

# Enhancing the environmental sustainability and performance of drilling fluids through the incorporation of silica nanoparticles and aloe vera powder extracts

Ahmed Sabri<sup>ID</sup>, Anas Elhederi\*<sup>ID</sup>

Department of Petroleum Engineering, University of Technology Malaysia, 81310, Malaysia

\* Corresponding author: Anas Elhederi, [anaselhoderi@gmail.com](mailto:anaselhoderi@gmail.com)

## CITATION

Sabri A, Elhederi A. Enhancing the environmental sustainability and performance of drilling fluids through the incorporation of silica nanoparticles and aloe vera powder extracts. *Materials Technology Reports*. 2025; 3(2): 3519. <https://doi.org/10.59400/mtr3519>

## ARTICLE INFO

Received: 27 June 2025

Revised: 20 August 2025

Accepted: 25 August 2025

Available online: 21 September 2025

## COPYRIGHT



Copyright © 2025 Author(s).  
*Materials Technology Reports* is published by Academic Publishing Pte. Ltd. This work is licensed under the Creative Commons Attribution (CC BY) license. <https://creativecommons.org/licenses/by/4.0/>

**Abstract:** This research explores the use of Aloe Vera powder and silica nanoparticles (SNPs) as environmentally friendly additives aimed at enhancing the rheological and filtration performance of water-based drilling muds. The work evaluates how different concentrations of SNPs (0.2 g, 0.3 g, and 0.4 g) combined with Aloe Vera affects key drilling fluid properties, including mud density, plastic viscosity, apparent viscosity, yield point, pH, gel strength, and filtration performance before and after hot rolling. The findings indicate that Aloe Vera alone can improve the drilling mud's rheology by increasing its viscosity and suspension ability, while also contributing to a noticeable reduction in pH. When paired with SNP, the interactions between the biopolymer and nanoparticles create a synergistic effect, especially at 0.3 g and 0.4 g SNP concentrations. At these levels, mud demonstrated better viscosity behavior, higher yield point values, and more effective control of fluid loss, suggesting a more reinforced internal structure. However, thermal stability declined after hot rolling, implying that high temperatures may weaken or alter the intermolecular forces responsible for the enhanced performance under normal conditions. Overall, the study demonstrates that blending Aloe Vera with SNPs offers a promising, sustainable approach to improve drilling fluid behavior while supporting more environmentally responsible drilling operations.

**Keywords:** silica nanoparticles; aloe vera; drilling fluids; water-based mud; environmental sustainability; green additives

## 1. Introduction

Drilling fluids, commonly known as drilling muds, play a fundamental role in the oil and gas industry. These fluids serve multiple critical functions during drilling operations, including maintaining wellbore stability, controlling formation pressures, transporting cuttings to the surface, cooling and lubricating the drill bit, and preventing formation damage. Among various types of drilling fluids, water-based muds (WBMs) are widely favored due to their cost-effectiveness, ease of handling, and lower environmental impact compared to oil-based or synthetic-based counterparts [1].

However, conventional WBMs often rely on chemical additives that can pose environmental hazards during disposal, especially when used in large-scale operations. As environmental regulations become increasingly strict, industry is under growing pressure to transition towards greener and more sustainable drilling fluid formulations. To address these challenges, researchers have turned to biodegradable and naturally derived materials that can match or exceed the performance of traditional additives

while minimizing ecological harm [2].

## 2. Experiment

Drilling mud samples were prepared following API RP 13B-1 standards. Base mud comprised deionized water and bentonite. Aloe Vera powder was added at a constant concentration, while SNPs were varied at 0.2 g, 0.3 g, and 0.4 g per 350 ml lab barrel. Rheological tests (mud density, plastic viscosity, apparent viscosity, yield point, pH, gel strength) and filtration properties (filtrate loss, mud cake thickness) were measured before and after hot rolling at 250 °F for 16 h. All experimental procedures for mud testing were conducted in accordance with established methodologies outlined in the literature. **Table 1** shows the formulation of base mud used in this study [1].

**Table 1.** Formulation of base mud [1].

Additive	Description/function	Quantity	Mixing time
Deionized water	Base liquid	350 mL	-
Bentonite	Clay for viscosity/API filtrate control	14 g	20 min
Aloe Vera powder	Fluid Loss Reducer	1 g	15 min
Nano silica (SNP)	Rheology modification	0.2 g, 0.3 g, and 0.4 g	15 min

## 3. Results

This section methodically presents and analyzes the comprehensive experimental results obtained from the severe evaluation of Aloe Vera powder and nano silica particles as functional additives incorporated into water-based drilling mud formulations [3]. The investigation includes a detailed examination of the findings with particular emphasis on their correlation with critical performance parameters that govern the operational efficacy of drilling fluids in petroleum engineering applications [4]. These fundamental parameters include mud density, plastic viscosity, apparent viscosity, yield point, gel strength (encompassing both initial and time-dependent measurements), mud cake thickness (representing filtration control efficiency), and pH (indicating the chemical stability and reactivity of the system) [5]. The comprehensive analytical framework employed in this study facilitates a thorough understanding of how each additive, when introduced either individually as a discrete component or in synergistic combination with other additives, exerts measurable and quantifiable influences on the rheological behavior and filtration control characteristics inherent to the base mud system.

The rheological properties, which encompass viscosity measurements and yield characteristics, are of paramount importance in determining the mud's capacity to suspend drill cuttings, transmit hydraulic horsepower to the drill bit, and maintain wellbore stability throughout drilling operations [6,7]. Similarly, the filtration properties, as evidenced by mud cake formation and associated thickness measurements, are critical indicators of the drilling fluid's ability to minimize fluid loss into permeable formations while maintaining an impermeable barrier that prevents formation damage and maintains wellbore integrity [8]. The pH parameter serves as a fundamental indicator of the chemical environment within the drilling fluid system, influencing factors such as

additive solubility, polymer stability, corrosion rates of drilling equipment, and potential interactions with formation minerals.

The comparative analysis methodology employed throughout this investigation involves systematic comparisons among the various formulated samples, encompassing the base mud system serving as the control reference, samples modified with individual additives at varying concentration levels, and samples incorporating multiple additives in combined formulations. This structured comparative approach provides valuable insight into the relative effectiveness of each additive combination, revealing patterns of enhancement or degradation in specific performance parameters [9]. Furthermore, the analysis addresses the stability characteristics of the formulated drilling fluids, which are essential for understanding their behavior during extended operational periods, their resistance to thermal degradation under elevated downhole temperatures, and their capacity to maintain consistent performance properties despite exposure to varying shear rates and mechanical stresses encountered during circulation through the drilling system [10].

The evaluation framework additionally considers the potential suitability and practical applicability of the tested formulations for enhancing overall drilling fluid performance under diverse operational conditions that may be encountered in field applications [11]. These operational conditions encompass variations in formation characteristics, wellbore geometry, drilling depth, temperature profiles, and specific drilling challenges such as fluid loss control in highly permeable formations, maintenance of adequate hole cleaning efficiency in deviated wellbores, and prevention of differential sticking scenarios. The investigation recognizes that optimization of drilling fluid properties requires a delicate balance among competing performance requirements, as improvements in certain parameters may potentially result in compromises in others.

The experimental design incorporates both low-temperature and high-temperature testing protocols, acknowledging the significant influence that thermal conditions exert on the performance characteristics of water-based drilling fluids and their constituent additives. This dual-temperature approach ensures that the findings possess relevance across a broad spectrum of drilling scenarios, from shallow, low-temperature environments to deep, high-temperature, high-pressure applications where thermal stability becomes increasingly critical. The comprehensive nature of this investigation thereby establishes a robust foundation for evidence-based recommendations regarding additive selection and concentration optimization in water-based drilling mud formulations.

### **3.1. Density measurement**

The base water-based mud (WBM) formulation utilized in this experimental investigation exhibited a stable and repeatable [12]. Density of 8.7 pounds per gallon (ppg), which was established as the fundamental reference parameter for systematic evaluation of the impact exerted by the incorporation of Aloe Vera powder and silica nanoparticles (SNPs) as functional additives within the drilling fluid matrix. This baseline density value represents a critical benchmark against which all subsequent formulations containing various additive concentrations and combinations

were rigorously compared, enabling quantitative assessment of density modifications attributable to the introduced materials [2].

When Aloe Vera powder was incorporated into the mud system through controlled mixing procedures, the resulting density measurements obtained from the treated formulations remained remarkably consistent, exhibiting values ranging from 8.20 ppg to 8.30 ppg across the spectrum of tested concentrations. This narrow range of density variation, representing a maximum deviation of merely 0.5 ppg from the lower bound to the upper bound of the observed range, provides compelling evidence demonstrating that the biopolymer constituent does not significantly influence or alter the overall weight characteristics of the mud system. The statistical consistency of these measurements suggests that Aloe Vera, despite its organic composition and potential for hydration and swelling behavior, does not contribute substantial mass per unit volume to the drilling fluid formulation.

In a parallel manner, the systematic addition of silica nanoparticles at precisely controlled concentrations spanning the range between 0.2 g and 0.4 g produced no meaningful or statistically significant change in the measured mud density parameters. All samples subjected to SNP treatment maintained density values that were closely aligned with those of the base fluid, indicating that even at the maximum investigated nanoparticle loading, the contribution to overall system density remained negligible. This observation is particularly noteworthy given that silica possesses a relatively high intrinsic density compared to organic materials; however, the small absolute quantities employed in the formulations resulted in insufficient mass addition to detectably alter the bulk density of the mud system [13].

This density stability characteristic is particularly important from both fundamental and applied perspectives, as density represents one of the most critical operational parameters for ensuring adequate wellbore pressure control and preventing undesirable phenomena such as formation fluid influx (kicks) or wellbore collapse due to insufficient overbalance pressure. The maintenance of consistent density values across all formulations assures that the hydrostatic pressure column exerted by the drilling fluid remains predictable and controllable, which is essential for safe drilling operations. The minimal variation observed across all experimental formulations, encompassing samples with Aloe Vera alone, SNPs alone, and combinations thereof, provides a clear indication that both Aloe Vera and silica nanoparticles function primarily as rheology-modifying and filtration-control agents rather than serving as weighting materials or barite substitutes in the traditional sense of density enhancement additives.

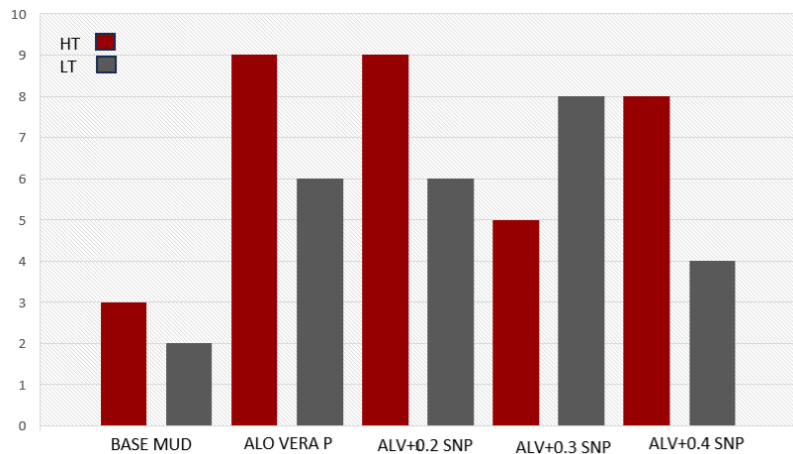
The mechanistic interpretation of these findings suggests that the additives exert their beneficial effects through mechanisms related to particle interaction, polymer network formation, surface chemistry modification, and pore-blocking phenomena rather than through simple mass contribution to the system. Their inclusion in the drilling mud formulation does not compromise the mud's fundamental capacity to generate sufficient hydrostatic pressure for effective wellbore stabilization, nor does it necessitate compensatory adjustments to the concentrations of conventional weighting agents such as barite or hematite to maintain the desired density specifications.

This characteristic is advantageous from a formulation optimization standpoint, as it allows for independent manipulation of rheological and filtration properties without necessitating concurrent density adjustments that might complicate the overall mud engineering process.

Overall, these comprehensive findings confirm with high confidence that both Aloe Vera powder and silica nanoparticles can be safely and effectively integrated into water-based drilling mud systems without adversely affecting the density parameter, thereby preserving one of the essential functional requirements of effective drilling fluid design while simultaneously enabling enhancement of other performance characteristics through their specialized functional contributions to the system.

### 3.2. Plastic viscosity (PV)

In **Figure 1**, both lower-temperature (LT) and higher-temperature (HT) conditions showed noticeable increases in plastic viscosity (PV) across all treated samples when compared with the base mud, which recorded a PV of 2 cP. The introduction of Aloe Vera alone produced a significant rise in PV, reaching 5 cP under LT conditions and 9 cP under HT conditions. This indicates that Aloe Vera enhances the internal resistance of the mud by contributing naturally derived polysaccharides and fibrous components that thicken the fluid and improve particle suspension. The more pronounced increase at higher temperatures suggests that Aloe Vera's biopolymeric structure becomes more reactive or expands under heat, thereby strengthening its viscosity-building capability [3].

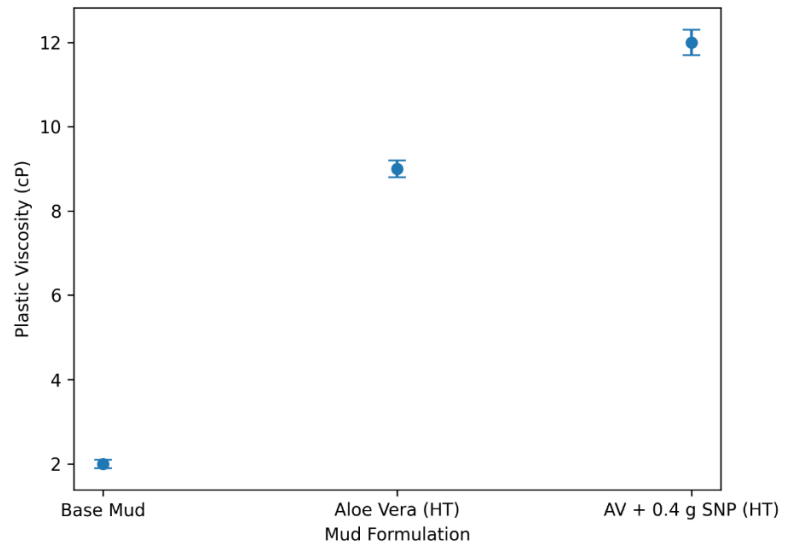


**Figure 1.** Plastic viscosity results for Aloe Vera and SNP.

When silica nanoparticles (SNPs) were incorporated alongside Aloe Vera, PV values increased further, demonstrating a synergistic interaction between the biopolymer and the nanoparticles. SNPs contribute a high specific surface area and active surface charges, which promote stronger particle interactions within the mud. As the SNP concentration increased from 0.2 g to 0.4 g, PV rose gradually at both temperature conditions. In LT settings, PV values ranged from 6 to 8 cP, while in HT conditions, PV increased from 9 to 12 cP. This consistent upward trend reflects the combined effect of Aloe Vera and SNPs in enhancing solids dispersion and reinforcing the fluid's internal structure.

Overall, the results indicate that Aloe Vera and SNPs effectively improve PV

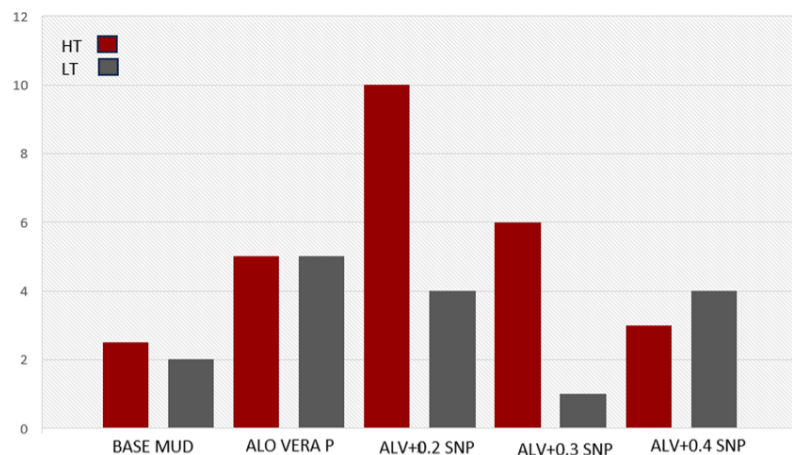
under both LT and HT conditions. Their combined application yields a more thermally responsive and rheologically stable drilling mud, suitable for enhanced performance in varying downhole environments in **Figure 2**.



**Figure 2.** Plastic viscosity with standard deviation.

### 3.3. Yield point (YP)

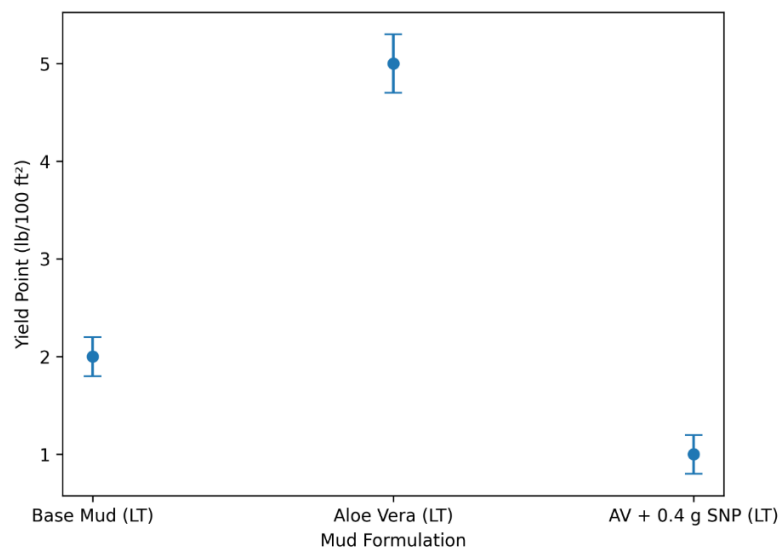
In **Figure 3**, under LT conditions, the base mud exhibited a yield point of 2, serving as the initial reference point for evaluating the effects of Aloe Vera powder and SNP additions. After Aloe Vera was incorporated, the yield point increased noticeably to 5, indicating that the biopolymer contributed to strengthening the mud's internal structure and enhancing its ability to carry and suspend solids. However, when SNPs were introduced in combination with Aloe Vera, a different trend emerged. All three SNP concentrations (0.2 g, 0.3 g, and 0.4 g) led to a decrease in yield point compared to the Aloe Vera-only sample, with values varying from 4 to 1. The peak SNP content (0.4 g) produced the most pronounced reduction, suggesting that higher nanoparticle loading may interfere with or dilute the structuring effect originally provided by Aloe Vera under LT conditions in **Figure 3** [3].



**Figure 3.** Yield point values for Aloe Vera and SNP.

Under HT conditions, the behavior of the mud changed significantly. The base

mud had a yield point of 19, which is very high compared to the LT value and reflects the increased interaction among mud components at elevated temperature. The presence of Aloe Vera caused a pronounced reduction in yield point, bringing it down to 5, demonstrating its strong thinning effect under HT conditions. Additionally, all SNP concentrations also caused a further fall in the yield point relative to the Aloe Vera-only sample, with values varying from 3 to 10. This indicates that SNPs consistently reduce the yield point under HT conditions as well, reinforcing the observation that the nanoparticles weaken the structural network formed by Aloe Vera at elevated temperatures in **Figure 4**.

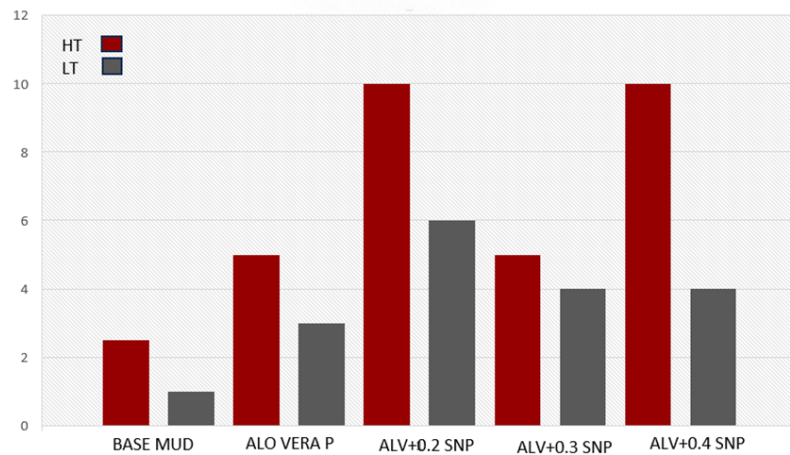


**Figure 4.** Yield point with standard deviation.

### 3.4. Gel strength (10 s and 10 min)

The high-temperature (HT) and low-temperature (LT) experimental conditions both demonstrated a measurable and consistent increase in gel strength parameters when compared to the base mud formulation, providing compelling evidence that the incorporated additives contributed substantively to improved structural behavior and time-dependent thixotropic characteristics of the drilling fluid system. These enhancements in gel strength are indicative of the development of more robust three-dimensional particle networks capable of resisting gravitational settling and maintaining suspension stability during periods of static or low-shear conditions.

Under the low-temperature standard condition, the incorporation of Aloe Vera powder produced a clear and statistically significant enhancement in gel strength at both the initial 10-second measurement interval and the extended 10-minute measurement interval, elevating the recorded values to 3 units and 4 units, respectively. These progressive increases in gel strength values demonstrate that Aloe Vera facilitates the development of a stronger internal colloidal network structure possessing enhanced capacity for suspending drill cuttings and weighting materials during static periods between circulation cycles. The mechanism underlying this enhancement likely involves the interaction of polysaccharide chains present in Aloe Vera with clay particles, creating bridging networks and hydrogen bonding associations that contribute to improved structural integrity in **Figure 5**.



**Figure 5.** Gel Strength 10 s.

When silica nanoparticles were subsequently added to the Aloe Vera-containing formulations, their influence under low-temperature conditions manifested as a complex dual effect characterized by divergent behaviors across different time scales of measurement. For the 10-minute gel strength parameter, which represents the longer-term structural development capacity of the drilling fluid, higher SNP concentration levels generally resulted in correspondingly higher measured values. This trend suggests that nanoparticles effectively supported and enhanced longer-term structural buildup through mechanisms potentially involving particle bridging, pore space filling, and enhanced interparticle attractive forces that stabilize the gel network over extended static periods.

In marked contrast, at the immediate 10-second measurement interval, all tested SNP concentrations caused a notable reduction in gel strength values compared to the Aloe Vera-only sample formulation. This observation indicates that silica nanoparticles may temporarily disrupt the immediate, short-term gel structure formation processes, possibly through interference with initial clay particle edge-to-face associations or through modification of the electrostatic environment surrounding suspended particles. This disruption effect, however, appears to be transient in nature, as the nanoparticles subsequently contribute to strengthening the gel structure over longer equilibration periods, suggesting a time-dependent reorganization of the particle network architecture [3].

In **Figures 5** and **6**, under high-temperature conditions, both Aloe Vera and silica nanoparticles produced consistently higher gel strength values at both the 10-s and 10-min measurement intervals across all formulated samples when compared to the baseline mud system. This consistent increase across all thermal treatment conditions suggests that elevated temperatures may enhance the physicochemical interactions occurring between Aloe Vera polysaccharides, silica nanoparticles, and the mud solids matrix, resulting in the formation of a more robust and thermally stabilized structural framework. Among the various SNP concentration levels evaluated in this investigation, the 0.2 g loading level resulted in the most substantial increase in 10-min gel strength, achieving a maximum value of 20 units. This finding indicates that lower SNP loading concentrations can be particularly effective in promoting optimal

long-term gel structure development under high-temperature conditions, possibly due to more favorable particle dispersion characteristics and reduced agglomeration tendencies at these moderate nanoparticle concentrations.

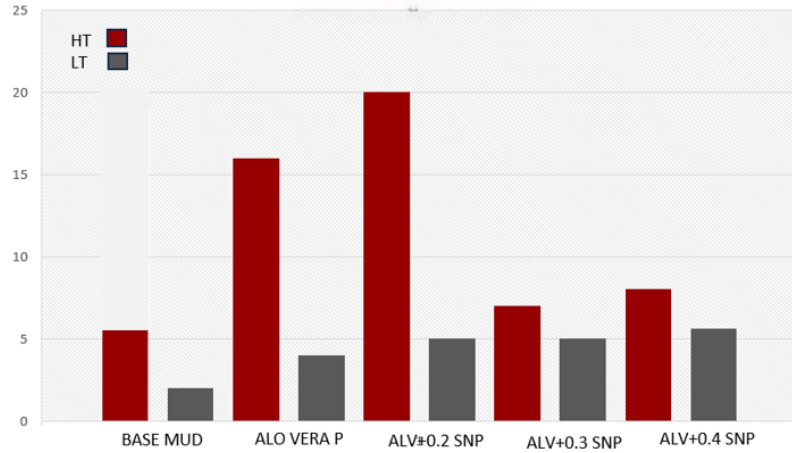


Figure 6. Gel Strength 10 m.

### 3.5. Filtrate loss mud cake thickness

Compared to the base mud filtrate loss of 10 mL, all samples formulated with Aloe Vera demonstrated a significant reduction in fluid loss, confirming the strong fluid-loss-control capability of the additive. Under LT conditions, the filtrate loss of the Aloe Vera-treated sample was reduced dramatically to 0.336 mL, showing a substantial improvement in filtration performance [14]. In addition to this, the inclusion of SNPs with Aloe Vera led to further decreases in filtrate loss under both LT and HT conditions. This consistent trend illustrates that the interaction between Aloe Vera and SNPs enhances the mud’s ability to form a tighter, less permeable filter cake [15]. However, greater levels of SNP concentration did not always result in a consistent benefit, indicating that filtration performance depends not only on concentration but also on the balance between nanoparticles and the biopolymer matrix. At certain ranges, excessive SNP loading may alter the structure of the mud or interfere with the uniformity of the formed filter cake, which can explain why increasing concentration does not necessarily provide linear improvement in Figure 7 [16].

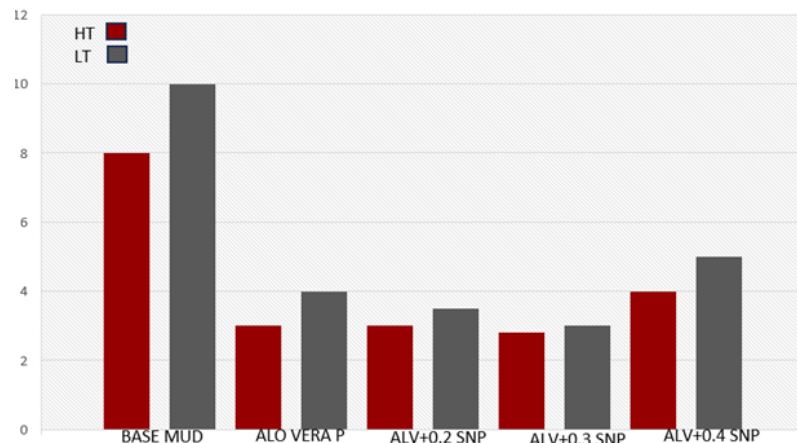
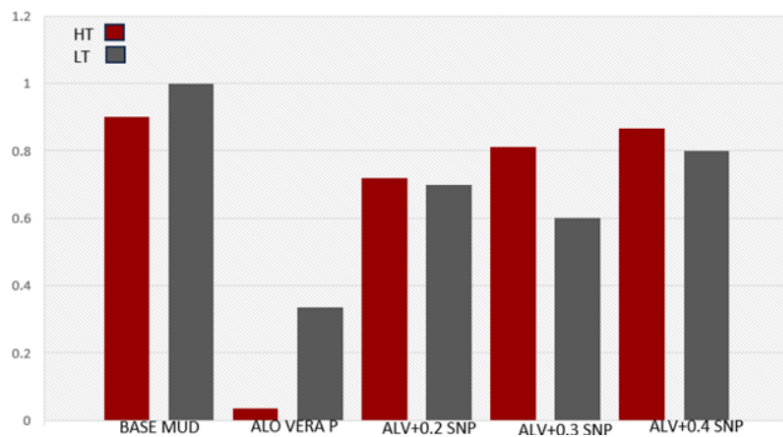


Figure 7. Filtrate Loss for Aloe Vera and SNP.

The mud cake thickness, which is directly influenced by filtrate loss, also showed considerable reductions in most treated samples when compared to the base mud. The base mud exhibited mud cake thicknesses of 1.78 mm under LT conditions and 1.50 mm under HT conditions. The samples containing Aloe Vera generally produced thinner cakes, demonstrating the biopolymer's effectiveness in forming compact layers that restrict fluid movement. However, at LT conditions, the highest SNP concentration (0.4 g) resulted in a mud cake thickness of 2 mm, which is significantly thicker than that produced by Aloe Vera alone (1.3 mm). This suggests that at LT, higher nanoparticle loading may create a denser but slightly bulkier filter cake, possibly due to particle aggregation or uneven distribution at lower temperatures. Such a response emphasizes the complex nature of nanoparticle interactions within the fluid and the possibility that performance can vary depending on thermal conditions in **Figure 8**.

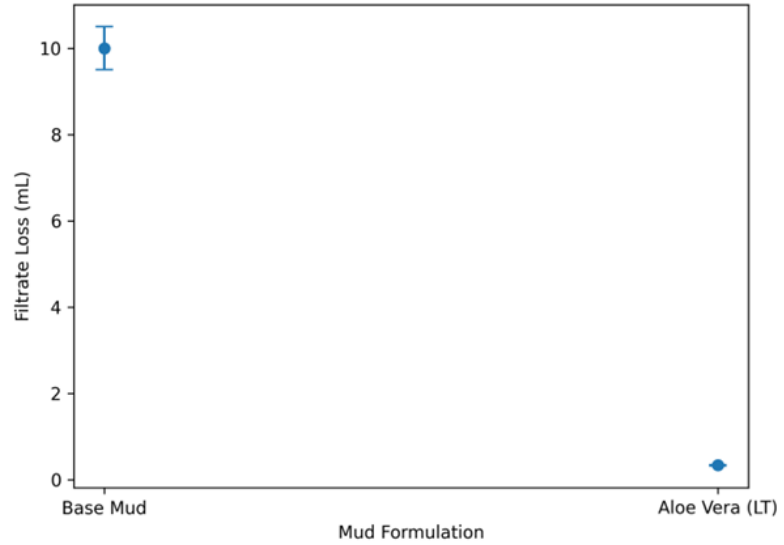


**Figure 8.** Mud cake thickness for Aloe Vera and SNP.

Despite this observation under LT conditions, all SNP concentrations combined with Aloe Vera under HT conditions produced mud cakes thinner than those formed by Aloe Vera alone. This demonstrates improved thermal stability and suggests notable advantages for long-term performance in high-temperature environments.

The enhanced behavior under HT conditions may be attributed to the greater dispersion and activation of SNPs when exposed to elevated temperatures, allowing them to integrate more efficiently into the filter cake structure. Among the tested concentrations, the 0.4 g SNP level produced the thinnest mud cake of only 0.15 mm, which is a highly desirable outcome. This exceptionally thin filter cake indicates a strong potential for maintaining good hydrocarbon flow and minimizing formation damage, as thinner cakes typically reduce frictional resistance and keep the wellbore surface cleaner (**Figure 8**).

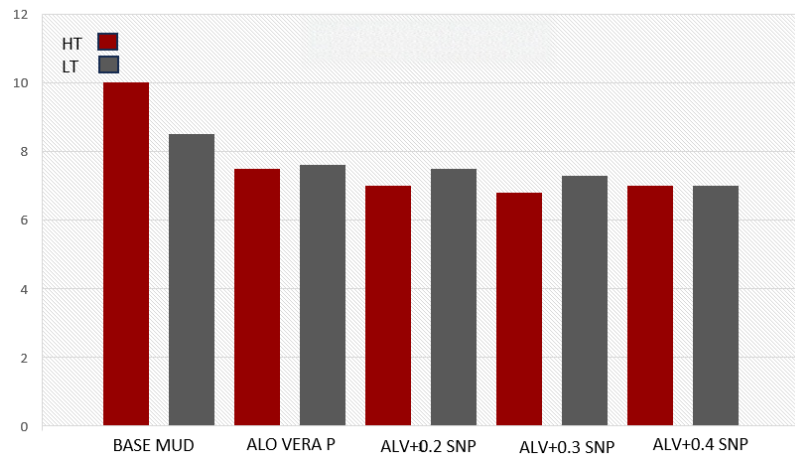
Overall, the results clearly show that Aloe Vera significantly enhances filtration control, and the addition of SNPs can further improve performance depending on their concentration and the temperature conditions. The promising outcomes under HT conditions highlight the potential value of these environmentally friendly additives for drilling operations that require high stability and efficient fluid-loss management in **Figure 9** [3].



**Figure 9.** Filtrate Loss with standard deviation.

### 3.6. PH

The pH values observed across both low-temperature (LT) and high-temperature (HT) experimental conditions in all tested samples containing aloe vera powder demonstrated a consistent trend of reduction when compared to the baseline mud system, which exhibited an initial pH of 9. This systematic decrease in pH levels represents a significant finding in understanding the chemical interactions between aloe vera powder and the mud matrix under varying thermal conditions in **Figure 10**.



**Figure 10.** PH values for Aloe Vera and SNP.

In the low-temperature experimental regime, the incorporation of aloe vera powder as an isolated additive resulted in a marked reduction of the pH level to 7.60. This substantial decrease from the baseline value of 9 to 7.60 indicates that aloe vera powder possesses inherent acidic properties or chemical constituents that actively modify the alkaline nature of the base mud system. The magnitude of this pH reduction suggests that aloe vera powder introduces organic acids or other pH-modulating compounds into the mud matrix, thereby shifting the hydrogen ion concentration toward a more neutral range.

The following experimental phase involved the systematic addition of silica

nanoparticles (SNPs) to each sample containing aloe vera powder, intending to investigate their synergistic or antagonistic influence on pH levels under low-temperature conditions. It is particularly noteworthy that the progressive increase in SNP concentration resulted in a continued decrease in pH values when compared to samples containing aloe vera powder exclusively. Specifically, when SNP concentrations were elevated to 0.2 g and 0.3 g, respectively, the corresponding pH measurements decreased to 7.50 and 7.30. This progressive reduction in pH with increasing nanoparticle concentration suggests a dose-dependent relationship between SNP content and the acidification of the mud system. The mechanism underlying this phenomenon may involve surface chemistry modifications, enhanced ion exchange processes, or the introduction of additional reactive sites that facilitate proton generation or buffering capacity alterations within the composite system as shown in **Figure 10**.

Under high-temperature experimental conditions, aloe vera powder maintained its pH-reducing capability, albeit with different quantitative characteristics compared to the low-temperature regime [17]. When introduced as a sole additive under elevated thermal conditions, aloe vera powder decreased the pH to 8.6 relative to the base mud system's pH of 9. This reduction, while less pronounced than that observed under low-temperature conditions, nevertheless confirms the thermal stability of aloe vera's pH-modulating properties across the investigated temperature range.

Following the establishment of this baseline behavior under high-temperature conditions, the subsequent addition of SNPs to the aloe vera-containing samples yielded a similar trend of pH reduction with increasing nanoparticle concentration. This consistency in behavior across different thermal regimes suggests that the chemical interactions between SNPs, aloe vera powder, and the mud matrix follow predictable patterns that are relatively insensitive to temperature variations within the investigated range. The maximum concentration of SNPs, set at 0.4 g, produced the most substantial pH reduction, achieving a minimum pH value of 6.8 under high-temperature conditions.

This lowest recorded pH value of 6.8 represents a deviation of 2.2 pH units from the baseline mud system, indicating a significant shift toward acidic conditions. The achievement of this minimum pH at the highest SNP concentration reinforces the dose-dependent relationship observed throughout the experimental series and suggests that further increases in nanoparticle loading might produce additional pH modifications, subject to solubility limits and potential saturation effects within the mud matrix system [3].

## 4. Discussion

### **Environmental impact and sustainability of aloe vera powder and silica nanoparticles (SNPs) into water-based drilling fluids**

The integration of Aloe Vera powder and silica nanoparticles (SNPs) into water-based drilling fluids presents a significant opportunity to enhance the environmental sustainability of drilling operations. Conventional drilling fluid additives often involve synthetic chemicals or non-renewable materials such as barite and oil-based components, which can lead to environmental concerns, including

groundwater contamination, toxicity to marine ecosystems, and complex disposal processes. In contrast, Aloe Vera is a biodegradable, plant-based substance rich in polysaccharides and natural compounds, making it an environmentally benign additive. It is renewable, readily available, and does not introduce harmful residues into the environment.

Silica nanoparticles, although synthetically produced, are considered to have low toxicity and are often used in environmentally sensitive applications due to their inert nature and high surface area, which enhances performance with minimal dosage. The combination of Aloe Vera and SNPs allows for reduced reliance on traditional chemical additives, leading to lower ecological footprints during formulation, application, and post-use disposal. Moreover, the natural acidity of Aloe Vera contributes to pH control, reducing the need for additional chemical pH modifiers.

The environmental advantages are especially important for offshore drilling and environmentally protected zones, where regulations strictly limit the discharge of harmful substances. By demonstrating comparable or superior performance in filtration control and rheology, Aloe Vera-SNP-based mud systems offer a sustainable alternative aligned with industry trends toward greener technologies. This supports global efforts to reduce carbon emissions, minimize hazardous waste, and ensure safer drilling operations.

## 5. Conclusion

This comprehensive investigation has successfully confirmed that the incorporation of Aloe Vera powder and silica nanoparticles (SNPs) as functional additives contributes significantly to enhancing both the environmental sustainability profile and the operational performance characteristics of water-based drilling mud (WBM) systems. The findings collectively demonstrate that these naturally-derived and engineered nanoscale materials offer viable pathways for improving drilling fluid properties while simultaneously addressing growing industry concerns regarding environmental impact, ecological footprint reduction, and the transition toward more sustainable drilling practices that minimize reliance on synthetic chemicals and potentially hazardous conventional additives.

The experimental results provide substantial evidence that silica nanoparticles exerted particularly pronounced improvements in the rheological properties of the treated drilling mud formulations, manifesting as enhanced viscosity profiles [18]. Optimized yield point characteristics, and improved gel strength development that collectively contribute to superior hole cleaning efficiency and cuttings transport capacity [19]. Furthermore, SNPs demonstrated remarkable effectiveness in enhancing filtration control efficiency, as evidenced by measurable reductions in mud cake thickness and improved fluid loss control characteristics. These beneficial effects were especially prominent and statistically significant at the intermediate and higher concentration levels, specifically at 0.3 g and 0.4 g of nanoparticle loading per standard mud volume. At these optimized concentration ranges, the nanoparticles appeared to achieve sufficient dispersion and surface area coverage within the mud matrix to effectively modify pore throat sizes in filter cakes, enhance particle packing efficiency,

and create more impermeable barriers against fluid invasion into permeable formations.

The mechanism underlying these improvements can be attributed to the unique physicochemical properties inherent to nanoscale materials, including their exceptionally high surface area-to-volume ratios, enhanced surface reactivity, and their capacity to occupy interstitial spaces between larger particles within the mud cake structure. These characteristics enable SNPs to function as highly efficient plugging agents that seal micro-fractures and pore spaces more effectively than conventional-sized particles, thereby reducing filtrate loss and minimizing formation damage potential. Additionally, the interaction between silica nanoparticles and clay platelets within the mud system likely contributes to the observed rheological enhancements through mechanisms involving edge-to-face association, hydrogen bonding networks, and the modification of electrical double-layer characteristics surrounding suspended particles.

However, despite these encouraging performance improvements observed under ambient and controlled laboratory conditions, the investigation revealed that thermal stability represents a persistent and significant challenge that requires further attention and resolution. Following exposure to elevated temperature conditions through hot-rolling procedures designed to simulate downhole thermal environments, the treated mud formulations exhibited varying degrees of property degradation, indicating that the structural integrity and functional effectiveness of both Aloe Vera and SNP additives may be compromised under extended thermal stress. This thermal instability manifests as changes in viscosity parameters, alterations in gel strength development patterns, and potential modifications to filtration control efficiency, all of which could adversely affect drilling fluid performance during actual field operations in high-temperature wellbore environments.

The observed thermal stability limitations may be attributed to several interconnected factors, including the thermal degradation of organic components within Aloe Vera powder, potential agglomeration or sintering of silica nanoparticles at elevated temperatures, disruption of hydrogen bonding networks that contribute to rheological structure, and possible chemical reactions or phase transformations that occur within the complex multi-component drilling fluid system under thermal stress. These thermal effects represent critical considerations for practical field applications, particularly in deep drilling operations where bottomhole temperatures may exceed 150 °C and where drilling fluids must maintain consistent performance properties throughout extended circulation periods [20].

Consequently, further optimization efforts are strongly recommended to establish an appropriate balance between enhanced performance characteristics and long-term thermal stability requirements [21]. Future research directions should encompass investigations into thermal stabilization strategies, such as the incorporation of high-temperature polymers, the use of cross-linking agents to enhance network stability, surface modification of nanoparticles to prevent agglomeration, and the development of hybrid additive systems that combine the beneficial properties of multiple materials while compensating for individual limitations [22]. Additionally, systematic studies examining the effects of varied hot-rolling durations, different temperature profiles,

and aging conditions would provide valuable insights into the degradation mechanisms and enable the formulation of more thermally robust drilling fluid systems suitable for demanding operational environments [23].

**Author contributions:** Conceptualization, AE and AS; methodology, AE; software, AE; validation, AE and AS; formal analysis, AS; investigation, AE; resources, AE; data curation, AE; writing—original draft preparation, AE; writing—review and editing, AS; visualization, AE; supervision, AS; project administration, AE; funding acquisition, AS. Both authors have read and agreed to the published version of the manuscript.

**Funding:** The authors declare that they have received no financial or non-financial support that could be considered a source of competing interest in relation to this research.

**Institutional review board statement:** Not applicable.

**Informed consent statement:** Not applicable.

**Data availability statement:** The data used in this study are available from the corresponding author upon reasonable request.

**Conflict of interest:** The authors declare no conflict of interest.

## References

1. Elhederi A, Zoveidavianpoor M. Evaluating eggshells as sustainable weighting agents in water-based drilling muds: A novel approach for enhanced efficiency and environmental consciousness. *Materials Technology Reports*. 2024; 2(1): 1721.
2. Amanullah M, Long L. Environmentally friendly fluid loss additives to protect the marine environment from the detrimental effect of mud additives. *Journal of Petroleum Science and Engineering*. 2005; 48(3–4): 199–208.
3. Bagum M. Development of an Environmentally Safe Additive with Natural Material for Drilling Fluid Application [PhD thesis]. Memorial University of Newfoundland; 2018.
4. Wojtanowicz, AK. Environmental control of drilling fluids and produced water. In *Environmental Technology in the Oil Industry*. Springer International Publishing; 2016. pp. 101–165.
5. Al-Hameedi ATT, Alkinani HH, Dunn-Norman S, et al. Insights into the application of new eco-friendly drilling fluid additive to improve the fluid properties in water-based drilling fluid systems. *Journal of Petroleum Science and Engineering*. 2019; 183: 106424.
6. Hossain ME, Al-Majed A. *Fundamentals of Sustainable Drilling Engineering*. John Wiley & Sons; 2015.
7. Alshubbar G, Coryell J, Atashnezhad A, et al. The effect of barite nanoparticles on the friction coefficient and rheology of water-based mud. In: *Proceedings of the ARMA USA Rock Mechanics/Geomechanics Symposium*; 25–28 June 2017; San Francisco, CA, USA.
8. Ikram R, Mohamed Jan B, Sidek A, et al. Utilization of Eco-Friendly Waste Generated Nanomaterials in Water-Based Drilling Fluids; State of the Art Review. *Materials*. 2021; 14(15), 4171.
9. Hossain ME, Wajheeuddin M. The use of grass as an environmentally friendly additive in water-based drilling fluids. *Petroleum Science*. 2016; 13(2), 292–303.
10. Asad MS, Jaafar MT, Rashid FL, et al. Sustainable drilling fluids: A review of nano-additives for improved performance and reduced environmental impact. *Processes*. 2024; 12(10): 2180.
11. Fink J. *Petroleum Engineer's Guide to Oil Field Chemicals and Fluids*. Elsevier; 2012.
12. Samavati R. Use of Cassava Derivative in Water Based Drilling Mud [PhD thesis]. Universiti Putra Malaysia; 2016.
13. Abdou MI, Alsabagh AM, Aboulrous AA, et al. *Application of Natural Polymers in Engineering*. Egyptian Petroleum Research Institute; 2015.

14. Zoveidavianpoor M, Samsuri A. The use of nano-sized Tapioca starch as a natural water-soluble polymer for filtration control in water-based drilling muds. *Journal of Natural Gas Science and Engineering*. 2016; 34: 832–840.
15. Ghosh B, AlCheikh IM, Ghosh G, et al. Development of hybrid drilling fluid and enzyme–acid precursor-based clean-up fluid for wells drilled with calcium carbonate-based drilling fluids. *ACS Omega*. 2020; 5(40): 25984–25992.
16. Anyanwu C, Mustapha Unubi M. Experimental evaluation of particle sizing in drilling fluid to minimize filtrate losses and formation damage. In: *Proceedings of the SPE Nigeria Annual International Conference and Exhibition*; 2–4 August 2016; Lagos, Nigeria.
17. Amani M, Al-Jubouri M, Shadravan A. Comparative Study of Using Oil-Based Mud versus Water-Based Mud in HPHT Fields. *Advances in Petroleum Exploration and Development*. 2012; 4(2): 18–27.
18. Wang L. Preparation and application of viscosifier for environmentally friendly oil-based drilling fluid. *Chemistry and Technology of Fuels and Oils*. 2015; 51(5): 539–544.
19. Wang S, Shu Z, Chen L, et al. Low temperature green nano-composite vegetable-gum drilling fluid. *Applied Nanoscience*. 2019; 9(7): 1579–1591.
20. ASME Shale Shaker Committee. *Drilling Fluids Processing Handbook*. Elsevier; 2011.
21. Al-Hameedi A, Alkinani H, Dunn-Norman S. Development of high-performance water-based drilling fluid using biodegradable eco-friendly additive (Peanut Shells). *International Journal of Environmental Science and Technology*. 2021; 19(6): 4959–4970.
22. Agbonifo P. Risk Management and Regulatory Failure in the Oil and Gas Industry in Nigeria: Reflections on the Impact of Environmental Degradation in the Niger Delta Region. *Journal of Sustainable Development*. 2016; 9: 126–131.
23. Waychal Y, Gawas S, Barage SH. Bioremediation of Petroleum-Contaminated Soil. In: *Advances in Bioremediation and Phytoremediation for Sustainable Soil Management: Principles, Monitoring and Remediation*. Springer International Publishing; 2022. pp. 157–170.