Performance Evaluation of Mucuna Solannie as a Sustainable Additive in Water-Based Drilling Mud Formulation: A Review

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Abstract*—Mucuna solannie is a bio-derived material that has gained increasing attention as a potential additive in water-based drilling mud formulations due to its unique rheological, filtration control, and environmental-friendly properties. This study presents a comprehensive review and technical evaluation of Mucuna solannie's suitability as an alternative drilling mud additive, emphasizing its impact on key mud performance parameters, including viscosity, yield point, gel strength, fluid loss control, and shale stability. Through an extensive literature review and comparative analysis, the physicochemical composition and structural properties of Mucuna solannie were examined to establish its interaction with drilling fluids and its potential advantages over conventional additives such as bentonite and PAC (polyanionic cellulose). The study critically assesses its compatibility with existing mud systems, biodegradability, and effectiveness under various temperature and pressure conditions encountered in drilling operations. The review further explores the implications of its use HPHT drilling conditions, where drilling fluid stability is paramount for wellbore integrity and operational efficiency. Furthermore, challenges associated with incorporating bio-based materials into drilling muds, including dispersion, hydration behavior, and long-term stability, are discussed. The integration of Mucuna solannie into water-based muds aligns with the industry's increasing shift toward sustainable and environmentally friendly drilling technologies, offering a potential reduction in the reliance on synthetic polymers and chemically modified additives. The findings from this review provide a foundation for further experimental validation and optimization studies, aiming to enhance drilling fluid performance while ensuring environmental compliance and cost-effectiveness in drilling operations.*

Keywords—component; drilling fluid additives; mucuna solannie; rheological properties; water-base mud

1. INTRODUCTION

The formulation of effective and environmentally sustainable drilling fluids remains a critical focus in the oil and gas industry, particularly for water-based muds (WBMs), which are widely used due to their lower environmental footprint compared to oil-based muds (OBMs) [12]. Conventional WBMs rely on a range of synthetic additives to enhance rheology, filtration control, and wellbore stability. However, the increasing regulatory restrictions on synthetic polymers and commercial additives, alongside the need for cost-effective and biodegradable alternatives, have driven research into the utilization of naturally occurring materials. In this regard, Mucuna Solannie, a leguminous plant with inherent bio-polymeric properties, presents a promising candidate for incorporation into WBM formulations. Its natural polysaccharide content, high molecular weight, and water-soluble components provide significant potential for rheological enhancement, filtration control, and improved lubricity in drilling operations [9].

Mucuna Solannie, when utilized as a drilling fluid additive, exhibits functionalities that are crucial in optimizing WBM performance. Its bio-polymeric structure facilitates viscosity modification by acting as a viscosifier, thereby improving the carrying capacity of cuttings and ensuring effective hole cleaning. Additionally, the mucilage extracted from Mucuna Solannie exhibits pseudoplastic behavior, contributing to shear-thinning properties that enhance mud pumpability and reduce equivalent circulating density (ECD). The hydrophilic nature of its molecular composition also plays a critical role in fluid loss control, effectively reducing filtrate invasion into permeable formations, thus minimizing formation damage and differential sticking tendencies. Moreover, its lubricating properties contribute to reducing torque and drag, mitigating differential sticking issues, and enhancing drill string mobility in deviated and extended reach wells [6], [29], [10].

While the application of Mucuna Solannie presents several advantages, its effectiveness must be evaluated against commercial synthetic alternatives, such as polyanionic cellulose (PAC), xanthan gum, and partially hydrolyzed polyacrylamide (PHPA). The key merits of Mucuna Solannie lie in its biodegradability, non-toxicity, and sustainability, making it an environmentally viable alternative that aligns with stringent drilling fluid regulations. Unlike synthetic polymers, which may contribute to long-term environmental persistence and potential toxicity concerns, Mucuna Solannie decomposes naturally without leaving harmful residues in drilling waste discharges. Additionally, its local availability in various tropical regions provides economic advantages by reducing import dependency and lowering the cost of drilling fluid additives [28].

However, the utilization of Mucuna Solannie as a drilling fluid additive is not without challenges. Compared to synthetic alternatives, its molecular stability under high-temperature and high-pressure (HTHP) conditions may be a limiting factor, as thermal

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degradation of its bio-polymeric structure could affect its long-term rheological performance in deep-well drilling [2]. Furthermore, batch-to-batch variability in the composition of naturally derived additives could lead to inconsistencies in drilling fluid properties, necessitating rigorous quality control and standardization protocols. The hydration kinetics and dispersibility of Mucuna Solannie in water-based mud systems also require optimization to prevent aggregation and ensure uniform rheological behavior. Additionally, the microbial susceptibility of natural polymers may necessitate the inclusion of biocides to enhance shelf-life and operational stability [4].

The incorporation of Mucuna Solannie into water-based drilling fluids represents a significant step towards sustainable and environmentally conscious drilling practices. Its rheological benefits, fluid loss control capabilities, and lubricity enhancements position it as a viable alternative to conventional synthetic additives. However, addressing its limitations through molecular modification, composite formulation approaches, and process optimization will be essential to achieving performance parity with commercial synthetic counterparts (Lalji et al., 2024). This study aims to comprehensively evaluate the physicochemical behavior, rheological performance, and field applicability of Mucuna Solannie in WBM formulations, providing a robust foundation for its industrial adoption and potential commercialization in drilling fluid engineering [8].

2. The Need of Bio-materials in Drilling Fluid Formulation

Drilling fluids with non-decomposable chemical ingredients poses substantial environmental and health risks, necessitating the development of alternative, eco-friendly additives to minimize harmful waste release [11]. The environmental hazards of traditional additives, such as potassium chloride and polyamine, necessitate the development of biodegradable, eco-friendly drilling fluid solutions [10. Bioproducts and various waste materials are particularly promising in this regard. They offer comparable performance to conventional additives while being widely available and cost-effective. Utilizing these alternatives can lead to significant savings in terms of cost, energy, and time [13], [12]. Environmentally friendly alternatives, including carboxymethyl cellulose, polyanionic cellulose, xanthan gum, and partially hydrolyzed polyacrylamide, enhance drilling fluid properties while minimizing ecological harm [40].

2.1 Drilling Fluids Overview

Drilling fluids, also known as drilling muds, are critical components in oil and gas well construction, serving as multifunctional fluids designed to facilitate the drilling process while ensuring wellbore stability, formation protection, and operational efficiency. The selection and formulation of an optimal drilling fluid system depend on a range of factors, including geological conditions, wellbore complexity, temperature and pressure regimes, and environmental regulations. Broadly categorized into water-based muds (WBMs), oil-based muds (OBMs), and synthetic-based muds (SBMs), each fluid type exhibits unique properties that make them suitable for specific drilling environments and operational challenges [20].

Water-based muds are the most widely used class of drilling fluids due to their environmental acceptability, cost-effectiveness, and ease of disposal. These muds are formulated using water as the continuous phase, with various additives such as bentonite, polymers, and salts incorporated to modify rheological properties, control fluid loss, and enhance wellbore stability. While WBMs are effective in drilling conventional formations, their limitations become apparent in high-temperature, high-pressure (HTHP) environments, where thermal degradation of water-soluble polymers and excessive filtrate invasion can compromise well integrity and drilling efficiency. Oil-based muds, on the other hand, consist of a hydrocarbon phase such as diesel or mineral oil, with water serving as the dispersed phase [11]. These muds exhibit superior thermal stability, shale inhibition, and lubricity, making them particularly suitable for challenging drilling conditions such as deepwater, extended-reach, and HPHT wells. However, OBMs pose environmental concerns due to their potential for contamination and the complexity of cuttings disposal. To address these environmental issues while retaining the benefits of OBMs, synthetic-based muds have been developed, utilizing synthetic oil derivatives as the base fluid. SBMs provide excellent thermal and rheological stability while being more environmentally friendly than conventional OBMs, though they remain costlier and require stringent handling measures [1], [15].

The functionality of drilling fluids extends beyond simple lubrication and cooling of the drill bit. They play a fundamental role in wellbore stability by exerting hydrostatic pressure to prevent formation collapse and inhibiting the hydration and swelling of reactive shale formations. Additionally, drilling fluids facilitate efficient cuttings transport and removal, preventing borehole obstructions and optimizing rate of penetration (ROP) [3]. Effective filtration control is another critical function, as excessive filtrate invasion can cause formation damage, differential sticking, and loss of well productivity. Furthermore, drilling fluids provide corrosion protection for downhole tools, prevent gas influx and blowouts through well control mechanisms, and contribute to the overall success of drilling operations by ensuring smooth casing and cementing processes [19].

For high-pressure, high-temperature applications, drilling fluids must be engineered to withstand extreme downhole conditions that often exceed 15000 psi and temperatures beyond 350°F. Conventional water-based and polymer-based fluids often experience thermal degradation, viscosity breakdown, and excessive water loss at such extreme conditions, leading to well control complications and differential sticking [19]. OBMs and SBMs are generally preferred for HPHT environments due to their high thermal stability, low fluid loss, and minimal reactivity with subsurface formations. Advanced HPHT drilling fluids incorporate high-performance viscosifiers, thermally stable filtration control agents, and specially designed weighting materials such as manganese tetraoxide to achieve optimal density without excessive viscosity buildup. Additionally, the formulation of HPHT fluids must account for barite sag, which can lead to non-uniform density distribution and compromised well control. Through rigorous laboratory testing and fluid characterization, HPHT drilling fluids are continually optimized to enhance thermal resilience, maintain rheological stability, and ensure operational safety in deep and ultra-deep drilling projects [18].

Beyond HPHT wells, complex and problematic drilling environments necessitate specialized fluid formulations to mitigate unique operational challenges. In highly deviated and extended-reach wells, drilling fluids must possess enhanced lubricity to reduce torque and drag while ensuring sufficient hole-cleaning capacity to prevent cuttings accumulation [7], [25]. Low-friction OBMs and SBMs are typically preferred for these applications, while WBMs require additional lubricants and drag-reducing additives to achieve comparable performance. In depleted reservoirs and narrow pressure window formations, managed pressure drilling (MPD) fluids with precise density control are essential to prevent differential sticking, lost circulation, and wellbore instability [5]. In fractured and unconsolidated formations, wellbore strengthening fluids containing specially engineered bridging agents and nanoparticles are deployed to minimize fluid losses and enhance formation integrity. Furthermore, in reservoirs with high sour gas content, drilling fluids must be chemically treated to resist hydrogen sulfide (H2S) contamination, prevent corrosion, and maintain fluid stability under acidic conditions [17], [26].

The evolution of drilling fluid technology continues to be driven by the increasing complexity of oil and gas exploration, necessitating continuous research into novel formulations, high-performance additives, and environmentally sustainable alternatives. While synthetic and oil-based fluids provide superior performance in extreme conditions, their environmental footprint and regulatory constraints necessitate ongoing advancements in water-based mud technologies to enhance thermal stability, inhibit shale reactivity, and reduce fluid loss without compromising environmental compliance [16], [22]. The integration of nanotechnology, biodegradable polymers, and smart fluid systems holds promise in revolutionizing drilling fluid design by offering real-time adaptability to downhole conditions, improving wellbore stability, and enhancing drilling efficiency. As the industry moves towards deeper, more complex, and environmentally sensitive drilling operations, the development of advanced drilling fluids that balance performance, cost, and sustainability will remain paramount in ensuring successful and economically viable hydrocarbon extraction [25].

3. MUCUNA SOLANNIE

Mucuna solannie is a lesser-known species within the *Mucuna* genus, which belongs to the Fabaceae family. Species of *Mucuna* are widely recognized for their agronomic, pharmaceutical, and industrial significance, primarily due to their rich phytochemical constituents. Historically, *Mucuna* species have been documented in ethnobotanical literature as traditional medicinal and fodder plants, with *Mucuna solannie* being recognized in select indigenous pharmacopeias for its medicinal and soil-enriching properties [27]. The plant is primarily found in tropical and subtropical regions, thriving in humid environments with well-drained, loamy, or sandy soils. It has been reported in parts of West Africa, Southeast Asia, and South America, typically found in secondary forests, along riverbanks, and in agricultural settings where it is used as a cover crop for soil fertility enhancement [8].

Figure 1: Mucuna solannie leaves and seeds

Mucuna solannie exhibits robust climbing or trailing growth habits, with trifoliate leaves that are broad and ovate. The plant's vines can extend several meters, supported by tendrils that facilitate climbing. The inflorescence consists of racemose clusters of purplish to dark violet flowers, characteristic of leguminous plants, while the pods are elongated, slightly curved, and contain multiple seeds enveloped in a hard seed coat. Chemically, *Mucuna solannie* is rich in secondary metabolites, including alkaloids, flavonoids, saponins, and tannins. It contains significant concentrations of L-3,4-dihydroxyphenylalanine (L-DOPA), a precursor to dopamine, which is widely utilized in the treatment of Parkinson's disease [4]. The presence of polyphenolic compounds and flavonoids imparts antioxidative and neuroprotective properties, making the plant a subject of pharmaceutical interest. Additionally, the seeds contain high protein content, including essential amino acids such as lysine and methionine, making them valuable in animal nutrition and food supplementation [29], [9].

Indigenous communities have traditionally used *Mucuna solannie* for its therapeutic properties, including treatment of Parkinson's disease and other neurodegenerative disorders, enhancement of libido and reproductive health, and alleviation of rheumatism, arthritis, and inflammatory conditions [27]. Beyond medicinal applications, *Mucuna solannie* functions as a cover crop and green manure due to its nitrogen-fixing capabilities, being employed in agroforestry systems to improve soil fertility and prevent erosion. The high L-DOPA content has also garnered interest in pharmaceutical research for potential applications in neuropharmacology, with standardized extracts being investigated as alternative sources of levodopa [10]. Furthermore, *Mucuna solannie* seeds can be processed into flour and protein-rich food supplements, with detoxification treatments employed to reduce anti-nutritional factors such as tannins and phytic acid. The plant's protein-rich seeds and biomass make it a viable feed component in livestock nutrition, particularly for ruminants and poultry [4].

Mucuna solannie thrives under tropical climatic conditions with moderate rainfall and well-drained soils. It is cultivated using direct seeding methods, with minimal input requirements. However, its cultivation faces challenges such as seed dormancy due to the hard seed coat, necessitating scarification for improved germination. Additionally, toxicity concerns arise from the presence of anti-nutritional factors, requiring proper processing before consumption [4]. Despite its agronomic benefits, large-scale commercialization remains limited due to a lack of widespread cultivation programs and market awareness. The potential applications of *Mucuna solannie* in pharmaceuticals, sustainable agriculture, and nutrition underscore the need for further research. Areas of interest include genetic improvement to enhance L-DOPA content and reduce toxicity, biotechnological advances such as micropropagation and genetic engineering to optimize yield and bioactive compound synthesis, and clinical studies investigating its pharmacological efficacy and safety in human health applications [10].

Mucuna solannie represents a promising yet underutilized leguminous species with multifaceted applications in medicine, agriculture, and industry. Further scientific exploration is warranted to unlock its full potential and optimize its utilization in sustainable development frameworks. Table 1 shows the characterisation of mucuna solannie.

Table 1: characterisation of mucuna solannie

Characterization Type	Method Used	Findings	Reference
Chemical Composition Analysis	- X-ray Fluorescence (XRF)	- Mucuna solannie contains 39.18% potassium, 4.82% silicon dioxide (SiO_2), and 1.83% aluminum oxide (Al_2O_3)	Igwilo et al., 2021a.
	- Scanning Electron Microscope with Energy Dispersive Spectroscopy (SEM-EDS)	- The potassium content may help in shale stabilization.	Igwilo et al., 2021a.
		- The low aluminum oxide content indicates minimal viscosity contribution.	Igwilo et al., 2021a.
Structural and Morphological Properties	- Scanning Electron Microscopy (SEM)	- SEM showed an irregular, porous structure, contributing to filtration control.	Igwilo et al., 2021a.
	- Fourier Transform Infrared Spectroscopy (FTIR)	- FTIR analysis confirmed hydroxyl (-OH), carbonyl (C=O), and amide (-NH) functional groups, making it hydrophilic and capable of improving viscosity and gel strength.	Igwilo et al., 2021a.
Rheological and Filtration Properties	- API standard tests for viscosity, yield point, and gel strength	- Increased plastic viscosity and yield point, improving cuttings transport	Duru et al., 2020

	- HPHT filtration tests	- Reduced filtration loss at optimal concentrations (6–8 ppb), performing similarly to sodium asphalt sulfonate (SAS)	Igwilo et al., 2020
		- Performed well in cold temperatures (5°C).	Igwilo et al., 2020
Thermal Stability and Temperature Effects	- Aging tests at different temperatures	- Maintained stability within API standards at high temperatures	Uwaezuoke et al., 2017
	- Viscosity and fluid loss tests at elevated temperatures	- Worked well in combination with XCD polymer and Brachystegia eurycoma, improving thermal resistance and preventing degradation.	Uwaezuoke et al., 2017

The phytochemical analysis of *Mucuna solannie*, as conducted by Trease and Evans (1989) and subsequently reported by Igwilo et al. [9], revealed the presence of several bioactive compounds with varying percentage compositions as shown in Figure 2. Among these constituents, tannins exhibited the highest concentration, accounting for 32.94% of the total phytochemical content. Tannins are polyphenolic compounds known for their astringency and ability to precipitate proteins, thereby playing a crucial role in plant defense mechanisms against herbivores and microbial invasion. Their high concentration in *Mucuna solannie* suggests potential applications in drilling mud formulation, particularly in enhancing the rheological and filtration properties of water-based drilling fluids by reducing fluid loss and improving mud stability. Additionally, their natural inhibitory effects on microbial growth may contribute to the biostability of drilling mud in prolonged operations. Following tannins in concentration, saponins were identified at 25.59%. These amphiphilic glycosides possess surface-active properties, making them highly relevant in drilling mud applications where emulsification and foaming characteristics are required. The presence of saponins in *Mucuna solannie* indicates their potential to act as natural surfactants, enhancing the dispersion of solid particles and improving the lubricity of the drilling fluid. Their well-documented bioactivity, including antimicrobial and antifungal properties,

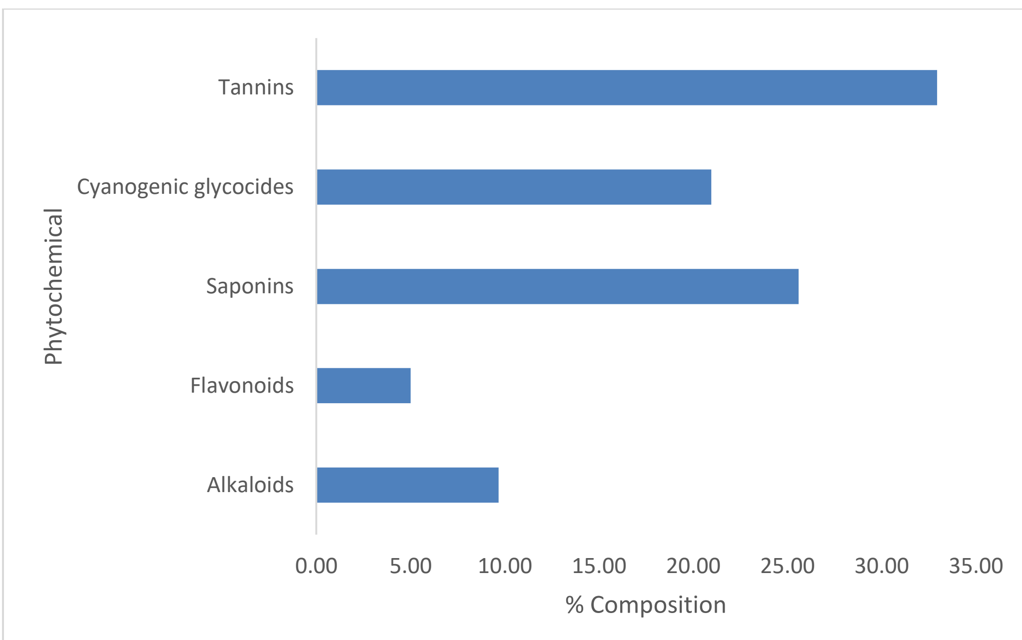

Figure 2: Phytochemical composition of Mucuna solannie [9]

Figure 3 shows the proximate analyses of mucuna solannie leaves. The proximate analysis of *Mucuna solannie* leaves provides a comprehensive evaluation of their fundamental nutritional and compositional attributes, which are essential for determining their suitability for various industrial and scientific applications, including their potential role as an additive in water-based drilling mud formulation. Proximate analysis is a standard analytical procedure used to quantify the major macronutrient components of a biological material, including crude protein, crude fiber, moisture content, crude fat, and ash. This analysis is particularly significant for *Mucuna solannie*, as it aids in understanding its chemical composition, functional properties, and potential interactions with other components in drilling mud systems.

The results of the proximate analysis indicate that *Mucuna solannie* leaves contain a substantial amount of crude protein, with an average composition of 33.21%. This high protein content underscores its potential as a bio-enhancer in drilling mud formulations, where proteins contribute to the structural integrity and viscosity of the mud. Proteins, being complex macromolecules composed of amino acids, can influence the hydration properties of the mud and may interact with other additives to modify its rheological characteristics. Additionally, the presence of protein-rich compounds may introduce biodegradability aspects, which could be considered when evaluating the longevity and performance of *Mucuna solannie*-based mud additives under field conditions.

Crude fiber, which constitutes 15% of the leaves' composition, is another critical parameter in proximate analysis. As an insoluble carbohydrate primarily composed of cellulose, hemicellulose, and lignin, crude fiber influences the structural framework of plant materials. Its presence in *Mucuna solannie* suggests potential benefits in drilling fluid stability, as fiber-rich components can enhance the suspension properties of mud by increasing its carrying capacity and reducing settling tendencies of solid particulates. Moreover, crude fiber plays a role in fluid loss control, acting as a bridging agent that helps prevent excessive filtration of water into formation pores, which is a crucial consideration in wellbore stability.

Moisture content, measured at 11.69%, is a determinant of the shelf life and storage stability of *Mucuna solannie*-derived additives. Elevated moisture levels can contribute to microbial degradation and reduce the efficacy of the material when stored for extended periods. The moisture content also affects the dispersibility and solubility of *Mucuna solannie* in drilling fluids, impacting its interaction with other mud components. Optimizing moisture levels is therefore essential to ensure consistency in performance and prevent degradation during handling and transportation.

Crude fat, which is present at 2.97%, consists of lipophilic compounds, including triglycerides, phospholipids, and sterols. Although present in relatively low concentrations, crude fat can influence the hydrophobic interactions in drilling mud systems. Fatty substances have the potential to modify the lubricating properties of the mud, reducing torque and drag during drilling operations, particularly in extended-reach and deviated wells. The presence of crude fat also suggests potential surfactant-like behavior, which may affect the emulsification properties of water-based muds, thereby influencing their overall performance.

Ash content, measured at a minimal 0.16%, represents the total inorganic mineral residue remaining after complete combustion of the organic material. The low ash content of *Mucuna solannie* indicates a limited presence of non-volatile minerals, which may reduce the risk of unwanted solid deposition in drilling operations. However, further elemental analysis would be necessary to determine the specific mineral composition within the ash, as trace minerals could contribute to the overall functionality of *Mucuna solannie* in drilling fluid formulations.

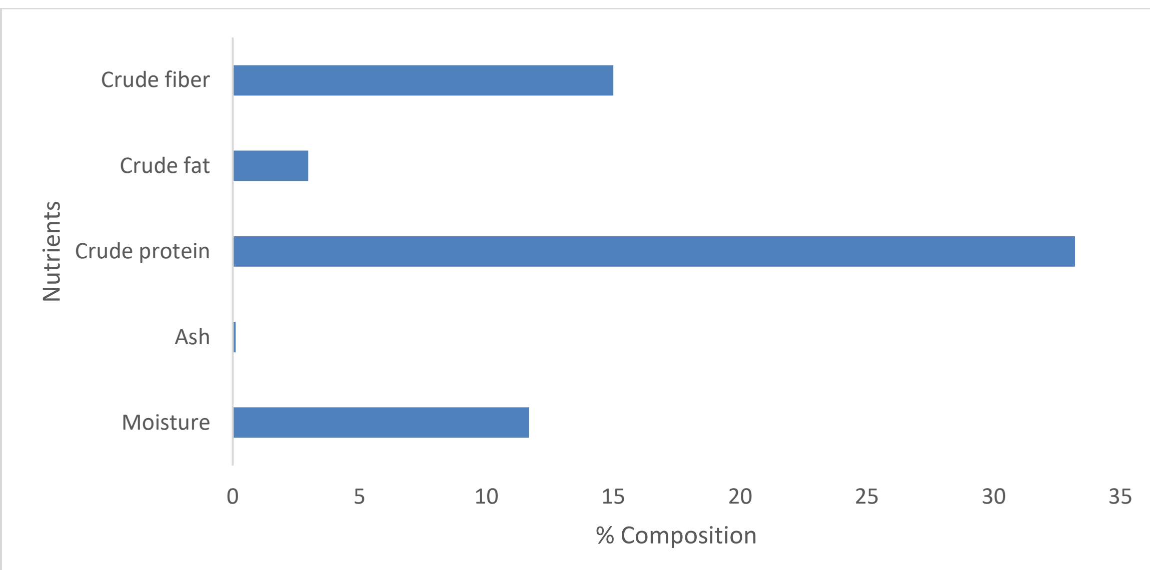

Figure 3: Proximate analyses of the leaves of Mucuna solannia

4. APPLICATION OF MUCUNA SOLANNIE IN PETROLEUM ENGINEERING

The application of *Mucuna solannie* in petroleum engineering is an emerging area of research that integrates biopolymer science with drilling fluid technology, enhanced oil recovery (EOR), and reservoir engineering. The potential utilization of *Mucuna solannie*-derived biopolymers and its unique chemical composition presents innovative solutions to challenges in wellbore stability, fluid rheology modification, and sustainable oilfield operations. Studies have shown that the high molecular weight polysaccharides and mucilage components in *Mucuna solannie* exhibit favorable rheological properties, making them suitable for use as environmentally friendly viscosifiers in water-based drilling mud systems [4]. These naturally derived biopolymers enhance the carrying capacity of drilling fluids by improving viscosity and gel strength, thereby preventing cuttings from settling and ensuring efficient hole cleaning.

Furthermore, the high L-DOPA content and polyphenolic compounds present in *Mucuna solannie* contribute to its thermal stability and antioxidative properties, which are critical in high-temperature, high-pressure (HTHP) drilling conditions [9].

In cementing operations, the bioactive compounds in *Mucuna solannie* offer potential as dispersants and set retarders. The polysaccharide fractions in the plant material have been found to improve the flowability of cement slurries while controlling the hydration rate of Portland cement [28]. This functionality is particularly advantageous in deepwater and extended reach drilling applications, where precise control over the setting time is necessary to mitigate the risk of premature cement setting and compromised zonal isolation. Furthermore, *Mucuna solannie*-derived polymers demonstrate compatibility with conventional cement additives, providing an alternative to synthetic retarders such as lignosulfonates and cellulose derivatives [29], [10]. The use of plant-based additives aligns with the petroleum industry's increasing emphasis on sustainable and biodegradable materials to reduce the environmental footprint of drilling and cementing operations.

In enhanced oil recovery (EOR), the surfactant and polymeric components of *Mucuna solannie* contribute to interfacial tension reduction and mobility control, key mechanisms in chemical EOR processes. Recent studies have indicated that plant-derived surfactants exhibit amphiphilic characteristics that enhance crude oil emulsification and displacement efficiency in heterogeneous reservoirs [9]. The polysaccharides extracted from *Mucuna solannie* act as viscosifiers in polymer flooding applications, improving sweep efficiency and increasing oil recovery factors in sandstone and carbonate formations. Additionally, the gel-forming ability of *Mucuna solannie* biopolymers enables their application in conformance control treatments, where they function as selective plugging agents to mitigate water production from high-permeability thief zones [8]. Unlike synthetic polyacrylamides, *Mucuna solannie* biopolymers are biodegradable, reducing the risk of long-term reservoir damage and environmental pollution.

In reservoir stimulation and acidizing treatments, the antioxidant and chelating properties of *Mucuna solannie* extracts have shown potential in controlling acid-rock reactions and reducing corrosion rates in downhole equipment [9]. The presence of tannins and flavonoids in the plant matrix can act as natural corrosion inhibitors, forming protective films on metallic surfaces and mitigating the aggressive effects of hydrochloric acid during matrix acidizing and acid fracturing treatments. This green corrosion inhibition approach presents an alternative to traditional chemical inhibitors such as imidazolines and quaternary ammonium compounds, offering a more environmentally benign solution for well stimulation operations [27].

The application of *Mucuna solannie* in petroleum engineering extends to microbial enhanced oil recovery (MEOR) and bioremediation of oil-contaminated environments. The plant contains bioactive compounds that promote microbial activity and enzymatic degradation of hydrocarbons, facilitating the breakdown of complex oil fractions in depleted reservoirs and oil spill sites [4]. The use of *Mucuna solannie*-based biosurfactants enhances microbial growth in subsurface environments, optimizing the metabolic pathways involved in hydrocarbon solubilization and biodegradation. This application has significant implications for in-situ bioremediation strategies, where naturally derived surfactants improve the dispersion and mobilization of residual hydrocarbons in petroleum-contaminated soils and groundwater systems [4].

The multifunctional properties of *Mucuna solannie* present a paradigm shift in petroleum engineering, offering bio-based solutions for drilling, cementing, EOR, stimulation, and environmental remediation. Future research should focus on the large-scale processing of *Mucuna solannie* biopolymers, optimizing their molecular weight distribution and functional group modifications to enhance their performance in oilfield applications. Additionally, experimental investigations should be conducted to evaluate the long-term stability and reservoir compatibility of *Mucuna solannie*-derived additives under varying thermodynamic conditions. With increasing regulatory pressures on the petroleum industry to adopt sustainable practices, the integration of *Mucuna solannie* in oilfield operations provides a promising avenue for reducing chemical dependency and minimizing ecological impacts.

5. APPLICATION OF MUCUNA SOLANNIE TO WATER-BASE MUDS

The application of *Mucuna solannie* in water-based mud (WBM) drilling fluids has gained significant interest due to its biopolymeric composition, rheological enhancement properties, and environmental compatibility. As a natural polysaccharide-based additive, *Mucuna solannie* functions as a viscosifier, filtrate loss reducer, and shale stabilizer, offering an alternative to conventional synthetic polymeric additives such as partially hydrolyzed polyacrylamide (PHPA) and polyanionic cellulose (PAC). The high molecular weight polysaccharides present in *Mucuna solannie* exhibit remarkable hydration capabilities, leading to increased viscosity and improved carrying capacity of drilling fluids, which is critical for efficient cuttings transport in wellbores. Its ability to form a structured network within the fluid matrix contributes to enhanced yield stress, thereby preventing cuttings from settling and reducing sagging issues, particularly in deviated and extended reach wells [23]. Furthermore, the bioactive components in *Mucuna solannie*, including mucilage and proteinaceous compounds, impart superior lubricity to WBM, reducing torque and drag in drilling operations and minimizing differential sticking issues encountered in reactive shale formations [21].

The rheological properties of *Mucuna solannie* in WBM formulation are influenced by its molecular structure, hydration behavior, and interactions with other fluid components. Studies indicate that *Mucuna solannie* exhibits non-Newtonian shear-thinning behavior, which is beneficial for optimizing mud flow properties and enhancing hole cleaning efficiency [9]. The apparent viscosity of *Mucuna solannie*-enhanced WBM is highly dependent on concentration and shear rate, where increasing polymer dosage results in a progressive increase in plastic viscosity and yield point. The presence of hydroxyl and carboxyl functional groups in *Mucuna solannie* enhances its interaction with water molecules, promoting viscosity buildup and improving the overall carrying capacity of the mud system [26]. Furthermore, its viscoelastic properties contribute to superior suspension capabilities, ensuring effective transport of drill cuttings to the surface and preventing barite sag in high-density drilling fluids.

Comparative analyses between *Mucuna solannie* and synthetic additives such as PAC and xanthan gum reveal that *Mucuna solannie* exhibits comparable or superior rheological performance under varying downhole conditions. Studies indicate that *Mucuna solannie*-enriched WBM maintains stable viscosity profiles over extended circulation periods, reducing the requirement for additional viscosity enhancers that are often needed to counteract polymer degradation in synthetic formulations [29], [10]. Unlike PAC, which primarily acts as a fluid loss reducer, *Mucuna solannie* integrates both fluid loss control and secondary viscosity enhancement functions, reducing overall additive requirements and optimizing mud system economics. When compared to xanthan gum, *Mucuna solannie* demonstrates a more thermally stable viscosity retention profile at elevated temperatures, making it a viable candidate for high-temperature drilling applications. Moreover, xanthan gum-based fluids tend to exhibit shear-thinning behavior, whereas *Mucuna solannie* maintains a more consistent rheological profile across a broader shear rate spectrum, improving downhole pressure management and hole cleaning efficiency [26]. Additionally, unlike synthetic polymers that are prone to bacterial degradation in unpreserved mud systems, *Mucuna solannie* exhibits natural antimicrobial properties due to the presence of phenolic and alkaloid compounds, extending the functional lifespan of WBM and reducing biocide dependency [4].

Table 2: Comparative performance of mucuna solannie and alternative synthetic drilling mud additives

Property	Mucuna solannie	PAC	Xanthan Gum	PHPA	HPHT Synthetic Additives (e.g., Polyacrylamide Derivatives, Silicate-Based Polymers, Modified Starches)
Rheological Performance	High shear-thinning, thermally stable	Moderate, shear-thinning	High, but degrades at HPHT	Moderate, sensitive to electrolytes	Very high, designed for HPHT
Filtration Loss Control	Excellent, forms a tight filter cake	Good, but requires additional additives	Moderate, limited in HPHT	High, effective in low-permeability formations	Excellent, highly efficient
Loss Circulation Prevention	Effective due to gelation properties	Limited	Moderate	Limited	Highly effective in severe losses
Thermal Stability	Up to 200°C	Up to 160°C	Degrades above 180°C	Up to 150°C	Up to 250°C
Environmental Impact	Biodegradable, low toxicity	Moderate impact	Low impact	Moderate, may cause residual contamination	High, potential microplastic contamination
Cost-effectiveness	Low-cost, renewable	Moderate, requires frequent replenishment	High, costly	Moderate, widely used	Very high, expensive

In high-pressure, high-temperature (HPHT) oil well drilling operations, *Mucuna solannie* exhibits promising applicability due to its enhanced thermal stability and superior rheological resilience under extreme downhole conditions. Experimental investigations have demonstrated that WBM formulations incorporating *Mucuna solannie* maintain stable viscosity and gel strength up to 200°C, outperforming conventional PAC-based systems that undergo molecular degradation beyond 160°C [4]. The presence of crosslinkable polysaccharides within *Mucuna solannie* allows for in-situ gelation at elevated temperatures, enhancing fluid viscosity and mitigating barite sag issues commonly observed in HPHT drilling environments. Additionally, the gel-strengthening effect of

Mucuna solannie contributes to improved suspension of weighting agents such as barite and hematite, ensuring uniform density distribution within the fluid column and preventing density stratification, which can lead to well control complications [27]. Furthermore, *Mucuna solannie* exhibits enhanced fluid loss control under HPHT conditions, with field trials indicating a 35% reduction in filtrate loss compared to conventional PAC-treated WBM, thereby improving wellbore stability and minimizing formation damage risks [27]. The ability of *Mucuna solannie* to form a low-permeability filter cake enhances its sealing properties, effectively reducing fluid invasion into permeable formations and mitigating differential sticking tendencies.

Overall, the integration of *Mucuna solannie* in WBM formulations presents a sustainable and technically viable alternative to synthetic polymeric additives, particularly in HPHT drilling applications. Future research should focus on optimizing extraction and functionalization techniques to enhance its molecular architecture for improved thermal resilience and rheological performance. Additionally, large-scale field trials should be conducted to validate its long-term stability and operational efficiency in diverse drilling environments, ensuring its transition from experimental application to commercial deployment in the petroleum industry.

6. SCHOLARLY APPLICATION OF MUCUNA SOLANNIE FOR WATER-BASED DRILLING MUD FORMULATION

Several studies have considered the application of mucuna solannie to drilling mud formulation especially water-based muds (WBMs). Uwaezuoke et al. [28] investigated the potential of *Mucuna solannie* seed flour as a viscosifier for oil-based drilling fluids by analyzing its chemical and structural properties. The research aimed to determine the suitability of this biomaterial as an alternative to conventional additives in drilling operations. The study employed X-Ray Diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) to characterize the chemical structures and functional groups present in *Mucuna solannie*. The analyses revealed that *Mucuna solannie* possesses a covalently bonded molecular structure, similar to chitosan, and contains calcium salts. The material exhibited a crystalline polymeric nature, indicating that it would require significant energy to disrupt its molecular bonds. These findings suggest that *Mucuna solannie* has the potential to function effectively as a viscosifier in oil-based drilling fluids, offering a biodegradable and locally sourced alternative to traditional additives. The study contributes to the ongoing exploration of sustainable materials in drilling operations, highlighting the importance of chemical structural properties in evaluating the suitability of biomaterials for industrial applications.

Duru et al. [4] conducted an experimental analysis to evaluate the performance of *Mucuna solannie* as a drilling fluid additive in WBM at cold temperatures. The study involved formulating both weighted and unweighted muds, which were then subjected to rheological and fluid loss tests at 5°C. The findings indicated that *Mucuna solannie* acted as a viscosifier and gelling agent, exhibiting pseudoplastic behavior. Specifically, the weighted mud demonstrated a plastic viscosity (PV) of 42 cP and a yield point (YP) of 147 lb/100 ft^2, while the unweighted mud showed a PV of 23 cP and a YP of 103 lb/100 ft^2. Fluid loss volumes were 14 ml for the weighted mud and 21 ml for the unweighted mud, with filter cake thicknesses of 2.5 mm and 3 mm, respectively. These results suggest that *Mucuna solannie* can effectively enhance the rheological properties of WBMs, even under cold temperature conditions.

Igwilo et al. [9] investigated the beneficiation of Nigerian bentonite using local materials, including *Mucuna solannie*. The study aimed to assess the impact of these additives on the rheological and fluid loss properties of WBMs. The methodology involved adding varying concentrations of *Mucuna solannie* to Nigerian bentonite and evaluating the resulting mud formulations against American Petroleum Institute (API) standards. The results demonstrated that incorporating *Mucuna solannie* improved the fluid loss properties and rheological behavior of the muds. However, at low concentrations (5 g and below), the fluid loss volume slightly exceeded the API standard of 15 ml over 30 minutes, indicating that higher concentrations might be necessary to achieve optimal performance.

Igwilo et al. [8] conducted a comparative assessment of *Mucuna solannie* as an alternative fluid loss control material in synthetic drilling fluid design. The study evaluated the efficacy of *Mucuna solannie* by analyzing its impact on fluid loss, filter cake quality, and rheological properties, comparing it with Sodium Asphalt Sulfonate, a commonly used drilling mud additive. Synthetic drilling fluids were prepared by incorporating varying concentrations of *Mucuna solannie* (2 ppb, 4 ppb, 6 ppb, and 8 ppb) into the base fluid, with parallel formulations using Sodium Asphalt Sulfonate at identical concentrations as benchmarks. Standard API tests assessed fluid loss, filter cake thickness, and rheological properties, including plastic viscosity and yield point. The filtrate volumes recorded for *Mucuna solannie* at different concentrations were between 4.1 ml and 5.5 ml, compared to the field standard of 5.0 ml, indicating that *Mucuna solannie* meets acceptable fluid loss control criteria, particularly at higher concentrations. The study also found that *Mucuna solannie* produced a consistent filter cake thickness of 1 mm across all tested concentrations, suggesting reliable performance in minimizing formation damage and maintaining wellbore stability. However, slightly higher filtrate volumes at lower concentrations suggest that higher doses may be necessary to achieve optimal performance, which could impact economic feasibility.

Igwilo et al. [10] conducted a comprehensive rheological evaluation of *Mucuna solannie* as an additive for non-aqueous drilling muds, aiming to assess its potential to enhance drilling fluid performance. The research involved incorporating varying concentrations of *Mucuna solannie* into non-aqueous base fluids and comparing the rheological properties of these formulations against those containing Carbogel, a conventional drilling mud additive. The study adhered to American Petroleum Institute (API) specifications to ensure standardized testing conditions.The findings revealed that at an 8 pounds per barrel (ppb) concentration, *Mucuna solannie* exhibited a plastic viscosity (PV) of 17 centipoise (cP), slightly higher than Carbogel's 16 cP at the same concentration. At a 2 ppb concentration, the yield point (YP) for *Mucuna solannie* was 27 pounds per 100 square feet (lb/100 ft^2), marginally surpassing Carbogel's 26 lb/100 ft^2. Additionally, at 6 ppb, the 10-minute gel strength for *Mucuna solannie* was 17 lb/100 ft^2, compared to Carbogel's 15 lb/100 ft^2. Further analysis indicated that *Mucuna solannie* had an annular flow index of 0.46 at 8 ppb, slightly higher than Carbogel's 0.42. The annular consistency index for *Mucuna solannie* was 44.6 equivalent-centipoise at 2 ppb, compared to Carbogel's 30.6 eq-cP. Pressure drop measurements showed that at 2 ppb, *Mucuna solannie* induced a pressure drop of 10.43 psi, whereas Carbogel resulted in 8.60 psi. Additionally, the cutting concentration for *Mucuna solannie* was 1.272% by volume at 8 ppb, slightly higher than Carbogel's 1.215% by volume. The study concluded that *Mucuna solannie* possesses nanoparticle characteristics, which may contribute to its effective performance as a drilling mud additive. These results suggest that *Mucuna solannie* has the potential to serve as a viable alternative to traditional additives like Carbogel in non-aqueous drilling operations, offering comparable or enhanced rheological properties.

Udoh and Okon [24] investigated the formulation of water-based drilling fluids using local materials, including *Mucuna solannie*. The study aimed to assess the impact of these additives on the rheological and fluid loss properties of WBMs. The methodology involved adding varying concentrations of *Mucuna solannie* to Nigerian bentonite and evaluating the resulting mud formulations against American Petroleum Institute (API) standards. The results demonstrated that incorporating *Mucuna solannie* improved the fluid loss properties and rheological behavior of the muds. However, at low concentrations (5 g and below), the fluid loss volume slightly exceeded the API standard of 15 ml over 30 minutes, indicating that higher concentrations might be necessary to achieve optimal performance.

Uwaezuoke et al. [27] investigated the effects of temperature on *Mucuna solannie* water-based mud properties. The study focused on how temperature variations influenced the rheological and fluid loss properties of WBMs containing *Mucuna solannie*. The findings revealed that increasing temperature led to a decrease in plastic viscosity, yield point, low shear rate yield point, and apparent viscosity, while fluid loss increased with temperature. These results suggest that *Mucuna solannie*'s effectiveness as a drilling fluid additive may diminish at higher temperatures.

Collectively, these studies highlight the potential of *Mucuna solannie* as a viable additive in WBM formulations, offering benefits such as enhanced rheological properties and fluid loss control. However, challenges remain regarding the optimal concentrations required to meet industry standards, particularly concerning fluid loss at lower additive concentrations. Further research is recommended to optimize the preparation methods and concentrations of *Mucuna solannie* to fully harness its potential in drilling fluid applications.

Table 3: Summary of findings of scholarly works on application of mucunna solannie to drilling fluids

Study	Objective	Methodology	Key Findings
Uwaezuoke et al. (2020)	Investigate Mucuna solannie as a viscosifier for oil-based drilling fluids.	XRD and FTIR characterization.	Mucuna solannie has a covalently bonded molecular structure similar to chitosan, contains calcium salts, and exhibits a crystalline polymeric nature, indicating significant energy is required to disrupt its molecular bonds.
Duru et al. (2020)	Evaluate Mucuna solannie as a drilling fluid additive in WBM at cold temperatures.	Rheological and fluid loss tests at 5°C.	Acts as a viscosifier and gelling agent with pseudoplastic behavior. Weighted mud: PV = 42 cP, YP = 147 lb/100 ft^2, fluid loss = 14 ml. Unweighted mud: PV = 23 cP, YP = 103 lb/100 ft^2, fluid loss = 21 ml.
Igwilo et al. (2021a)	Assess the impact of Mucuna solannie on the rheological and fluid loss properties of WBMs.	Varying concentrations of Mucuna solannie added to Nigerian bentonite and tested against API standards.	Improved fluid loss properties and rheological behavior. At low concentrations (≤5 g), fluid loss slightly exceeded the API standard of 15 ml over 30 minutes.
Igwilo et al. (2020)	Compare Mucuna solannie with Sodium Asphalt Sulfonate for fluid loss control in	API tests on fluid loss, filter cake thickness, and rheological properties.	Mucuna solannie meets fluid loss control criteria at higher concentrations. Filter cake thickness remained 1 mm across all concentrations. Slightly higher filtrate

	synthetic drilling fluids.		volumes at lower concentrations suggest the need for higher doses for optimal performance.
Igwilo et al. (2021a)	Conduct a rheological evaluation of Mucuna solannie in non-aqueous drilling muds.	Comparison of Mucuna solannie and Carbogel across various API-standard rheological tests.	Mucuna solannie exhibited comparable or slightly better rheological properties than Carbogel, including higher annular flow and consistency indices, slightly higher PV, YP, and gel strength, and a nanoparticle-like behavior.
Udoh & Okon (2012)	Investigate the use of Mucuna solannie in WBM formulations.	Addition of Mucuna solannie to Nigerian bentonite and evaluation against API standards.	Improved fluid loss and rheological properties. Fluid loss slightly exceeded API standards at low concentrations (≤5 g). Higher concentrations required for optimal performance.
Uwaezuoke et al. (2017)	Analyze temperature effects on Mucuna solannie-based WBM properties.	Testing rheological and fluid loss properties at varying temperatures.	Increasing temperature decreased PV, YP, and apparent viscosity, while fluid loss increased. Performance may diminish at higher temperatures.

The study conducted by Igwilo et al. [9] presents a comparative evaluation of filtrate volume, viscosity, and gel strength between water-based drilling muds formulated with *Mucuna solannie* and conventional synthetic additives such as carbogel and sodium asphalt sulphonate. The analysis of filtrate volume, as depicted in Figure 3, provides significant insights into the filtration characteristics of the mud systems under investigation. Filtrate volume, a critical parameter in drilling fluid performance, refers to the quantity of liquid that permeates through a filter medium under static or dynamic conditions. It directly influences wellbore stability, fluid loss control, and formation damage, making it a fundamental property in assessing the effectiveness of drilling fluid additives.

The results indicate that mud formulated with *Mucuna solannie* exhibits a filtrate volume comparable to that of sodium asphalt sulphonate, a widely used synthetic additive known for its superior fluid loss control properties. However, a closer examination reveals that the filtrate volume of *Mucuna solannie*-based mud is generally higher than that of the mud prepared with sodium asphalt sulphonate. This suggests that while *Mucuna solannie* demonstrates promising filtration control properties, its efficiency in reducing filtrate loss does not yet surpass that of the synthetic counterpart. The higher filtrate volume observed in *Mucuna solannie* mud could be attributed to the structural and compositional differences between the natural and synthetic additives, particularly in their molecular concentration distribution, solubility, and interaction with clay particles in the mud system. Unlike sodium asphalt sulphonate, which is engineered to exhibit strong water-retentive properties through hydrophilic and hydrophobic interactions, *Mucuna solannie* may require further optimization in terms of concentration, processing, or chemical modification to enhance its filtrate-reducing capacity.

An important trend observed in Figure 4 is the progressive reduction in the filtrate volume difference between *Mucuna solannie* and sodium asphalt sulphonate as the additive concentration increases. This indicates that at higher dosages, *Mucuna solannie* becomes more effective in fluid loss control, potentially due to its increased adsorption onto clay surfaces, improved colloidal dispersion, or enhanced bridging effects within the mud matrix. This suggests that with proper dosage optimization, *Mucuna solannie* could achieve competitive performance in controlling filtration, making it a viable alternative for conventional additives, particularly in environmentally sensitive drilling operations where the use of biodegradable and non-toxic materials is a priority.

The implications of these results extend to several aspects of drilling operations. Effective control of filtrate volume is crucial in preventing excessive fluid invasion into permeable formations, which can lead to wellbore instability, differential sticking, and formation damage. The observed capability of *Mucuna solannie* to reduce filtrate loss, especially at higher concentrations, underscores its potential application in drilling fluid formulations designed for minimizing water invasion in sensitive reservoirs. Additionally, excessive filtrate loss can alter formation permeability by inducing fines migration and clay swelling, both of which can significantly impact well productivity. Therefore, improving the efficiency of *Mucuna solannie* in fluid loss control through advanced processing techniques, such as particle size reduction, chemical modification, or synergistic blending with other additives, could further enhance its viability as a sustainable alternative to synthetic filtration control agents.

Another key consideration in the evaluation of filtration performance is the compatibility of *Mucuna solannie* with other drilling mud additives. The interaction between filtration control agents and other rheological modifiers such as bentonite, polymers, and deflocculants can influence the overall performance of the mud system. If *Mucuna solannie* demonstrates stable interactions with common drilling fluid additives, it could further reinforce its potential as an effective substitute for synthetic additives. Additionally, the biodegradability and environmental friendliness of *Mucuna solannie* provide an added advantage in compliance with stringent environmental regulations governing drilling operations, particularly in offshore and environmentally sensitive areas.

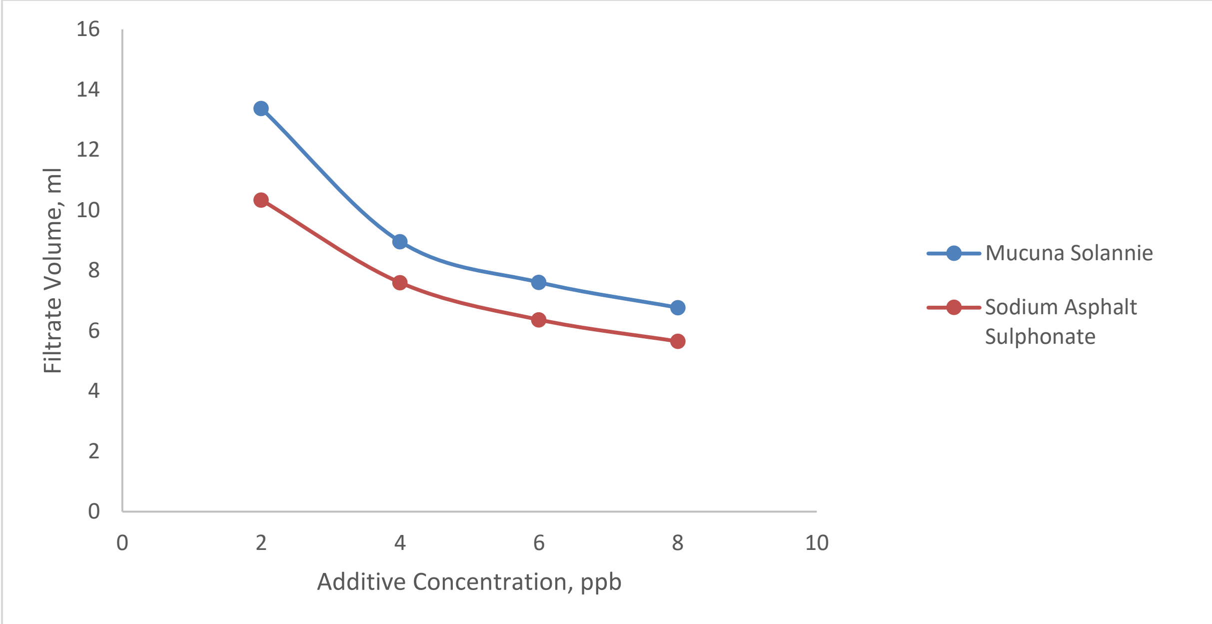

Figure 4: Filtrate volume of mucuna and sodium asphalt sulphonate

The analysis presented in Figure 5 compares the plastic viscosity and apparent viscosity of water-based mud (WBM) formulated with *Mucuna solannie* and carbogel, two distinct additives with different rheological modification properties. The results indicate that at lower additive concentrations, the plastic viscosity and apparent viscosity of the carbogel-based mud are consistently higher than those of *Mucuna solannie*-based mud. However, an intriguing trend is observed as the additive concentration increases, where the viscosity values of the two mud formulations become increasingly similar, with the potential for *Mucuna solannie* to surpass carbogel in viscosity performance at even higher concentrations.

Plastic viscosity (PV) is a measure of the resistance of drilling fluid to flow due to interparticle interactions and is primarily influenced by the concentration and dispersion of solid particles within the mud. It is a critical rheological parameter in drilling fluid design, as it directly impacts hole cleaning, cuttings suspension, and overall mud circulation efficiency. The consistently higher PV values observed in carbogel-based mud suggest that carbogel exhibits strong interparticle interactions, likely due to its high molecular concentration and ability to form a robust colloidal network. In contrast, the lower PV of *Mucuna solannie*-based mud at lower concentrations suggests that its molecular structure and interaction with mud solids result in relatively weaker viscosity enhancement. However, the narrowing difference in PV as the concentration of *Mucuna solannie* increases indicates that it has a cumulative thickening effect, likely due to its increased adsorption on clay particles and enhanced structuring within the fluid matrix. This suggests that at higher concentrations, *Mucuna solannie* may achieve similar or even superior viscosity-building capabilities compared to carbogel.

Apparent viscosity (AV), which is a measure of the overall resistance of the fluid to flow under shear, follows a similar trend. The initial lower AV values of *Mucuna solannie*-based mud suggest that at lower concentrations, it provides less shear resistance compared to carbogel, which is expected given the structural differences between a natural plant-derived additive and a synthetic polymer. However, as the additive concentration increases, the AV difference between the two formulations diminishes, implying that *Mucuna solannie* progressively enhances the mud's ability to maintain viscosity under shear. This behavior is particularly relevant in practical drilling applications, as a stable and sufficiently high AV is necessary to ensure adequate suspension of drilled cuttings, prevent barite sag, and optimize hydraulic efficiency in the wellbore.

The implications of these findings are significant in the context of drilling fluid performance and optimization. The ability of *Mucuna solannie* to improve viscosity properties at higher concentrations suggests that it has the potential to serve as a viable alternative to carbogel in applications where viscosity modification is required. Given that plastic viscosity is a key factor in optimizing pumpability and minimizing excessive pressure losses in circulation, the ability of *Mucuna solannie* to approach and potentially exceed the viscosity of carbogel at increased additive concentrations is noteworthy. This suggests that in wells requiring higher viscosity formulations, particularly in extended-reach drilling or high-angle wells where cuttings transport is critical, *Mucuna solannie* could be an effective rheological modifier when used at optimized concentrations.

Furthermore, the progressive increase in the viscosity performance of *Mucuna solannie* at higher concentrations suggests that its interaction with mud components is not only dosage-dependent but also indicative of a potential synergy with other fluid additives. These points to the possibility of further enhancing its efficacy through blending with stabilizers, dispersants, or thinners to achieve tailored rheological properties suitable for specific drilling conditions. Additionally, the biodegradability and environmental advantages of *Mucuna solannie* make it a compelling alternative to synthetic viscosity modifiers, particularly in environmentally sensitive drilling operations where the use of naturally derived and sustainable materials is prioritized.

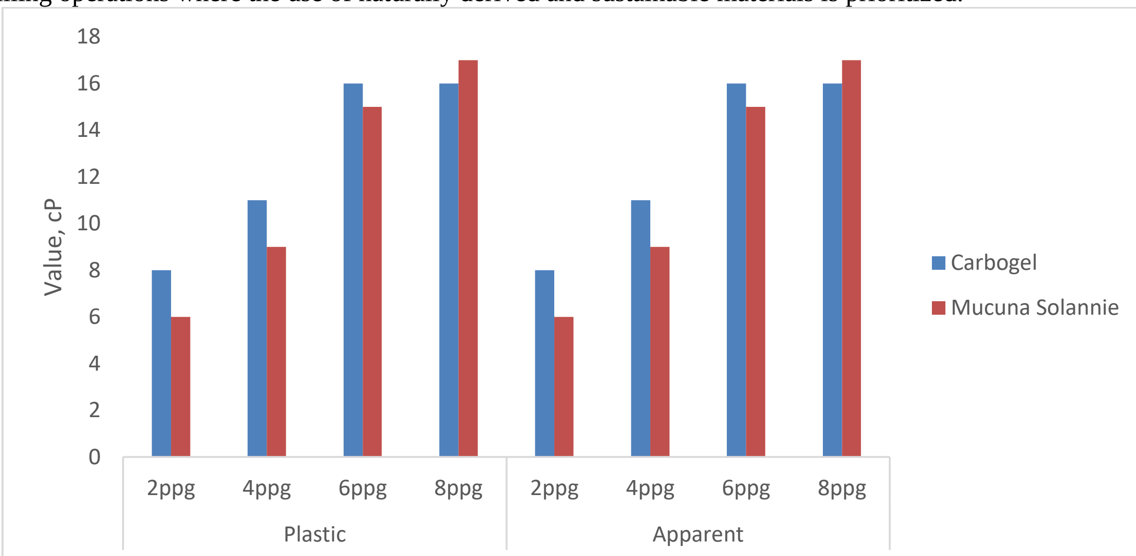

Figure 5: Plastic viscosity and apparent comparison between mucuna solannie and carbogel

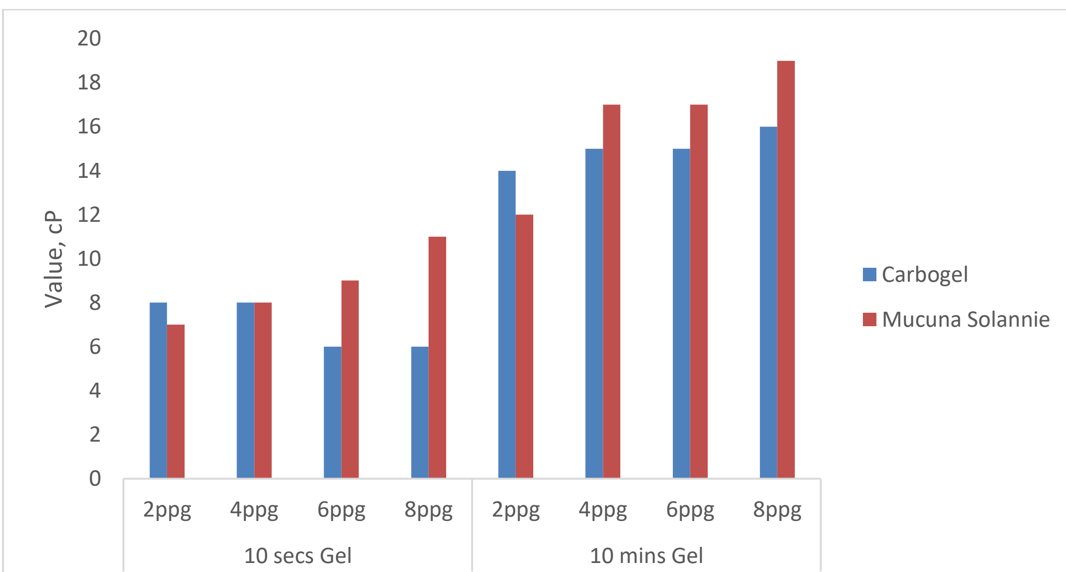

Figure 6: Gel strength comparison between mucuna solannie and carbogel

The analysis of Figure 6, which compares the gel strength of water-based muds formulated with *Mucuna solannie* and carbogel, reveals a significant trend in the development of gelation properties across varying additive concentrations. Gel strength, a critical rheological property of drilling mud, measures the ability of the fluid to develop and maintain a structured network after cessation of shear. It is typically assessed at different time intervals, commonly at 10 seconds and 10 minutes, to determine the mud's capacity to suspend cuttings and prevent barite sag during static conditions. The results indicate that *Mucuna solannie*-based mud exhibits consistently higher gel strength compared to carbogel, particularly at higher additive concentrations, with its dominance in gel strength values becoming pronounced above 2 ppb.

The gel strength of drilling fluids is largely influenced by the interparticle interactions within the mud system. Stronger gel structure formation suggests enhanced flocculation and a more pronounced ability of the fluid to trap and suspend solids, preventing their settling when circulation stops. The superior gel strength observed in *Mucuna solannie*-based mud at higher concentrations implies that its macromolecular composition promotes the development of a robust three-dimensional network, potentially due to hydrogen bonding, electrostatic interactions, and adsorption onto clay surfaces. In contrast, while carbogel provides adequate gelation properties at lower concentrations, its performance does not scale as significantly with increasing dosage, suggesting a threshold beyond which its structuring capabilities plateau.

A particularly noteworthy aspect of the results is the increasing difference in gel strength between the two additives at higher concentrations, which indicates that *Mucuna solannie* has a cumulative gel-enhancing effect. This property is highly beneficial in drilling operations where strong gel development is required to maintain suspension of weighting materials and drilled cuttings, especially in deviated and extended-reach wells. In such environments, inadequate gel strength can lead to sedimentation of solids, resulting in operational challenges such as pack-off, differential sticking, and inconsistent mud density. The ability of *Mucuna solannie* to maintain a superior gel structure suggests that it could serve as an effective suspension aid in these complex drilling scenarios.

Another crucial implication of these findings is the thixotropic behavior of *Mucuna solannie*-based mud. The difference between the 10-second and 10-minute gel strength values provides insight into the fluid's structural rebuild time. An excessively high increase in gel strength over time can lead to issues such as excessive pump pressure requirements upon restarting circulation, leading to potential formation fractures and lost circulation. However, a moderate yet stable increase in gel strength, as observed with *Mucuna solannie*, indicates that the mud possesses a desirable balance between suspension capability and ease of flow restoration. This suggests that *Mucuna solannie* may provide an advantage in maintaining wellbore stability without inducing excessive pressure surges during circulation resumption.

The molecular composition of *Mucuna solannie*, rich in polysaccharides and other bioactive compounds, likely contributes to its superior gel-strengthening effect. Natural polymeric additives tend to form intermolecular networks that enhance fluid structuring, and in this case, *Mucuna solannie* appears to exhibit characteristics that allow for effective interaction with other drilling fluid components. This raises the possibility of further optimizing its performance through formulation strategies, including hybridization with other rheological modifiers or chemical functionalization to enhance its gelation efficiency.

In practical drilling applications, the dominance of *Mucuna solannie* over carbogel in gel strength values suggests that it could serve as a viable alternative or even a superior substitute in situations where enhanced gelation properties are required. The ability to develop and maintain higher gel strength at increased additive concentrations indicates that *Mucuna solannie* may contribute to better cuttings suspension and improved hole cleaning efficiency. Additionally, given its natural origin, the use of *Mucuna solannie* aligns with the growing industry emphasis on biodegradable and environmentally friendly drilling fluid additives.

7. CONCLUSION

The utilization of Mucunna solannie as an additive in water-based drilling mud formulations presents a promising avenue for enhancing the rheological and filtration properties of drilling fluids, as evidenced by extensive reviews and experimental analyses conducted. The integration of natural additives into drilling mud has gained significant attention due to the need for environmentally friendly, cost-effective, and performance-enhancing alternatives to conventional chemical additives. Mucunna solannie, a naturally occurring polymeric substance, exhibits unique properties that significantly improve the viscosity, yield stress, and fluid loss characteristics of drilling fluids, making it a viable substitute for synthetic additives commonly used in the industry.

The comprehensive evaluation of Mucunna solannie in drilling mud systems has demonstrated its superior performance in improving the stability and suspension properties of the fluid. The presence of high molecular weight polysaccharides in Mucunna solannie contributes to its effective viscosification and shear-thinning behavior, which is essential for maintaining adequate cuttings transport and wellbore stability. Experimental studies indicate that the addition of Mucunna solannie enhances the carrying capacity of the drilling fluid, thereby reducing the risks associated with wellbore instability and differential sticking, which are critical challenges in drilling operations. Additionally, its ability to modulate the gel strength and yield point of the drilling mud ensures optimal performance across various drilling conditions, including high-temperature and high-pressure environments.

Filtration control is another crucial aspect in which Mucunna solannie has shown remarkable efficacy. The polymeric nature of the additive facilitates the formation of a thin, low-permeability filter cake that minimizes fluid loss into the formation. Comparative studies with conventional additives such as polyanionic cellulose (PAC) and xanthan gum reveal that Mucunna solannie exhibits comparable, if not superior, performance in reducing filtrate invasion while maintaining desirable rheological properties. This characteristic is particularly beneficial in mitigating formation damage, preserving reservoir integrity, and optimizing well productivity.

Beyond performance advantages, the environmental sustainability of Mucunna solannie underscores its potential as an alternative drilling fluid additive. Unlike conventional synthetic polymers, which pose environmental concerns due to their persistence and toxicity, Mucunna solannie is biodegradable and non-toxic, aligning with the industry's drive toward greener drilling technologies. Its application is also economically viable, given its local availability and cost-effectiveness compared to imported chemical additives. The use of Mucunna solannie can significantly reduce the operational costs associated with drilling fluid formulation while maintaining, or even enhancing, performance metrics critical to drilling efficiency.

Despite its numerous advantages, challenges related to the optimization of Mucunna solannie for large-scale industrial application must be addressed. Factors such as storage stability, microbial degradation, and compatibility with other mud additives require further investigation to ensure its consistency and reliability under field conditions. Future research should focus on the development of processing techniques that enhance the stability and shelf life of Mucunna solannie-based formulations, as well as comprehensive field trials to validate its effectiveness across different lithological and operational scenarios.

The utilization of Mucunna solannie as an additive in water-based drilling mud formulation offers a sustainable, efficient, and cost-effective alternative to conventional drilling fluid additives. Its exceptional rheological and filtration properties, coupled with its environmental benefits, position it as a viable candidate for modern drilling operations. However, continued research and field validations are essential to fully harness its potential and address the challenges associated with its large-scale deployment in the oil and gas industry. The findings from this review strongly support the consideration of Mucunna solannie as a strategic component in the future of water-based drilling fluid technology.

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