances like heavy metals and salts that pose environmental risks if not properly managed (Ghazi *et al.,* 2011; Ilinykh *et al.,* 2023).

Oil-Based Muds (OBMs): Composed of oil as the continuous phase, these muds are effective for deep drilling but are associated with higher environmental risks due to their persistence and toxicity. They can release hydrocarbons and other pollutants into the environment, affecting marine life and ecosystems (Seyedmohammadi, 2017).

Synthetic-Based Muds (SBMs): These are designed to offer the performance benefits of OBMs while reducing environmental impact. However, they still pose challenges, particularly in terms of waste management and potential contamination (Seyedmohammadi, 2017).

Drilling fluids and cuttings can contaminate soil and water resources, particularly in arid regions where water is scarce. The presence of heavy metals and hydrocarbons in these wastes can lead to long-term environmental damage (Ilinykh *et al.,* 2023). Offshore drilling operations discharge fluids and cuttings into the sea, which can disrupt marine biodiversity and habitats. The bioaccumulation of toxic substances in marine organisms can lead to ecological imbalances and affect the food chain (Daan *et al.*, 1996; Seyedmohammadi, 2017). The life-cycle assessment of drilling muds highlights human toxicity and terrestrial eco-toxicity as major impact categories, with emissions from reserve pits and treated cuttings being significant contributors (Ilinykh *et al.,* 2023).

Various treatment methods, such as solidification, reinjection, and thermal desorption, are employed to manage drilling waste. These methods aim to minimise environmental impact by isolating pollutants and recovering valuable resources (Ghazi *et al.,* 2011; Ilinykh *et al.,* 2023). The use of biodegradable and non-toxic additives, such as cellulose derivatives, in WBMs is gaining traction. These additives improve the performance of drilling fluids while reducing their environmental footprint (Khan *et al.,* 2024; Moffatt, 2022). Processing hydrocarbon-contaminated cuttings offshore and recycling recovered oil and water back into the drilling fluid can reduce the environmental and safety risks associated with transporting waste to onshore facilities.

Ecological concerns

The discharge of drilling fluids and cuttings into marine and terrestrial environments can lead to the destruction of habitats and the loss of biodiversity. For instance, oil-based drilling fluids are prohibited in many regions due to their inability to biodegrade and their toxicity to marine organisms (Imarhiagbe and Obayagbona, 2019; Siddique *et al.,* 2017).

Improper disposal of drilling fluids can result in the contamination of groundwater, which is a critical resource for both human consumption and agricultural use. This contamination can have long-lasting effects on ecosystems and human health (Ghasemi *et al.,* 2024; Hossain *et al.,* 2017). Onshore drilling operations often result in the discharge of drilling fluids and cuttings onto land. These materials can pollute soil, reducing its fertility and making it unsuitable for agricultural use. Additionally, toxic substances in the soil can leach into groundwater, further exacerbating environmental damage (Caenn, 2017).

The long-term ecological impacts of oil spills, such as those from drilling discharges, include changes in community structure, reduced biodiversity, and altered trophic interactions. These effects can persist for years, as seen in major oil spills like the Deepwater Horizon, which caused extensive damage to marine ecosystems and reduced populations of key species (Barron *et al.,* 2020).

Bioremediation: Bioremediation offers a promising approach to mitigate the impacts of petroleum pollution. It leverages the metabolic capabilities of microorganisms to degrade hydrocarbons, providing a cost-effective and environmentally friendly solution. However, its success depends on various environmental factors, including temperature, pH, and nutrient availability (Hazaimeh *et al.,* 2021).

Regulatory frameworks and environmental standards

Regulatory agencies, such as the U.S. Environmental Protection Agency (EPA) and the Department of Petroleum

Resources (DPR) in Nigeria, have implemented strict guidelines for the disposal of drilling fluids and cuttings. These regulations often require environmental impact assessments (EIAs) and biodegradation tests to ensure that drilling operations do not harm the environment (Imarhiagbe & Obayagbona, 2019) (Caenn, 2017). Environmental standards for drilling fluids focus on reducing toxicity, improving biodegradability, and minimising waste. For example, the American Petroleum Institute (API) has established standards for the use of environmentally friendly drilling fluids, such as plant-based esters, which are biodegradable and non-toxic (Ismail *et al.,* 2014; Amorin, 2017).

Waste management protocols for drilling fluids include methods such as underground injection, onshore and offshore disposal, and recycling. These protocols aim to minimise the environmental impact of drilling waste by ensuring that it is handled and disposed of in an environmentally responsible manner (Caenn, 2017; Caenn *et al.,* 2011).

The need for biodegradable alternatives

Bio-based drilling fluids, such as those derived from vegetable oils, have emerged as a promising alternative to conventional fluids. These fluids are biodegradable, non-toxic, and environmentally friendly, making them suitable for use in sensitive ecosystems ("A review on applications of bio-products employed in drilling fluids to minimise environmental footprint", 2022) (Yang *et al.,* 2023). Ester-based drilling fluids (EBDFs) are another biodegradable option that has gained traction in recent years. These fluids are derived from renewable resources and offer excellent drilling performance while minimising environmental impact. However, challenges such as high kinematic viscosity and hydrolytic degradation must be addressed to optimise their use (Razali *et al*., 2018; Amorin, 2017).

Researchers have explored the use of waste-derived nanomaterials as additives in drilling fluids. These materials not only enhance the performance of drilling fluids but also reduce their environmental footprint by utilising waste products that would otherwise be discarded (Ikram *et al.,* 2021; Hossain *et al.,* 2017).

INNOVATIONS IN BIODEGRADABLE DRILLING FLUIDS

Starch, derived from plants such as corn, potato, and tapioca, is a widely used natural polymer in drilling fluids. Its biodegradability, low cost, and ability to improve rheological properties make it an attractive additive. However, native starch has limitations, such as poor thermal stability and solubility, which restrict its application in high-temperature environments (Davoodi *et al*., 2023) (Ali *et al*., 2021). To overcome these limitations, researchers have developed modified starches through chemical and physical modifications. For instance, carboxymethylated tapioca starch has been shown to enhance the thermal stability and rheological performance of WBDFs, making it suitable for high-temperature drilling operations (Ali *et al*., 2021). Similarly, cross-linked graft copolymers of starch, such as Starch, Acrylic Acid, Acrylamide, N-Vinylpyrrolidone, N,N'-Methylenebisacrylamide, (St-AA/AM/NVP/MBA), have demonstrated excellent thermal stability up to 170 °C and improved fluid loss control (Wu *et al*., 2023).

Cellulose derivatives, such as carboxymethyl cellulose (CMC), polyanionic cellulose (PAC), and cellulose nanocrystals (CNCs), are increasingly utilised in water-based drilling fluids (WBDFs) due to their biodegradability, rheological modification capabilities, and fluid loss reduction properties. These derivatives are derived from cellulose, a natural polymer, and are valued for their environmental friendliness and multifunctionality in various industrial applications. Their unique properties, such as high surface area, nanoscale dimensions, and the ability to form complex networks, make them particularly effective in enhancing the performance of WBDFs.

Cellulose derivatives like CNCs and CNFs are effective rheological modifiers due to their ability to form percolation networks and interact with other components in the fluid, such as bentonite. This interaction results in shear-thinning behaviour, which is beneficial for drilling operations as it allows for easy pumping and circulation of the fluid while maintaining structural integrity when at rest (Khan *et al.,* 2024; Li *et al*., 2021).

CNCs, in particular, have been shown to improve the viscosity and shear-thinning properties of WBDFs, with carboxylated CNCs (C-CNC) demonstrating superior performance in enhancing rheological properties under various temperature conditions (Peng *et al.,* 2023; Moffatt, 2022).

The nano-size and surface chemistry of CNCs enable them to effectively reduce fluid loss by plugging nanopores in the formation, thus preventing water penetration. This is crucial in maintaining wellbore stability and preventing formation damage (Khan *et al.,* 2024; Peng *et al.,* 2023).

Studies have shown that CNCs can form thin, compact filter cakes that minimise fluid loss, even under high-temperature conditions, making them suitable for challenging drilling environments (Moffatt, 2022).

The biodegradability and non-toxicity of cellulose derivatives make them an environmentally friendly alternative to conventional synthetic additives in WBDFs. Their use aligns with the growing demand for sustainable and green technologies in the oil and gas industry (Khan *et al*., 2024; Tyagi and Thakur, 2023).

Economically, cellulose derivatives are cost-effective due to their abundance and ease of extraction from natural sources. This makes them a viable option for large-scale industrial applications (Chen *et al.,* 2024; Tyagi and

Table 3. Comparison of materials and formulations.

Materials	Source/Modification	Key Benefits	Citation
Carboxymethylated Starch	Tapioca starch modified with carboxymethylation	Improved thermal stability, enhanced rheological properties, and reduced fluid loss	Ali *et al*., 2021
Cellulose Nanocrystals	CNCs derived from cellulose	High surface area, improved rheological properties, and fluid loss reduction	Khan *et al*., 2024; Moffatt, 2022
Xanthan Gum and Diutan Gum	Combination of xanthan and diutan gum	Enhanced rheological properties and fluid loss control under high temperatures	Akpan *et al*., 2020
Plant Press Slag (PPS)	Modified PPS to produce CMCS	Excellent filtration loss performance and thermal stability	Long *et al*., 2022
Ultrafine Potato Powder	Ultrafine powder derived from potatoes	Reduced fluid loss and improved rheological properties	Ali *et al*., 2024

Thakur, 2023).

Despite their advantages, the application of cellulose derivatives in WBDFs faces challenges such as optimising their concentration and functionalization to achieve desired performance under varying operational conditions (Peng *et al.,* 2023).

Cellulose nanomaterials, including nanofibrils (CNFs) and nanocrystals (CNCs), have gained attention for their unique properties, such as high surface area and nanoscale dimensions. These materials can form a stiff gel network, improving the rheological properties of WBDFs and reducing fluid loss under high-temperature conditions (Khan *et al*., 2024; Moffatt, 2022).

Xanthan gum, a biopolymer produced by the bacterium Xanthomonas campestris, is commonly used in drilling fluids to provide viscosity, suspend solids, and control fluid loss. However, its sensitivity to high temperatures and contamination limits its application in harsh drilling environments (Akpan *et al.,* 2020). To enhance the performance of xanthan gum, researchers have explored the use of eco-friendly biopolymers like diutan gum. The combination of xanthan gum and diutan gum in a 1:1 ratio has been shown to improve the rheological properties and fluid loss control of WBDFs, even after ageing at high temperatures (Akpan *et al.,* 2020). Guar gum, another biopolymer derived from the guar bean, is also used in drilling fluids. However, its application is limited due to its poor thermal stability and susceptibility to enzymatic degradation. Modified guar gum derivatives, such as hydroxypropyl guar gum, have been developed to address these challenges (Sulaimon *et al*., 2020).

Recent advancements in formulation and performance

Recent advancements in drilling fluid formulations have focused on the development of composite materials and hybrid systems. For example, the combination of starch and cellulose derivatives has been shown to enhance the rheological and filtration properties of WBDFs. Carboxymethylated starch and cellulose nanocrystals have been used together to create a synergistic effect, improving the overall performance of the drilling fluid (Long *et al.,* 2022; Li *et al.,* 2021).

The use of novel additives, such as plant press slag (PPS) and natural deep eutectic solvents (NADES), has also been explored. PPS, a byproduct of agricultural processing, has been modified to produce carboxymethyl cellulose and carboxymethyl starch (CMCS), which exhibit excellent filtration loss performance and thermal stability (Long *et al.,* 2022). NADES, derived from calcium chloride and glycerine, has been shown to improve the rheological properties of WBDFs, inhibit hydrate formation, and suppress shale swelling. This eco-friendly additive has the potential to replace traditional additives in drilling fluids (Rasool *et al*., 2023). Table 3 looks at the comparison of recent materials and formulations in drilling fluid.

Experimental studies have been conducted to optimise the formulation of WBDFs using natural polymers and biopolymers. For instance, the use of response surface methodology (RSM) has been employed to optimise the concentration of carboxymethylated tapioca starch in WBDFs, leading to improved rheological and filtration properties (Ali *et al.,* 2021). Similarly, the application of ultrafine potato powder (PP) as an eco-friendly additive has been evaluated. PP has been shown to reduce fluid loss and improve the rheological properties of WBDFs, making it a promising alternative to conventional additives (Ali *et al.,* 2024).

Table 4 maps the research landscape of the literature on Recent advancements in biodegradable drilling fluid formulations, focusing on component analysis, performance metrics, critical analysis, and contextual relevance. Table 4 explores the roles and interactions of components like weighting agents, viscosifiers, filtration control additives, pH controllers, lubricants, and H_2S scavengers. Table 4 reviewed studies encompass a broad spectrum of biodegradable additives derived from natural polymers, agricultural wastes, nanomaterials, and bio-based oils, evaluated primarily through laboratory experiments assessing rheological and filtration properties under various conditions.

Table 4. Recent advancements in biodegradable drilling fluid formulations.

Study	Rheological Performance	Filtration Control Efficiency	Environmental Biodegradability	Additive Synergism	Operational Robustness
Rahman *et al*., 2024	Improved rheology with alginate and taro root reducing fluid loss and friction	Reduced fluid loss and thin filter cake formation	Uses waste materials; environmentally friendly	Alginate and taro root improve rheology and filtration synergistically	Effective under HPHT conditions
Thibodeaux *et al*., 2023	Increased viscosity and shear-thinning behavior; yield points >40 lbf/ft²	Fluid loss as low as 13.5 mL; improved lubricity by 27%	Algal biomass is biodegradable and sustainable	Biomass enhances lubricity and fluid loss control	Tested under standard API conditions
Li *et al*., 2024	STA additive increases viscosity and colloidal stability	62.71% fluid loss reduction at 170 °C; thin, compact filter cake	STA is easily biodegradable with high thermal stability	Cross-linked starch interacts with clay to improve stability	High temperature resistance up to 170 °C
Ali *et al*., 2024	Ultrafine potato powder improves gel strength and plastic viscosity	43% filtration rate reduction; 70% filter cake thickness reduction	Potato powder is eco-friendly and biodegradable	Particle size and concentration optimize rheology and filtration	Performance maintained at elevated temperatures
Abdullah *et al*., 2024	PEI-GO nanocomposite enhances plastic viscosity and yield point	Filtration loss reduced by up to 67%; pore plugging observed	Nanocomposite is stable and compatible with bentonite	Electrostatic interactions improve filtration and rheology	Effective at 160 °C and high salinity
Zhang *et al*., 2023	XOS increases viscosity and cohesive strength; reduces friction	Reduced fluid loss; smoother mud cake microstructure	Derived from black fungus; biodegradable	Lubrication and inhibition via hydration film formation	Stable below 150 °C; improved high-temperature performance
Ali *et al*., 2023	Wheat nano-biopolymers improve gel strength and plastic viscosity	Fluid loss decreased from 19.5 to 14 mL; fine powders more effective	Nano-biopolymers are biodegradable and alkaline	Enhanced rheology and filtration via nano-scale effects	Tested up to 70 °C; thinning behavior improved
Al-Yasiri, 2023	Broad bean peels increase plastic viscosity and yield point	12% filtrate loss reduction; thinner filter cake	Agricultural waste; biodegradable and sustainable	Rheology and filtration improved synergistically	Tested at ambient conditions
Shuvo *et al*., 2023	Sawdust increases plastic viscosity and gel strength; shear-thinning	Significant fluid loss reduction; optimal at 0.5% concentration	Sawdust is biodegradable and low-cost	Particle size and concentration affect filtration and rheology	Performance stable under API conditions
Doley *et al*., 2023	CM-CS additive improves filtration and rheology compared to PEG	Filtrate loss reduced by up to 53%; improved shale recovery	Carboxymethyl chitosan is biodegradable	Shale inhibition and filtration synergism	Effective in Indian shale formations
Ali *et al*., 2023	Modified tapioca starch enhances plastic viscosity, yield point, gel strength	Improved filtration under high temperature and salt conditions	Biodegradable starch derivative	Salt and temperature influence rheology synergistically	High temperature and salt resistance demonstrated
Fadhil & Hadi, 2024	Potassium sorbate increases viscosity significantly	Potassium sorbate reduces filtration volume effectively	Biodegradable potassium salts	pH control and filtration improved	Maintains pH ~8 at elevated concentrations
Assi, 2024	Orange peel and Sidr leaf powders affect rheology and filtration	Reduced density and improved filtration; Sidr leaf more effective	Natural plant powders; biodegradable	Flavonoids and acids contribute to performance	Tested at varying additive concentrations

Table 4. Contd.

Study	Rheological Performance	Filtration Control Efficiency	Environmental Biodegradability	Additive Synergism	Operational Robustness
Liu *et al*., 2023	Lignocellulose nanomaterials improve rheology and filtration	Enhanced emulsion stability and filtration control	Fully biomass-derived; biodegradable	Synergistic effects of nanomaterials and bentonite	Suitable for emulsion-based fluids
Moffatt, 2022	Carboxylated cellulose nanocrystals improve rheology and inhibition	Low fluid loss; thin, compact filter cakes	Biodegradable cellulose nanomaterials	Gel network formation enhances stability	Effective up to 140 °C
Wei *et al*., 2022	Sodium alginate maintains viscosity under salt contamination	Lower filtration volume than CMC and PAC under salt stress	Biopolymer with excellent salt tolerance	Strong adsorption on bentonite improves performance	Effective in high salt environments
Ricky *et al*., 2022	Modified corn starch enhances rheology and fluid loss control	Improved fluid loss by 1.7 times at 220 °C	Biodegradable starch with hydroxyl groups	Herschel-Bulkley model fits rheology	High temperature stability
Ebuzeme *et al*., 2021	Sweet potato peel extract increases yield point and plastic viscosity	Improved hole cleaning and viscosity under temperature variation	Biodegradable agricultural waste	Synergistic effects with xanthan gum	Effective at elevated temperatures
Sid *et al*., 2023	Eggshell powder and calcium carbonate improve rheology and filtration	Calcium carbonate slightly better in pH effect; both reduce fluid loss	Eggshell powder is biodegradable waste	Additive concentration critical for performance	Optimal below 20 g concentration
Patidar *et al*., 2020	Groundnut husk cellulose acts as fluid loss retarder and rheology modifier	Filtration loss decreased by over 80% compared to base mud	Biodegradable and cost-effective	Particle size and concentration influence sealing	Tested under API RP 13B-1 standards
Ismail *et al*., 2020	Henna and hibiscus leaf extracts improve rheology and reduce fluid loss	Filtrate loss reduced by up to 76%; improved mud cake	Plant extracts are biodegradable	Inhibition of bentonite swelling observed	Tested at elevated temperatures
Raza *et al*., 2023	Rice husk ash improves plastic viscosity, yield point, gel strength	Increased fluid loss and mud cake thickness at high concentrations	Agricultural waste; sustainable additive	Concentration-dependent rheology and filtration	Acidic pH shift at higher concentrations
Arain *et al*., 2022	Castor oil biodiesel increases plastic viscosity and yield point	Lower filtrate loss than diesel-based mud at high temperature	Biodegradable biodiesel base fluid	Ester-based fluid improves rheology and filtration	Tested at ambient and reservoir temperatures
Al-Hameedi *et al*., 2021	Peanut shell powder enhances filtration and viscosity	Suitable for aged and fresh mud; withstands 79 °C	Biodegradable and low-cost additive	Multifunctional additive replacing synthetic chemicals	Tested under surface and subsurface conditions
Prakash *et al*., 2021	Litchi leaves powder increases plastic viscosity and gel strength	Filtration loss reduced by 70.6% at 100 psi	Natural biodegradable product	Effective fluid loss control agent	Stable after hot rolling at 100 °C
Bassey *et al*., 2024	Plant-based additives increase viscosity and yield point in oil-based mud	Filtration loss reduced by up to 94%; filter cake thickness varied	Biodegradable plant materials	Additives show fragile gel strength and good cake quality	NaCl susceptibility varies among additives
Assi & Haiwi, 2024	Flaxseed oil and walnut shell powder improve emulsion stability and rheology	High stability and viscosity at 400 °F	Biodegradable oils and cellulose-based emulsifiers	Synergistic effects in emulsion stability	Tested at high temperature

Table 4. Contd.

Study	Rheological Performance	Filtration Control Efficiency	Environmental Biodegradability	Additive Synergism	Operational Robustness
Guowei *et al*., 2021	Wild jujube pit powder enhances viscosity and reduces filtration loss	Forms grid structure in mud cake to prevent water penetration	Natural and biodegradable additive	Particle size affects rheology and filtration	Slightly acidic suspension
Medved *et al*., 2022	Mandarin peel powder reduces API and PPT filtration significantly	Rheological parameters increased but within acceptable limits	Food waste-derived biodegradable additive	Optimal concentration up to 1.5% by volume	Tested at room temperature
Al-Hameedi *et al*., 2020	Mandarin peel powder modifies rheology and reduces fluid loss	Fluid loss decreased by 44–68%; filter cake improved	Biodegradable food waste additive	Comparable to PAC-LV chemical additive	Negligible effect on mud weight
Al-Hameedi *et al*., 2020	Palm tree leaves powder reduces yield point and gel strength	Improved filtration and thin mud cake formation	Biodegradable bio-enhancer additive	Particle size irregularity affects rheology	Effective at 1.5–3% concentration
Sarbast *et al*., n.d.	Green magnetite nanoparticles with spent caustic improve rheology	Lower mud cake thickness and filtration volume	Waste alkali and nanoparticles are eco-friendly	Synergistic effect of nanoparticles and alkali	Herschel-Bulkley model fits flow behavior
Al-Hameedi *et al*., 2020	Potato peel powder enhances viscosity and reduces fluid loss	Improved filter cake thickness and reduced swelling	Biodegradable food waste additive	Alternative to resinex and synthetic additives	Tested under standard API conditions
Awl *et al*., n.d.	Broad bean peel powder improves plastic viscosity and gel strength	Reduced filter cake thickness and fluid loss	Biodegradable agricultural waste	Fine powder more effective than medium size	Tested at ambient conditions
Broni–Bediako *et al*., 2024	Dry mango leaves powder reduces alkalinity and fluid loss	Decreased plastic viscosity; improved gel strength	Biodegradable plant-based additive	Limited weighting agent effectiveness	Tested at multiple temperatures
Ni *et al*., n.d.	Modified shaddock peel improves rheology and filtration	Preservatives prevent mildew and maintain performance	Natural biodegradable additive	Mold inhibits viscosity and inhibition	Tested with preservative additives
Ikram *et al*., 2021	Review of waste-derived nanomaterials for rheology and lubricity	Nanomaterials improve filtration and rheology	Emphasis on biodegradability and environmental safety	Nanomaterials enhance multiple fluid properties	Broad literature synthesis
Al-Hameedi *et al*., 2020	Black sunflower seed shell powder reduces fluid loss and improves viscosity	Effective under fresh and aged conditions	Biodegradable and locally available waste	Multifunctional additive for viscosity and filtration	Stable under 50 °C aging
Al-Yasiri, 2023	Corn husks powder modifies viscosity and reduces filtration	Comparable to conventional chemical additives	Biodegradable agricultural waste	Particle size and concentration critical	Tested with spud mud formulations
Prakash *et al*., 2021	Grewia optiva fiber reduces filtration loss significantly	Comparable or better than CMC and PAC additives	Biodegradable cellulosic material	Effective under HPHT conditions	Tested at 100 °C and 500 psi
Li *et al*., 2021	Starch composite additives improve fluid loss and rheology	Environmentally friendly and high-performance	Biodegradable starch-based additives	Composite structure enhances filtration control	Suitable for water-based fluids
Sousa *et al*., 2021	Pine oil microemulsion drilling fluid shows low fluid loss	High lubricity and thermal stability	Biodegradable surfactant and oil phase	Pseudoplastic behavior with Herschel-Bulkley model	Stable across salinity ranges
Bataee *et al*., 2024	Palm oil biodiesel mud shows comparable rheology to diesel mud	Favorable filtration loss and gel strength	Biodegradable biodiesel base fluid	Minor differences in plastic viscosity	Suitable for wellbore stability

Table 4. Contd.

Study	Rheological Performance	Filtration Control Efficiency	Environmental Biodegradability	Additive Synergism	Operational Robustness
Akintola *et al*., 2024	Coconut and shea butter oils improve rheology and emulsion stability	Thicker mud cake; needs optimization	Renewable and biodegradable oils	Viscosifier and emulsifier effects	Tested at 120°F and 300°F
Yalman *et al*., n.d.	Rice husk ash improves rheology and reduces fluid loss	Increased yield point and apparent viscosity	Sustainable and low-cost additive	Concentration-dependent performance	Tested with bentonite mud
Le *et al*., n.d.	Orange peel waste reduces filtration volume by 18%	Improved fluid loss control at low concentrations	Biodegradable and cheap additive	Concentration-dependent filtration improvement	Tested at room temperature
Al-Hameedi *et al*., 2020	Banana peel powder increases plastic viscosity and reduces fluid loss	Improved gel strength and filter cake thickness	Biodegradable food waste additive	Multipurpose drilling fluid additive	Tested at 1–3% concentrations
Li *et al*., 2020	Tea polyphenols reduce filtration and improve mud cake	Biodegradable fluid loss additive	Natural plant-based additive	Filtration mechanism studied	Suitable for water-based fluids
Lei *et al*., 2024	Fully bio-based drilling fluid shows low plastic viscosity	Strong inhibition and temperature-enhanced plugging	Non-toxic and readily biodegradable	Synergistic effects among multiple additives	Effective above 140 °C and salt contamination
Khan *et al*., 2024	Cellulose derivatives improve rheology, filtration, and inhibition	Biocompatible and biodegradable additives	Nano-scale cellulose materials	Network formation enhances fluid stability	Challenges and future perspectives discussed

Case studies of successful applications of biodegradable drilling fluids in the oil and gas industry

In the Tarim and Karamay oilfields, a green drilling fluid system was developed to address the environmental challenges posed by traditional polymer sulfonate and oil-based drilling fluids. This system was designed to be non-toxic, biodegradable, and reservoir-protective. The application of this fluid system ensured pollution-free disposal of waste drilling fluids, significantly reducing secondary pollution (Xie *et al.,* 2012).

In Vietnam, a tailored drilling fluid solution was developed for HP/HT wells. The solution combined the PERFLEX™ and PYRO-DRILL™ with water-based drilling fluid systems, which are environmentally friendly and high-performance. This approach reduced emissions by 21% and saved $4.2 million by drilling 14 days ahead of schedule. The success of this operation demonstrated the efficiency and reliability of high-performance water-based mud (HPWBM) systems in challenging conditions (Ahsan and Gobe, 2024). A study comparing high-performance water-based muds (HPWBMs) and oil-based muds (OBMs) was conducted in North Central Texas and the Permian Basin. HPWBMs significantly outperformed OBMs, reducing CO2 emissions by 50% and hazardous waste generation. In North Central Texas, HPWBMs saved over $100,000 per well, while in the Permian Basin, they reduced drilling costs by 18.2% and lateral days by 57% (Bageri and Vordick, 2024). A biodegradable polymer drilling fluid system was successfully applied in the Panzhuang Block of the Qinshui Basin for coalbed methane (CBM) reservoirs. The system reduced gas permeability damage by 27% and demonstrated excellent resistance to coal fines pollution. The drilling fluid could be degraded by enzymes, improving reservoir protection and CBM production (Shuaifeng *et al.,* 2019).

A novel green water-based drilling fluid system (HBDF) was developed and applied in the SL oilfield. The system exhibited stable rheological and filtration performance, with a biodegradability index of 16.2% and low biological toxicity. After drilling, the fluid met environmental protection requirements, making it a benchmark for green drilling fluid research (Li, 2021). A novel graft and cross-linked copolymer starch (SAANM) was used as an additive in a water-based drilling fluid for a high-temperature offshore well. The additive provided excellent thermal stability up to 170°C and improved rheological and filtration properties.

The fluid system was non-toxic and biodegradable, ensuring environmental friendliness (Wu *et al.,* 2023). A biodegradable ester-based lubricant was tested in various water-based drilling fluids. The lubricant reduced torque and pipe drag by over 40%, improving drilling efficiency. Its biodegradability and non-toxicity made it suitable for environmentally sensitive areas (Argillier *et al*., 1997). An environmentally friendly oil-based drilling fluid was developed using jojoba oil as the base. The fluid was non-toxic, biodegradable, and free of diesel and mineral oil. It demonstrated good performance at high temperatures (160°C) and was suitable for shale oil and gas horizontal wells (Hossain, 2019).

A fully bio-based drilling fluid (Pure-Bio system) was formulated for unconventional oil and gas fields. The fluid exhibited strong inhibition and temperature-enhanced plugging properties, with a biodegradability index of 0.26. It was non-toxic and could withstand high temperatures (140°C) and contamination from NaCl and $CaCl_2$ (Lei *et al.,* 2024). Waste biomass materials such as banana peel powder, eggshell powder, and date seed powder were used as eco-friendly additives in drilling fluids. These additives improved rheological properties, reduced filtration loss, and enhanced environmental sustainability. Their use demonstrated the potential of sustainable alternatives to traditional chemical additives (Khan *et al*., 2024). Broad bean peels were evaluated as a natural additive in drilling fluids. The addition of these peels improved rheological characteristics, reduced fluid loss, and provided a cost-effective and environmentally friendly solution for drilling operations (Al-Yasiri, 2023).

Sawdust was tested as a biodegradable additive in water-based drilling fluids. It improved plastic viscosity by 71.4%, reduced fluid loss, and demonstrated shear-thinning behaviour. The use of sawdust as an additive highlighted the potential of agricultural waste in sustainable drilling practices (Shuvo *et al.,* 2023).

Wheat nano-biopolymers were used to enhance the rheological and filtration properties of water-based drilling fluids. The addition of these biodegradable additives improved gel strength and reduced fluid loss, demonstrating their potential for sustainable drilling operations (Ali *et al.,* 2023). Locally sourced agricultural waste materials such as sugarcane husks, palm kernel fibre, and tiger-nut husks were used as bio-additives in water-based drilling fluids. These additives improved rheological properties, reduced fluid loss, and provided a cost-effective and environmentally friendly solution for drilling operations (Nwala, 2024). A drilling fluid system incorporating green silver nanoparticles and mastic gum was developed. The system exhibited non-Newtonian behaviour, improved rheological properties, and met environmental standards. The use of these additives demonstrated the potential of renewable materials in sustainable drilling practices (Kamal *et al*., 2023). The above case studies are discussed in Table 5.

Future directions in biodegradable drilling fluids

The replacement of traditional lubricants with environment-tally friendly alternatives has gained significant attention. Bio-oil, synthetic esters, amides, and polyols are being explored as raw materials for biodegradable lubricants. These materials offer improved thermal stability and reduced toxicity compared to conventional lubricants. Additionally, the use of recycled vegetable oil, polysaccharides, and nanomaterials has been proposed as future directions for enhancing the performance of drilling fluid lubricants (Yang *et al*., 2023). A novel fully bio-based drilling fluid (Pure-Bio system) has been developed, incorporating chitosan-derived shale inhibitors, thermal-responsive plugging agents, and optimised thickeners (Table 6). This system demonstrates non-toxicity and high biodegradability, with a biodegradability index exceeding 0.26. Its engineering performance includes low plastic viscosity, high yield point, and effective filtration control under High-Temperature and High-Pressure (HTHP) conditions. The system also exhibits strong inhibition and temperature-enhanced plugging properties, making it a promising alternative for unconventional oil and gas drilling operations (Lei *et al.,* 2024).

Citric acid-based, Natural Deep Eutectic Solvents (NADES) have emerged as sustainable additives for drilling fluids. These solvents are non-toxic, cost-effective, and highly efficient in reducing shale swelling and improving rheological properties. NADES enhance the yield point-to-plastic viscosity ratio, reduce mud-cake thickness, and decrease filtrate volume. Their ability to modify surface activity, zeta potential, and clay layer spacing makes them effective shale inhibitors. NADES are poised to replace conventional ionic liquids and deep eutectic solvents in environmentally conscious drilling practices (Rasool *et al.,* 2024). Potassium sorbate, potassium citrate, and potassium bicarbonate have been evaluated as biodegradable alternatives to traditional shale inhibitors like KCl. These additives demonstrate significant reductions in shale swelling, with potassium sorbate showing the lowest swelling percentage at 4% concentration. Their performance is comparable to KCl, making them viable options for environmentally friendly drilling operations (Fadhil and Hadi, 2024).

Agricultural wastes such as sugarcane husks, palm kernel fibres, and tiger-nut husks are being utilised as eco-friendly additives to enhance drilling fluid properties. These materials improve rheological characteristics, such as plastic viscosity, apparent viscosity, and yield point, while reducing fluid loss and mud-cake thickness. Their biodegradability and low cost make them attractive alternatives to toxic chemical additives (Nwala, 2024). Modified starches and cellulose derivatives are gaining traction as environmentally friendly additives.

Starch microspheres and carboxymethyl cellulose (CMC) have been shown to enhance fluid loss control and rheological properties. These materials are biodegradable, non-toxic, and cost-effective, with applications in both drilling fluids and enhanced oil recovery (EOR) techniques. Their high-temperature resistance and ability to form stable networks make them suitable for complex drilling environments (Zhang *et al.,* 2024; Davoodi *et al.,* 2023; Khan *et al*., 2024).

Table 5. Key case studies of biodegradable drilling fluids.

Location	Drilling fluid type	Key benefits	Citation
Tarim and Karamay Oilfields	Green drilling fluid system	Pollution-free disposal, reduced secondary pollution	Xie et., 2012
Vietnam	HPWBM system	21% reduction in emissions, $4.2 million savings	Ahsan & Gobe, 2024
North Central Texas	HPWBM system	50% reduction in CO_2 emissions, $100,000 savings per well	Bageri & Vordick, 2024
Panzhuang Block, Quinshui Basin	Biodegradable Polymer system	27% reduction in gas permeability damage, improved CBM production	Shuaifeng *et al*., 2019
SL Oilfield	Green water-based drilling fluid system	Stable rheological performance, low biological toxicity	Li, 2021
Offshore oil field	Graft and cross-linked copolymer starch	Thermal stability up to 170^0C, improved filtration properties	Wu *et al*., 2023
African, North Sea, and US	Biodegradable ester-based lubricant	40% reduction in torque and pipe drag	Argillier *et al*., 1997
Shale oil and Gas Fields	Jojoba Oil-based drilling fluid	Non-toxic, biodegradable, suitable for high-temperature wells.	Hossain, 2019
Unconventional Oil/Gas Fields	Fully bio-based drilling fluid	Strong inhibition and plugging properties, non-toxic	Lei *et al*., 2024
Broad Beans Peels	Broad bean peels as natural additives	Improved rheological characteristics, reduced fluid loss	Al-Yasiri, 2023
Sawdust	Sawdust as a green additive	Improved plastic viscosity, reduced fluid loss	Shuvo *et al*., 2023
Wheat Nano-Biopolymers	Wheat Nano-Biopolymers	Improved gel strength, reduced fluid loss	Ali *et al*., 2023
Locally Sourced Bio-Additives	Agricultural waste as additives	Cost-effective, environmentally friendly, improved rheological properties	Nwala, 2024
Green Silver Nanoparticles	Green silver nanoparticles and mastic gum	Non-Newtonian behaviour, improved rheological properties	Kamal *et al*., 2023

Table 6. Comparison of biodegradable additives in drilling fluids.

Additive type	Key function	Environmental benefit	Citation
Natural Deep Eutectic Solvents (NADES)	Reduces shale swelling, improves rheology	Non-toxic, biodegradable, and cost-effective	Rasool *et al*., 2024
Biodegradable Shale Inhibitors	Mitigates shale swelling	Potassium sorbate and citrate are biodegradable and non-toxic	Fadhil & Hadi, 2024
Starch and Cellulose Derivatives	Enhance fluid loss control, rheology	Biodegradable, non-toxic, and derived from renewable resources	Li *et al*., 2024; Davoodi *et al*., 2023; Khan *et al*., 2024
Ultra-Fine Particles	Improves filtration, wellbore stability	Derived from agricultural waste, biodegradable	Ali *et al*., 2024
Bio-Based Polymers	Controls fluid loss, maintains rheology	Sustainable, derived from renewable resources	Alsaba *et al*., 2024; Li *et al*., 2024; Maitra & Bhardwaj, 2024

Ultra-fine particles derived from potato and other natural sources are being explored as eco-friendly additives. These particles improve filtration properties, reduce fluid loss, and enhance wellbore stability. Their biodegradability and ability to plug nanopores in formations make them promising candidates for sustainable drilling operations (Ali *et al.,* 2024). The use of waste biomass, such as banana peels, eggshells, and date seeds, as drilling fluid additives has shown encouraging results. These materials enhance rheological properties, including plastic viscosity and yield point, while maintaining environmental sustainability.

Their integration into drilling fluids aligns with global efforts to reduce environmental impact and promote circular economy practices (Khan *et al.,* 2024). Bio-based polymers and blends are being developed to replace conventional polymers in drilling fluids. These materials are derived from renewable resources and offer improved biodegradability and sustainability. Advances in polymer design, such as high-temperature-resistant lignosulfonates, have demonstrated superior performance in controlling fluid loss and maintaining rheological properties under harsh conditions (Alsaba *et al.,* 2024; Zhang *et al*., 2024; Maitra and Bhardwaj, 2024).

The future of biodegradable drilling fluids lies in the development of high-performance, eco-friendly additives and formulations. Key trends include:

Sustainable Materials: Increased use of agricultural wastes, starches, and cellulose derivatives.

Advanced Polymers: Development of bio-based polymers with enhanced thermal stability and rheological properties.

Nanotechnology: Integration of nanomaterials for improved fluid loss control and shale inhibition.

Circular Economy: Utilisation of waste biomass and recycled materials in drilling fluid.

Conclusion

The development and application of biodegradable drilling fluids mark a pivotal advancement in addressing the environmental challenges associated with oil and gas exploration. This review highlights the transition from conventional, environmentally harmful drilling fluids, such as oil-based muds, to sustainable alternatives formulated with renewable resources like natural oils, biopolymers, and waste-derived additives.

Innovations, including modified starches, cellulose derivatives, and eco-friendly lubricants, have demonstrated comparable rheological performance and thermal stability, as evidenced by successful applications in regions such as the Tarim oilfields, Vietnam, and the Permian Basin. These case studies underscore the potential of biodegradable fluids to reduce emissions, minimise ecological damage, and achieve significant cost savings while enhancing reservoir protection.

Despite these advancements, challenges such as material compatibility, scalability, and cost-effectiveness persist, necessitating further optimisation. Future research should prioritise sustainable materials, advanced bio-based polymers, nanotechnology, and the integration of waste biomass to align with circular economy principles. By fostering collaboration between academia and industry, the oil and gas sector can fully realise the potential of biodegradable drilling fluids, achieving a balance between operational efficiency and environmental stewardship, and contributing to a more sustainable energy future.

Recommendation

Despite these advancements in biodegradable materials, challenges such as material compatibility, scalability, and cost remain. Continued research and collaboration between academia and industry are essential to overcome these barriers and realise the full potential of biodegradable drilling fluids. Future research directions should emphasise sustainable materials, advanced bio-based polymers, nanotechnology, and waste biomass utilisation to optimise performance and environmental compliance.

CONFLICT OF INTEREST

There is no conflict of interest.

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