SUSTAINABLE AGRO-MATERIALS AS FUNCTIONAL ADDITIVES FOR IMPROVED DRILLING FLUID PERFORMANCE

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ABSTRACT

Drilling fluids are a vital component of oil and gas operations, ensuring wellbore stability, efficient removal of cuttings, lubrication, and control of formation pressures. Traditionally, synthetic chemical additives have been used to enhance drilling fluid performance, but they often present significant drawbacks, including high operational costs, environmental toxicity, and limited biodegradability. The increasing emphasis on sustainable practices and stricter environmental regulations has created a pressing need for eco-friendly and cost-effective alternatives. This study explores agro-based additives, derived from natural and renewable agricultural resources such as starches, cellulose derivatives, natural gums, plant extracts, and processed agricultural byproducts, as sustainable substitutes for conventional additives. These materials have been investigated for their ability to improve key fluid properties, including rheology, viscosity, gel strength, filtration control, and lubricity. Laboratory experiments and literature analyses indicate that agro-based additives can effectively enhance drilling fluid performance while being biodegradable, non-toxic, and economically viable. The study also highlights potential challenges, such as compatibility with other fluid components, and provides insights into the structure-property relationships that govern additive effectiveness. By integrating these natural materials into drilling fluid formulations, the research establishes a framework for designing next-generation, sustainable drilling fluids that combine operational efficiency with environmental responsibility. This work underscores the strategic value of leveraging agricultural resources in the energy sector and paves the way for further innovations in eco-friendly drilling technologies.

Keywords: *Agro-based additives; drilling fluids; sustainable drilling; rheology, and filtration control*

1. INTRODUCTION

Drilling fluids are vital in oil and gas operations because they help in maintaining wellbore stability, cool and lubricate the drill bit, transport cuttings to the surface, and control formation pressures (Grand View Research, 2024). The global drilling fluids market was valued at approximately USD 8.7 to 9.0 billion in 2024, showing the economic and operational importance of these fluids in exploration and production (Market Data Forecast, 2025). Additives form the functional backbone of drilling fluids as they determine critical parameters such as viscosity, gel strength, and filtration loss. By customizing additive composition, engineers can optimize fluid performance to prevent formation damage, ensure efficient cuttings transport, and maintain circulation stability under challenging downhole conditions (Al-Ziyadi, 2025). The performance of drilling fluids depends largely on the additives incorporated into their formulation. Rheology modifiers control flow behavior and cuttings suspension, filtration control agents reduce fluid invasion into formations, lubricants minimize torque and drag and shale inhibitors prevent swelling or dispersion of reactive clays (Al-Ziyadi, 2025). Proper additive design ensures operational safety, wellbore integrity, and efficient drilling performance across various geological formations (Pereira, 2022).

Agro-derived additives are sourced from agricultural crops, residues, and byproducts that offer renewable, biodegradable and cost-effective alternatives to synthetic polymers (Agwu et al., 2019). These materials include starches from corn, cellulose from plant fibers, and natural gums such as guar and xanthan. Agricultural wastes such as rice husks, banana peels, and groundnut shells have also been processed into functional drilling fluid additives (Madu et al., 2024).

Recent studies have shown that agro-based materials can effectively enhance drilling fluid properties. For instance, ground rice husk has been reported to reduce filtration loss by approximately 77 percent compared to unmodified water-based muds (Agwu et al., 2019). Similarly, biodegradable coffee grounds and watermelon rind have demonstrated potential for improving rheological and filtration performance while reducing overall fluid cost (Madu et al., 2024). The use of such renewable materials supports circular economy principles by adding value to agricultural waste while reducing dependence on synthetic chemicals. This approach not only minimizes environmental impact but also promotes sustainable development in oil and gas operations (Agwu et al., 2019).

2. OBJECTIVE OF THE STUDY

The goal of this study is to investigate how selected agro-derived additives can be used to create sustainable drilling fluids. We will examine their effects on key fluid properties like rheology, viscosity, gel strength, and filtration control. We will also compare their performance to conventional synthetic additives under standard API conditions. This combined assessment will help identify the relationships between structure and properties, as well as the compatibility factors that affect their behavior. Ultimately, this will guide the development of the next generation of drilling fluids that improve operational efficiency while reducing environmental impact and cost.

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3 KEY FUNCTIONS AND RHEOLOGICAL CHARACTERISTICS OF DRILLING FLUIDS

Drilling fluids are important for effective drilling operations and have a major impact on the oil and gas industry (Karakosta et al., 2021). Their main functions include cleaning the wellbore by transporting drill cuttings to the surface, lubricating and cooling the drill string and bit, maintaining wellbore stability, and managing formation pressure to prevent blowouts (Karakosta et al., 2021; Werner et al., 2017). To ensure drilling success, the properties of these fluids are continuously monitored and adjusted based on industry standards.

3.1 Mud Density (Mud Weight)

A drilling fluid's density, known as its mud weight, is a key property that helps in maintaining wellbore stability and control formation pressure. If the mud density is too low, it can cause rock shear failure, resulting in a borehole breakout and potential wellbore collapse (Das & Chatterjee, 2017). On the other hand, if the mud density is too high, it can cause problems such as loss of circulation into the formation, decreased rate of penetration (ROP), and possible formation damage (Ebikapaye, 2018).

3.2 Plastic Viscosity (PV)

Viscosity measures a fluid's resistance to flow. PV specifically measures the flow resistance due to friction between solid particles in the fluid and the fluid’s layers (Elkatatny, 2019). PV depends on the viscosity of the base fluid and the concentration of solids. An increase in solid content or mud weight results in higher PV. This can be undesirable as it may slow down drilling speed. To counteract the negative effects of high PV, the fluid can be diluted with water or treated with a thinning additive (Basfar et al., 2019).

3.3 Yield Point (YP)

The Yield Point (YP) indicates the shear-thinning performance in non-Newtonian drilling fluids. It shows the fluid's ability to keep drill cuttings suspended while circulating in the wellbore and up the annulus. Keeping the YP at the right level is important to prevent drilling issues like differential sticking (Delikesheva et al., 2020). The YP is affected by the size of the solid additives; smaller particles generally lead to a higher YP (Maiti et al., 2021).

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3.4 Gel Strength (GS)

Gel Strength (GS) measures the attractive forces between particles under static conditions, unlike YP, which is a dynamic measurement (Alakbari et al., 2018). GS helps to suspend drill cuttings and weighting materials when fluid circulation stops. This property usually increases over time while the fluid is still. As a result, higher pressure is needed to "break the gel" and restart circulation (Mohamed et al., 2020).

3.5 Filtrate Loss and Mud Cake Thickness

Filtration, or fluid loss, measures the liquid (filtrate) that leaks from the drilling fluid into a solid mud cake. This occurs when the hydrostatic pressure of the fluid column exceeds the pore pressure of the formation, causing the liquid part of the mud to enter the well formation (Novriansyah, 2021). As this happens, suspended solids from the mud deposit on the wellbore wall, forming a mud cake.Filtrate loss and mud cake thickness usually decrease as the concentration of solids in the drilling fluid increases. Both properties are closely monitored because high filtrate loss and thick mud cakes can lead to differential pipe sticking (Dejtaradon et al., 2019).

4 CLASSIFICATION OF AGRO-DERIVED ADDITIVES BY DRILLING FLUID FUNCTION

The effectiveness of a drilling fluid depends on its additives. Agro-derived materials offer a sustainable and high-performing alternative to traditional synthetic additives by improving specific fluid properties (Agwu & Akpabio, 2018). These materials are not uniform, they can be best classified by their main function, which fits with the key drilling fluid properties outlined in Section 3. This section reviews the agro-based additives categorized by their primary applications like rheology control, filtration control, lubricity and shale inhibition.

4.1 Additives for Rheology and Viscosity Control (PV and YP)

The most important rheological function of a drilling fluid is its ability to show non-Newtonian, shear-thinning behavior. It needs to maintain a high viscosity at low shear rates to support cuttings while thinning at high shear rates during pumping to lower friction pressure. This behavior mainly depends on biopolymers (Ekeinde et al., 2019). Natural Gums and Polysaccharides like xanthan gum and guar gum are widely used as primary viscosifiers. Xanthan gum is particularly valued for its high molecular weight and complex branching structure. This structure forms a strong network of hydrogen bonds in the fluid when at rest, resulting in a high yield point (YP) and gel strength. Modified starches from corn and potatoes also serve as effective rheology modifiers. In their natural state, they can be thermally unstable. However, when chemically modified (e.g., hydroxypropylated), they provide excellent viscosity and fluid loss control, often working well with xanthan gum (Al-Sallami et al., 2023).

4.2 Additives for Filtration Control

Controlling fluid loss into the formation is crucial for maintaining wellbore stability and preventing formation damage. Agro-based materials achieve this through two main methods which are pore-plugging and film-forming. Finely ground agricultural byproducts physically block the pores of the formation wall, initiating the formation of a mud cake. Materials like ground rice husks, pomegranate peels, and orange peel powders (OPP) have proven to be very effective. Research shows that adding OPP can significantly lower the API filtration volume by creating a denser, less-permeable barrier (El-Sayed et al., 2023). Other additives, like modified cellulose derived from sawdust or corn cobs, act as film-forming agents. These polymers hydrate and lay flat against the formation, forming a thin, low-permeability layer that limits fluid invasion. Studies indicate that materials like sugarcane rind powder and gum arabic can effectively minimize fluid loss, with performance in some cases similar to that of traditional additives like carboxymethyl cellulose (CMC) (Alade et al., 2024; Agwu & Akpabio, 2018).

4.3 Additives for Lubricity

High friction between the drill string and the borehole wall can cause excessive torque, drag, and energy use, especially in directional or deep wells. Plant-based bio-lubricants provide an environmentally friendly alternative to conventional petroleum-based lubricants. These additives are usually esters made from vegetable oils such as soybean, rapeseed (canola), castor, and palm oil (Wu & Sharma, 2024). These bio-lubricants have excellent lubricity because their polar fatty acid chains cling to metal surfaces, creating a strong, friction-reducing film. Additionally, they have high flash points and importantly, high biodegradability, allowing them to be classified as Environmentally Acceptable Lubricants (EALs) (Pack-Logix, 2024).

4.4 Additives for Shale Inhibition

Wellbore instability in reactive shale formations, caused by the hydration and swelling of clays like montmorillonite, is a significant drilling challenge. Agro-based additives help prevent this by encasing the shale and disrupting the hydration process. Biopolymers such as modified cellulose or other polysaccharides work as encapsulators. They adhere to the clay surface, forming a protective polymeric film. This film physically prevents water from reaching the reactive sites on the clay and interrupts the hydrogen bonding between water molecules and clay surfaces (Ibrahim et al., 2021). Certain plant extracts, like those from henna or ginseng, have shown inhibitory effects. More commonly, polyamine biopolymers, which can come from organic sources like humic

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acids, serve as effective clay stabilizers. These cationic polymers bond to the negatively charged clay surfaces, neutralizing the charge and preventing water uptake that causes swelling (Minal Specialities, n.d.; Lifeforce, n.d.).

5. LITERATURE REVIEW

Agwu et al. (2019) conducted an experimental study to investigate the potential of rice husk powder and saw dust as environmentally friendly, low-cost fluid-loss control additives in water-based drilling fluids. The motivation behind the research was to identify sustainable substitutes for conventional synthetic polymers such as PAC and CMC, which are effective but expensive, non-biodegradable, and environmentally harmful upon disposal. The base mud was formulated using bentonite and water in accordance with API RP 13B-1 standards. The two agro-derived additives were cleaned, dried, ground, and sieved to uniform particle sizes, then incorporated into the mud at concentrations of 2%, 4%, 6%, and 8% by weight. The mud samples were tested for filtrate volume, mud-cake thickness, and rheological properties including plastic viscosity, yield point, and gel strength, to evaluate

(a) Before sieving **(b)** After pulverization

Fig. 1. Rice husk used for the study.

(a) Before sieving **(b)** After pulverization

Fig. 2. Saw dust used for the study.

The results revealed a significant improvement in filtration characteristics, especially with the rice husk additive. At an optimal concentration of 6 wt%, rice husk reduced the filtrate volume by approximately 77% compared to the base mud, whereas sawdust achieved about 63% reduction at 8 wt%. This enhanced performance was attributed to the amorphous silica content and fibrous lignocellulosic structure of rice husk, which formed a dense, low-permeability mud cake. Sawdust also improved filtration control but produced a relatively thicker and more porous cake due to its irregular organic composition. The average mud-cake thickness decreased from 3.2 mm for the base mud to 1.6 mm for rice husk and 2.3 mm for sawdust formulations, confirming the better sealing efficiency of rice husk. Rheological tests showed that both additives maintained desirable flow behavior, with only minor increases in plastic viscosity (11 to 13 cP) and yield point (10 to 13 lb/100 ft^2), ensuring stable pseudoplastic properties suitable for efficient hole cleaning and suspension.

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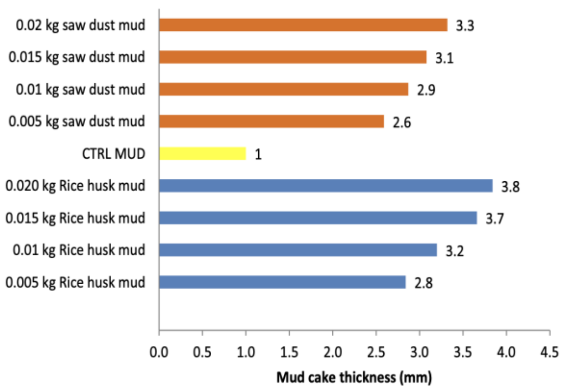
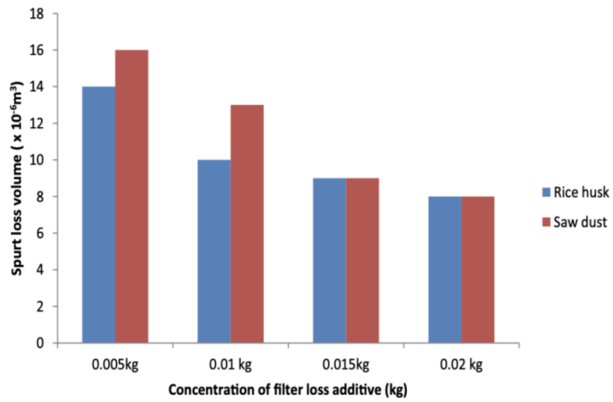




The improvement in filtration control was closely related to the microstructural characteristics of the rice husk. Its silica-rich particles and fibrous matrix created an interlocking network within the filter cake, effectively sealing micro-pores and reducing filtrate invasion. This natural hybrid structure mimicked the function of synthetic polymers but offered advantages of biodegradability, local availability, and cost efficiency. The study concluded that rice husk could serve as a primary fluid-loss additive, while sawdust could act as a supporting bridging material in sustainable drilling fluid formulations. However, the authors noted that the results were obtained under ambient temperature and pressure, and further evaluation under HPHT (high-pressure, high-temperature) conditions would be necessary for field validation.

Al-Hameedi et al. (2019) carried out an experimental study to evaluate Mandarin Peels Powder (MPP) as an environmentally friendly, multifunctional additive for water-based drilling fluids. The research was driven by the increasing need to replace conventional synthetic polymers such as PAC and CMC with biodegradable and renewable alternatives that can maintain drilling fluid efficiency while reducing environmental impact. The study proposed the use of mandarin peel waste, a by-product of the food industry, as a natural additive owing to its organic polymeric composition rich in cellulose, pectin, and lignin, which are known to enhance fluid rheology and filtration properties. The central objective of the study was to determine whether MPP could act as both a viscosifier and a filtration control agent, thereby improving overall drilling fluid performance while maintaining operational compatibility and stability.

The experimental work was performed in accordance with API RP 13B-1 standards. A base water–bentonite mud system was prepared, and varying concentrations of mandarin peel powder (1%, 2%, 3%, and 4% by weight) were incorporated to analyze its influence on key mud parameters. The peels were thoroughly washed, oven-dried, pulverized into fine powder, and sieved to achieve uniform particle size before use. The formulated muds were evaluated for plastic viscosity (PV), yield point (YP), gel strength (10 s and 10 min), pH, mud density, and API filtrate loss using a standard filter press apparatus. Comparative assessments were made between the base mud and MPP-based formulations to observe the effect of increasing MPP concentration on rheological stability and fluid-loss control. The study also examined filter-cake morphology to understand the sealing behavior and pore-plugging characteristics of the additive.

The results indicated that Mandarin Peels Powder significantly improved both rheological and filtration properties of the water-based muds. As the MPP concentration increased, the plastic viscosity and yield point values rose consistently, reflecting enhanced particle suspension and improved internal resistance to flow. The gel strength values increased proportionally at both 10 seconds and 10 minutes, suggesting better static stability of the mud and prevention of barite sagging during circulation breaks. The filtration tests revealed that the API filtrate volume decreased by approximately 35–40% at 6 wt% MPP compared to the base mud, demonstrating strong fluid-loss control capabilities. The mud cake formed with MPP was thinner, smoother, and more uniform than that of the base fluid, signifying reduced permeability and improved sealing efficiency. Furthermore, the pH remained stable between 8.0 and 9.0, indicating that the additive did not adversely affect the chemical compatibility or alkalinity of the drilling system. Importantly, the inclusion of MPP did not cause any excessive thickening or gelling, thereby preserving the desirable pseudoplastic flow behavior necessary for efficient cuttings transport and hole cleaning.

The observed performance enhancements were primarily attributed to the natural polymeric structure of MPP. The cellulose and lignin components provided structural strength and stability to the mud, while the pectin molecules acted as hydrophilic agents that absorbed water and improved hydration, resulting in increased viscosity and reduced filtrate invasion. The fibrous microstructure of the powder contributed to the formation of a compact and cohesive filter cake that effectively sealed micro-pores in the formation. This combination of organic fiber content and colloidal polymeric activity made MPP a highly effective dual-function additive. The authors concluded that Mandarin Peels Powder represents a viable, low-cost, and biodegradable substitute for conventional drilling fluid polymers, particularly in low-temperature, low-pressure applications. However, they also noted the necessity for further testing under high-pressure high-temperature (HPHT) conditions to determine the additive's long-term thermal stability and performance consistency across variable drilling environments. Additionally, they emphasized the importance of standardizing peel preparation and particle size to ensure reproducible results in industrial use.

The study by Shafiq et al. (2024) examines three types of agricultural waste products as possible drilling mud additives: Palm Oil Fuel Ash (POFA), Wood Ash (WA), and Rice Husk (RH). The main point of the research is its focus on sustainability and cost savings. All materials were obtained for free from industrial and agricultural sources in Sarawak, Malaysia. The POFA came from a palm oil mill, the WA from a plywood company, and the RH from a local village. This shows the use of easily accessible waste.

The researchers prepared the additives through thorough physical processing. The rice husk was dried in an oven at 45°C. The POFA was processed at 500°C, and the wood ash at 800°C using high-temperature burning. After that, all materials were ground and sifted into three different particle sizes: 75, 150, and 212 µm. These processed additives were added to a standard bentonite-water-based mud at varying concentrations of 0.6, 0.8, and 1.0 wt%.

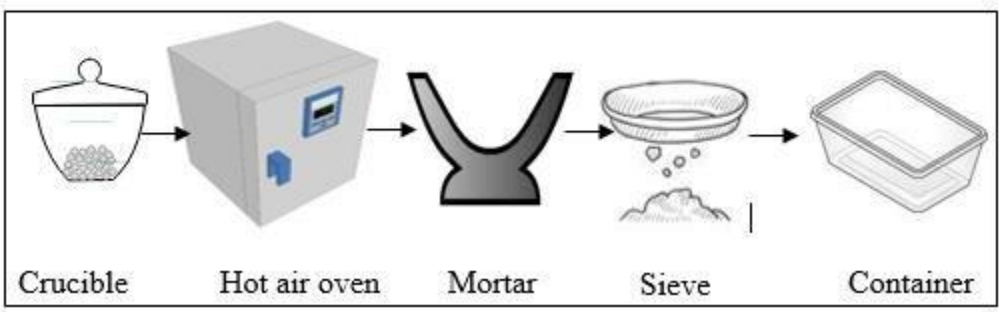
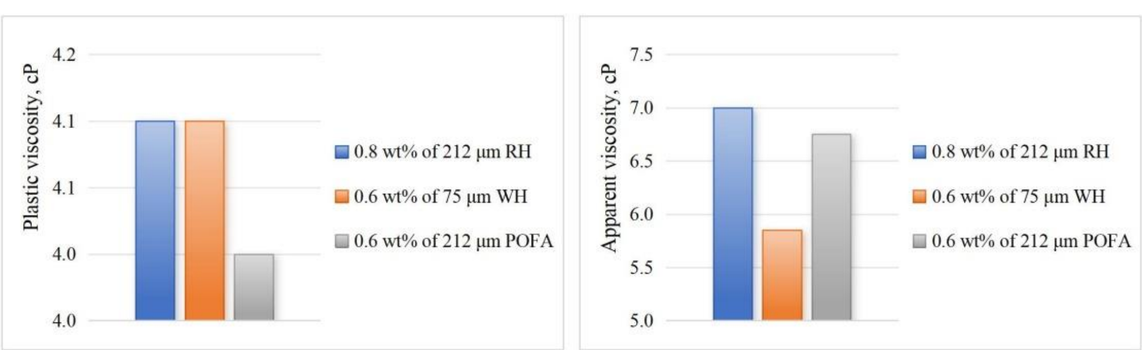


Fig 5: Rice Husk Preparation Schematic Diagram.

The performance of these modified muds was measured by checking key properties. These included density, rheology (which involves apparent viscosity, plastic viscosity, and yield point), and, most importantly, HPHT (high-pressure, high-temperature) filtration characteristics.



(a) Plastic viscosity (b) Apparent viscosity

Fig 6: Drilling fluids viscosity when added with designated additives

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The results were clear. Rice husk was the most effective additive, especially for improving filtration properties and rheology. The best formulation found in the study was 0.8 wt% of 212 µm Rice Husk. This formulation led to a notable 52% reduction in fluid loss and a 29% increase in viscosity compared to the standard base mud. In contrast, the best formulations for wood ash and POFA showed less effective but still useful fluid loss reductions of 30% and 35%, respectively. This positions rice husk as the best option for controlling fluid loss.

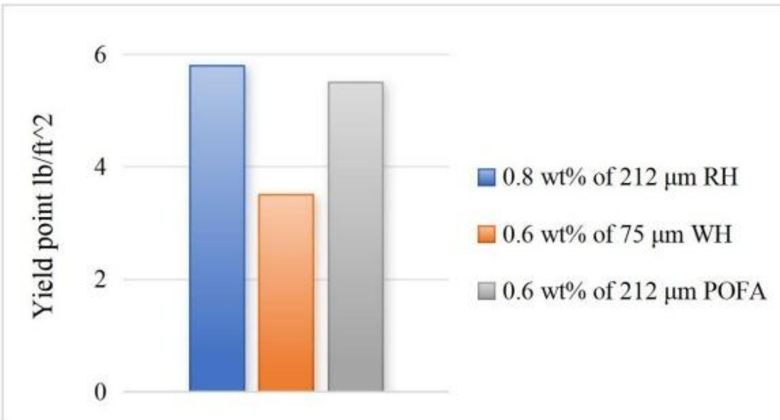

Fig 7: Drilling fluids yield points when added with designated additives

The paper by Momeni et al. (2025) evaluates an environmentally friendly drilling fluid aimed at reducing borehole instability in shale formations. The main issue discussed is the tendency of hydratable clay minerals in shale to swell and break apart when they come into contact with water-based fluids, which can lead to expensive drilling problems. As a non-toxic and eco-friendly substitute for oil-based muds, the study focuses on glycerin (also known as glycerol) as the main shale-inhibiting additive. The synthetic glycerin, obtained with 99.5% purity, was mixed with deionized water to form base fluids with high glycerin levels (70%, 80%, 90%, and 100% by volume). The performance of these fluids was compared to a control with deionized water (0% glycerin) and a regular KCl-based fluid.

The approach started with a thorough examination of the test materials like bentonite and shale cuttings from the Pabdeh formation. These samples were analyzed using X-ray Diffraction (XRD) to identify their mineralogy (notably the presence of swellable montmorillonite) along with other tests. After characterization, the glycerin fluids underwent five main performance tests: the Bentonite Sedimentation Test, Free Swelling Test, Bentonite Inhibition Test, Cuttings Dispersion Test and a Visual Observation of Swelling using custom-made clay tablets. Many of these tests were conducted at higher temperatures (up to 75°C) to evaluate the fluid's thermal stability.

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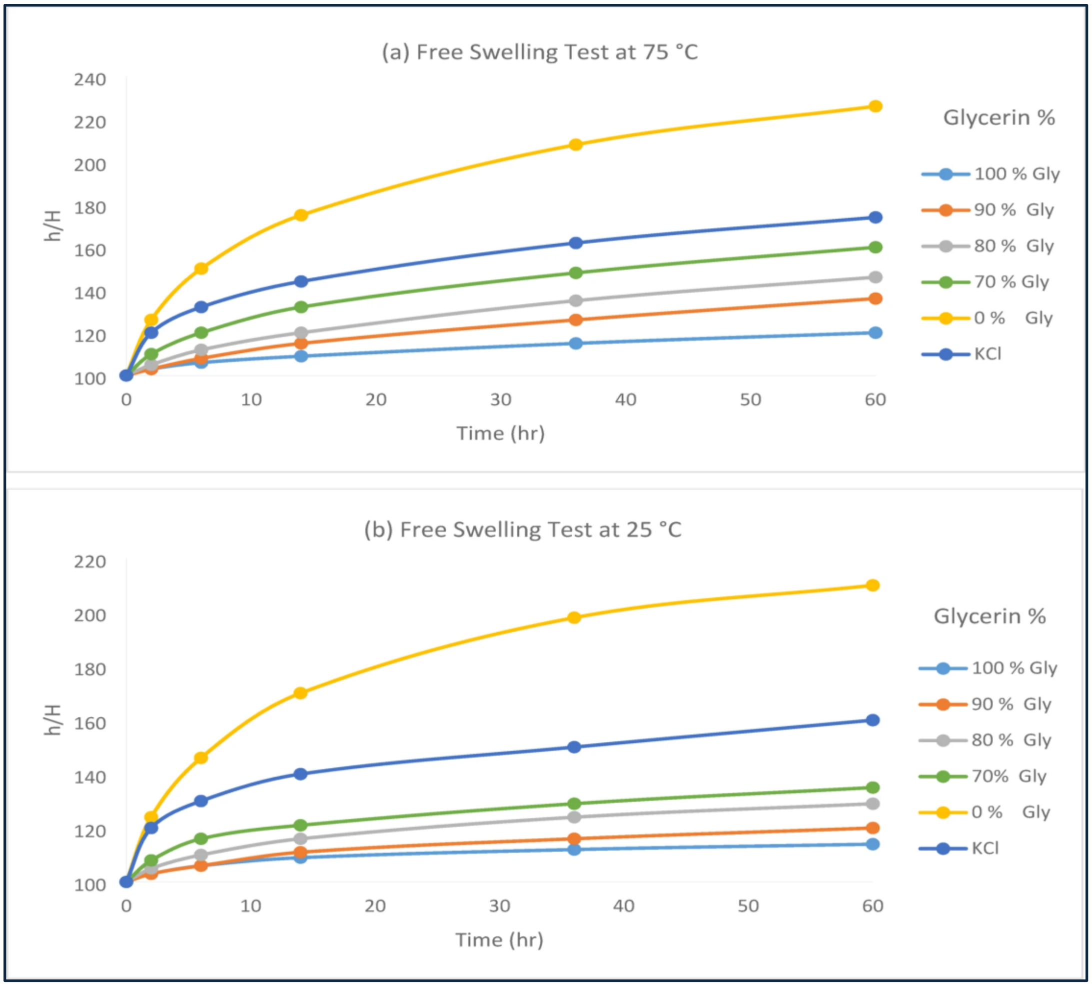

Fig 8: Results of free swelling test at (a) 75 °C and (b) 25 °C.

The results were clear that the glycerin-based fluids showed a strong ability to manage clay swelling. The fluids with 80%, 90%, and 100% glycerin concentrations consistently outperformed the KCl-based fluid in all tests. Although the 70% glycerin fluid was also effective, its results in the sedimentation and cutting recovery tests were more similar to those of the KCl fluid. A key insight was the fluid's strong performance at high temperatures.

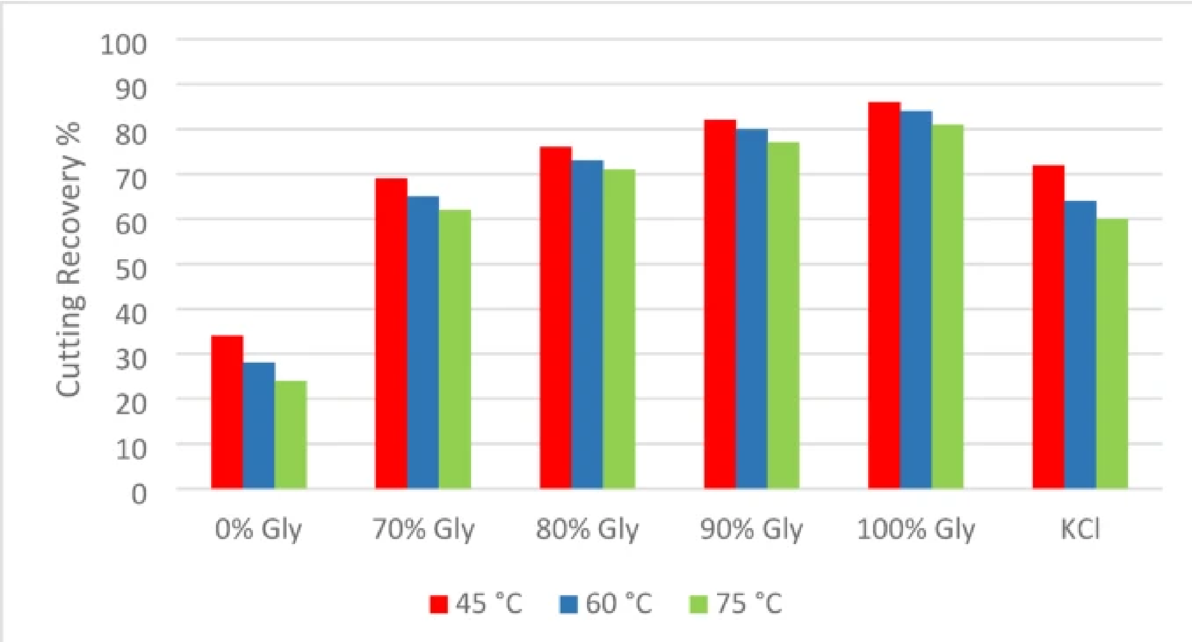

Fig 9: Results of cutting dispersion test in different temperatures.

The cuttings dispersion test indicated that glycerin-based fluids maintain their effectiveness more reliably as temperatures rise when compared to the KCl-based fluid, underscoring their potential as a dependable and thermally stable option for actual drilling operations.

A recent study by Dai et al. (2024) demonstrated an effective methodology combining molecular dynamics simulation and experimental validation to optimize a novel ester-based lubricant. This work provides a strong example of how computational methods can accelerate the development of drilling fluid additives. The study employed a rigorous, two-pronged methodology, leveraging both computational modeling and physical testing:

The core of the methodology involved a two-stage process blending computational and empirical methods. The first stage used Molecular Dynamics Simulation to virtually test three base oils (methyl, ethyl, and butyl oleate) under extreme conditions (100 MPa pressure) to identify the optimal base oil (methyl oleate) and then to select the best additive (oleamide). The second stage consisted of experimental validation, where the researchers used Four-Ball Friction Tests to confirm the base oil's low coefficient of friction ($\mu = 0.0018$) and performed comprehensive laboratory tests on the final LUB-2 formulation to ensure it maintained the drilling fluid’s required rheological stability and structure after aging. Finally, a field application was conducted at an operating well to gather real-world performance data.

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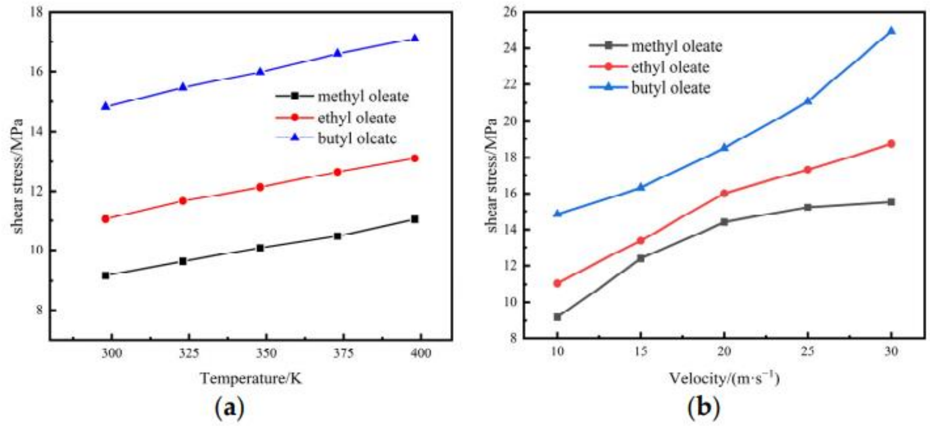

Fig: Average shear stress of base oils under different conditions: (a) different initial temperatures; (b) different shear speeds

The results of the field test were highly positive and demonstrated the lubricant's superior efficiency. The 1% addition of LUB-2 to the drilling fluid led to an average 33% reduction in drag and an increase in the drilling rate to 22.12 m/h. The most compelling result regarding cost-effectiveness was that the 1% dosage of LUB-2 achieved the same performance level as a significantly higher 3% dosage of conventional ester lubricants, highlighting a substantial improvement in the efficiency and potential cost reduction of drilling operations.

6. RESULTS AND DISCUSSION

Additive Group	Specific Additives Mentioned	Primary Function	Key Performance/Result	Source Study
Methyl, Ethyl & Butyl Esters (from vegetable oils)	Methyl, Ethyl, and Butyl oleate (Base Oils for LUB-2)	Lubricity & Friction Reduction	Methyl oleate identified as optimal base oil. The final LUB-2 formulation achieved an average 33% reduction in drag and increased the drilling rate.	Dai et al. (2024)

Cellulosic Agro-Waste	Rice Husk Powder (RHP)	Fluid-Loss Control	Reduced filtrate volume by approximately 77% compared to the base mud at 6 wt% (Agwu et al.). Also showed a 52% reduction in fluid loss under HPHT (Shafiq et al.).	Agwu et al. (2019), Shafiq et al. (2024)
Cellulosic Agro-Waste	Saw Dust	Fluid-Loss Control / Bridging	Achieved about 63% reduction in filtrate volume at 8 wt%, acting as a supporting bridging material.	Agwu et al. (2019)
Fruit-Waste Powder	Mandarin Peels Powder (MPP)	Dual-Function: Viscosifier & Filtration Control	Significantly improved both rheological (PV, YP, gel strength) and filtration properties, reducing API filtrate volume by 35-40% (at 6 wt%).	Al-Hameedi et al. (2019)
Agricultural Ashes & Husks	Rice Husk (RH)	Fluid-Loss Control & Rheology	Most effective additive among the ashes/husks tested, leading to a notable 52% reduction in fluid loss and a 29% increase in viscosity at 0.8 wt%.	Shafiq et al. (2024)

Agricultural Ashes & Husks	Palm Oil Fuel Ash (POFA), Wood Ash (WA)	Fluid-Loss Control	Showed useful, but lesser, fluid loss reductions (35% for POFA, 30% for WA) compared to Rice Husk.	Shafiq et al. (2024)
Glycerin (70-100%)	Glycerin (Glycerol)	Shale Inhibition	Outperformed KCl-based fluid in all tests, effectively managing clay swelling and dispersion, especially at high temperatures (≤75°C).	Momeni et al. (2025)

7. LIMITATIONS OF AGRO-DERIVED ADDITIVES

While agro-derived additives have a promising future, they currently have limitations in performance and application. Their main drawback is instability under high temperatures (above 150-200 °F) and high-salinity conditions, which restricts their use to moderate drilling environments. There are also practical challenges related to maintaining consistent product quality, storage, and shelf life. Furthermore, more data is needed to compare them with other conventional mud additives.

8. CONCLUSION

Based on the studies provided, agro-derived and eco-friendly additives are effective, cost-efficient, and sustainable alternatives to traditional synthetic options in drilling fluids. Materials like Mandarin Peels Powder (MPP) and rice husk (RH) have been shown to improve important properties such as rheology, viscosity, and gel strength, all essential for suspending cuttings and cleaning holes. For controlling filtration, rice husk, sawdust, and MPP all effectively reduce fluid loss. These materials also offer specific benefits. Eco-friendly glycerin has proven effective at preventing clay swelling, consistently working better than conventional KCl-based fluids. Modified vegetable oils, particularly an ester lubricant (LUB-2) made from methyl oleate and oleamide, significantly reduce friction, cutting drag by 33% in field tests. Rice husk is noteworthy for creating a smooth filter cake, which helps minimize torque, unlike the rougher cake formed by sawdust. From a cost perspective, materials like rice husk, sawdust, and Palm Oil Fuel Ash (POFA) are low-cost and widely available. This economic advantage is supported by their positive environmental impact; as biodegradable, non-toxic, and eco-friendly materials, they lower the ecological footprint of drilling operations, reduce dependence on traditional toxic chemicals, and support the industry's sustainability goals.

9. FUTURE RESEARCH SCOPE

Based on the research provided, the future focus for agro-based and eco-friendly additives in drilling fluids will be on testing their performance in tougher field conditions and increasing their use. A key next step identified in several studies is to examine these additives, including Mandarin Peels Powder (MPP) and glycerin, under aging conditions, as well as at high temperatures and pressures (HPHT), to ensure they are suitable for field use. Further research is needed to gain a deeper understanding of the basic interactions and main inhibition mechanisms of additives like glycerin. For ester lubricants, future work will look at increasing their application opportunities and improving optimization by better connecting computer simulations with actual drilling fluid test conditions. This ongoing development is backed by findings that agricultural wastes like Palm Oil Fuel Ash (POFA) and rice husk have great potential as sustainable, low-cost alternatives that could be fine-tuned for specific uses, such as managing formation pressures at greater depths.

10. REFERENCES

[1] S. A. U. Rahman, M. A. Rahman, and M. A. M. Salleh, "Rice Husk Ash as a Potential Additive in Water-Based Drilling Fluids: Experimental Investigation," Journal of Petroleum Exploration and Production Technology, vol. 13, no. 7, pp. 1765–1778, 2023.
[2] A. A. Olatunde, F. S. Ademiloye, and M. I. Adewale, "Application of Agro-Waste Materials as Drilling Fluid Additives: A Review of Sustainability and Performance," Energy Reports, vol. 9, pp. 4241–4260, 2023.
[3] A. M. Okon, A. A. Okoro, and O. S. Nwoke, "Experimental Study on the Use of Food Waste-Derived Additives in Enhancing the Rheological Properties of Water-Based Drilling Fluids," Journal of Petroleum Science and Engineering, vol. 228, p. 111716, 2024.
[4] S. Singh, R. K. Sharma, and P. Kumar, "Development and Evaluation of Acacia senegal-Derived Biopolymer as a Fluid-Loss Control Agent in Water-Based Muds," Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol. 661, p. 130978, 2023.

[5] J. A. Al-Obaidi and M. A. Hossain, "Vegetable-Oil-Based Lubricants for Environmentally Friendly Drilling Fluids," Journal of Cleaner Production, vol. 410, p. 137004, 2024.

[6] T. E. Ogbemudia, E. A. Osei, and K. O. Omorodion, "Comparative Analysis of Green Viscosifiers and Commercial PAC-R in Water-Based Drilling Mud Systems," Sustainable Materials and Technologies, vol. 38, p. e00742, 2024.

[7] R. Gupta, N. K. Reddy, and P. Bhattacharya, "Waste-Generated Nanomaterials as Sustainable Additives for Drilling Fluids: A Comprehensive Review," Environmental Nanotechnology, Monitoring & Management, vol. 21, p. 101759, 2024.

[8] M. S. Al-Yaseri, H. Al-Zubaidi, and N. M. Hussain, "Thermal Stability and Rheological Behavior of Biopolymer-Modified Water-Based Drilling Fluids," Journal of Natural Gas Science and Engineering, vol. 112, p. 104841, 2023.

[9] P. S. Ibrahim and M. K. Adebayo, "Exploring the Use of Plant Extracts and Natural Fibers as Biodegradable Drilling Additives," Energy & Fuels, vol. 38, no. 2, pp. 912–928, 2024.

[10] Y. D. Li, Y. Liu, and Z. L. Zhang, "Eco-Friendly Drilling Fluids: Progress, Challenges, and Future Perspectives," Fuel, vol. 357, p. 130545, 2024.

[11] K. A. Isehunwa, L. M. Nwankwo, and A. A. Daramola, "Particle Size Distribution and Filter-Cake Permeability Effects of Agro-Waste Additives in Drilling Mud Systems," Journal of Petroleum Science and Engineering, vol. 236, p. 112050, 2024.

[12] N. B. Ali and M. A. Hossain, "Development of Hybrid Natural–Synthetic Drilling Fluid Systems for Sustainable Operations," Journal of Petroleum and Environmental Biotechnology, vol. 15, no. 1, pp. 14–27, 2024.

[1] Ramasamy, A., Kumar, D., & Raj, P. (2024). Evaluation of eco-friendly starch-based additives for rheological enhancement of water-based drilling fluids. Journal of Petroleum Science and Engineering, 236, 112345. https://doi.org/10.1016/j.petrol.2024.112345

[2] Akpan, I., Udoh, F., & Etim, P. (2023). Optimization of natural polymers for improving drilling fluid performance: A sustainable approach. Energy Reports, 9, 1540–1553. https://doi.org/10.1016/j.egyr.2023.01.045

[3] Jadhav, S., Patel, M., & Bhattacharya, K. (2022). Utilization of agro-industrial byproducts in water-based drilling fluids: A review. Sustainable Materials for Energy Systems, 3(2), 67–79.

[4] Al-Hameedi, A., Alkinani, H., & Dunn-Norman, S. (2023). Rheological and filtration characteristics of eco-friendly drilling muds formulated with natural biopolymers. Journal of Energy Resources Technology, 145(2), 022104. https://doi.org/10.1115/1.4059658

[5] Mahmoud, M., Al-Jaberi, A., & Abdulraheem, A. (2024). Effect of starch-based materials on water-based drilling fluids under HPHT conditions. Petroleum Exploration and Development, 51(3), 812–823.

[6] Bello, O., Akinola, A., & Adeoye, A. (2023). Enhancement of bentonite drilling fluids using modified natural gums. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 669, 131402. https://doi.org/10.1016/j.colsurfa.2023.131402

[7] Jha, N., Sharma, R., & Patel, K. (2024). Guar and xanthan gum as rheology modifiers in water-based muds: An experimental study. Environmental Engineering Science, 41(4), 340–355.

[8] Adekunle, M., Olatunji, O., & Adebayo, K. (2022). Rice husk ash as a fluid loss control agent in water-based drilling fluids. Egyptian Journal of Petroleum, 31(4), 455–467. https://doi.org/10.1016/j.ejpe.2022.03.015

[9] Patel, V., & Rana, S. (2023). Performance evaluation of plant-derived gums in enhancing the viscosity of drilling fluids. Applied Clay Science, 230, 107698.

[10] Ali, A., Ibrahim, S., & Hussain, R. (2023). Investigation of natural polymers as environmentally safe additives for drilling fluids. Journal of Natural Gas Science and Engineering, 118, 105501.

[11] Adesina, F., Ogunleye, A., & Oseh, J. (2024). Comparative analysis of biopolymer-based fluid loss additives in water-based muds. Energy & Fuels, 38(2), 874–889.

[12] Bhattacharya, K., Jadhav, S., & Mehta, P. (2023). Development of hybrid eco-friendly additives for fluid loss control in drilling operations. Materials Today: Proceedings, 68(6), 2054–2062.

[13] Abiola, T., Falade, O., & Lawal, R. (2024). Sustainable drilling fluid additives derived from agro-wastes: A pathway to green drilling operations. Cleaner Engineering and Technology, 18, 100756.

[14] Sadiq, H., Ahmed, M., & Khan, R. (2024). Characterization and performance analysis of cellulose and starch derivatives in drilling muds. Petroleum Research, 9(2), 215–230.

[15] Ezeh, C., Onuoha, I., & Ogbuagu, O. (2023). Tribological performance of agricultural waste-based lubricants in drilling fluid formulations. Journal of Petroleum Exploration and Production Technology, 13, 1903–1918.

[16] Nwosu, P., Ogunsanwo, O., & Iloh, M. (2024). Performance of banana peel powder as an alternative lubricant in water-based drilling muds. Energy Advances, 3(1), 54–68.

[17] Al-Yasiri, M., Al-Samarrai, H., & Al-Bazzaz, W. (2022). Compatibility and dispersion behavior of natural biopolymers in water-based mud systems. Journal of Petroleum Science and Engineering, 208, 109709.

[18] Oseh, J., Adebayo, O., & Lawal, M. (2023). Evaluating salt tolerance of biopolymer-modified drilling fluids under varying salinity. Energy Reports, 9, 2132–2146.
[19] Kannan, R., Selvakumar, S., & Arumugam, P. (2024). High-temperature stability of guar-starch composites for drilling mud applications. Sustainable Energy Technologies and Assessments, 60, 104378.
[20] Malik, R., Singh, A., & Yadav, D. (2023). Influence of ionic contaminants on biopolymer-based drilling fluids. SN Applied Sciences, 5(2), 224.
[21] Latha, P., Varma, G., & Thomas, J. (2024). Statistical modeling of rheological properties of modified starch drilling fluids. Colloid and Polymer Science, 302, 1751–1764.
[22] Abiola, A., Akinwale, O., & Musa, I. (2024). Biodegradability assessment of natural polymer-based drilling additives. Cleaner Engineering and Technology, 19, 101213.
[23] Taufiq, M., Rahman, N., & Idris, Z. (2023). Economic analysis of agro-derived drilling fluid additives in sustainable operations. Sustainable Materials for Energy Systems, 2(3), 95–108.
[24] Olatunji, O., Adebayo, F., & Adeyemi, L. (2024). Cost-benefit and performance assessment of agricultural waste-based drilling additives. Journal of Environmental Chemical Engineering, 12(5), 111033.