Materials Technology Reports 2026, 4(1), 3999.
doi: https://doi.org/10.59400/mtr3999

Article

Investigating the effects of wood ash as an alkaline additive and deflocculant in water-based mud

Abdelaziz Belmahdi[1], **Anas Elhederi**[2,*]

[1] Prudence Dimensions, Riyadh 133313, Saudi Arabia

[2] Faculty of Mining and Energy Engineering, Polytechnic University of Madrid, 28003 Madrid, Spain

*** Corresponding author:** Anas Elhederi, anaselhoderi@gmail.com

CITATION

Belmahdi A, Elhederi A. Investigating the effects of wood ash as an alkaline additive and deflocculant in water-based mud. Materials Technology Reports. 2026; 4(1): 3999. https://doi.org/10.59400/mtr3999

ARTICLE INFO

Received: 5 February 2025
Revised: 19 March 2026
Accepted: 23 March 2026
Available online: 8 April 2026

Abstract: The environmental impact of chemical additives used in drilling fluids has increased interest in sustainable alternatives. Wood ash, a byproduct of biomass combustion, represents a potential alkaline and rheological modifier for water-based drilling mud systems. This study investigates the performance of wood ash (45–75 µm) at concentrations of 2–8 wt% in bentonite-based water-based mud under both ambient and thermal (hot rolling) conditions. Results demonstrated a clear concentration-dependent response. Plastic viscosity and gel strength decreased progressively up to 6 wt%, indicating improved dispersion and reduced structural buildup. At 8 wt%, partial reversal of this trend was observed, suggesting excessive solids loading may counteract dispersion effects. Yield point values decreased from 6 to 3 lb/100 ft^2 as concentration increased, confirming enhanced flowability. Wood ash effectively increased mud pH into the desired operational range (9–11) under ambient conditions, while higher concentrations under thermal aging approached the upper alkaline limit. Mud density remained stable (~8.7 lb/gal) across all concentrations, confirming that wood ash does not adversely affect hydrostatic pressure control. Thermal aging generally reduced rheological parameters due to structural weakening of the bentonite network, although moderate concentrations maintained relatively stable performance. The findings indicate that 4–6 wt% wood ash provides an optimal balance between rheological control and alkalinity enhancement. While promising as a sustainable additive, further investigation is required to evaluate extended filtration performance and compositional variability under field conditions.

Keywords: wood ash; drilling fluids; water-based mud; environmental sustainability; green additives

1. Introduction

Drilling fluids, commonly referred to as drilling muds, play a fundamental role in oil and gas operations. They are essential for maintaining wellbore stability, controlling formation pressures, transporting drill cuttings to the surface, cooling and lubricating the drill bit, and minimizing formation damage. Among the various types of drilling fluids, water-based muds (WBMs) are widely used due to their cost-effectiveness, operational simplicity, and comparatively lower environmental impact relative to oil-based or synthetic-based systems [1].

Despite these advantages, conventional WBMs frequently rely on chemical additives that may pose environmental concerns, particularly during disposal and large-scale operations. With increasingly stringent environmental regulations, the industry is under growing pressure to adopt more sustainable drilling fluid formulations. As a result, research efforts have focused on biodegradable and naturally derived materials capable of maintaining or enhancing drilling performance while reducing environmental risk [2].

Drilling fluid properties significantly influence overall well performance and cost efficiency. Although drilling fluid expenses represent a relatively small fraction of total well costs, improper fluid design can lead to borehole instability, stuck pipe, excessive fluid loss, and reduced penetration rate, ultimately increasing operational time and expenses [1]. Achieving appropriate rheological properties and forming a thin, stable mud cake are therefore critical objectives in WBM formulation. The mud cake formed along the borehole wall acts as a barrier that minimizes fluid invasion into permeable formations; however, excessive cake thickness may increase the risk of differential sticking and associated operational complications [3].

Wood ash is a byproduct of biomass combustion whose physical and chemical properties depend on wood type, combustion temperature, and duration [4]. Hardwoods generally produce ash with higher calcium, magnesium, and potassium contents than softwoods [5]. The outer components of the tree, such as bark and leaves, typically generate higher ash yield than inner woody portions. Reported ash yield from wood combustion ranges between 6–10% [6]. Combustion temperature also significantly affects ash characteristics; increasing temperature has been shown to reduce ash yield and alter chemical composition [7]. Additionally, reported pH values of wood ash range between 9 and 13.5, reflecting its strongly alkaline nature [8].

In recent years, eco-friendly drilling fluid additives derived from biomass and agricultural residues have attracted increasing attention [9]. Materials such as rice husk ash, fly ash, nano-additives, and lignocellulosic fibers have been investigated primarily for filtration control and general rheological enhancement [10,11]. In addition to performance considerations, the transition toward environmentally responsible drilling fluids is closely linked to broader sustainability concepts such as waste valorization and circular economy principles. The reuse of industrial by-products, including biomass-derived materials, provides an opportunity to reduce reliance on conventional chemical additives while minimizing the environmental burden associated with waste disposal. Wood ash, as a readily available byproduct of biomass combustion, represents a potential low-cost and sustainable alternative that can be integrated into drilling fluid systems. Its utilization not only contributes to reducing landfill accumulation but also supports resource efficiency by converting waste into a functional engineering material. Therefore, evaluating such materials within drilling applications is essential for developing environmentally compatible and economically viable fluid systems [12, 13]. However, many of these studies focused on basic performance evaluation without systematically examining concentration-dependent threshold behavior or deflocculation mechanisms in bentonite-based systems [14,15].

2. Experiment

Drilling mud samples were prepared following API RP 13B-1 standards. Base mud comprised deionized water and bentonite. Five samples of bentonite-based water-based mud were formulated by adding 14 g of bentonite to 350 mL of deionized water. The mixture was then mixed in the mud mixer for 15 min to ensure thorough mixing. One of the samples served as the control sample [1]. After the bentonite-based water-based mud was mixed, (2%, 4%, 6%, 8%) by weight of wood ash was added to each sample, respectively. The mixture was then mixed with a mud mixer for 20 min to ensure thorough mixing of the mud samples (**Table 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
Wood ash	Alkaline	w/w%	15 min
	Deflocculant	2%, 4%, 6%, 8%.	20 min

The wood ash used in this study was sourced in Malaysia and sieved to obtain a particle size range of 45–75 μm prior to mixing. The experimental scope of this study focused on evaluating drilling fluid performance; therefore, no independent chemical or mineralogical characterization (e.g., XRF or XRD analysis) was included.

Rheological measurements were conducted using a standard rotational viscometer in accordance with API recommended practices. The measured dial readings were used to calculate plastic viscosity and yield point based on the Bingham plastic model, which is widely adopted in drilling fluid engineering due to its practical applicability and direct interpretation of viscometer data. The Bingham model provides a simplified representation of drilling fluid behavior and is commonly used for field evaluation and operational decision-making. It is acknowledged that bentonite-based suspensions may exhibit more complex non-Newtonian characteristics that can be described by alternative models such as Herschel–Bulkley, Ostwald–de Waele, Casson, or Shulman models. However, the present study focuses on comparative performance evaluation using standard industry methodology, and therefore, extended rheological modeling was considered beyond the scope of this work.

3. Results

This section presents and analyzes the experimental results obtained from evaluating wood ash as an additive in water-based drilling mud formulations. The analysis focuses on key performance parameters, including mud density, plastic viscosity, apparent viscosity, yield point, gel strength, mud cake thickness, and pH. These parameters were examined under both ambient and hot rolling conditions to assess rheological behavior, filtration characteristics, and thermal stability. Comparative evaluation among different concentration levels was conducted to identify performance trends and determine the optimal additive range.

3.1. Density measurement

The base water-based mud (WBM) formulation exhibited stable and consistent density measurements throughout the experimental evaluation. The addition of wood ash did not significantly alter mud density, which remained approximately 8.7 lb/gal across the tested concentration range (2–8 wt%). This indicates that the selected additive concentrations were insufficient to modify the overall mass-to-volume ratio of the system, and that wood ash primarily influenced rheological properties rather than bulk density characteristics. Similar observations have been reported in studies where low concentrations of solid additives did not significantly affect mud density [7].

After hot rolling, mud density increased slightly to approximately 9 lb/gal. This increase is attributed to partial water loss during thermal exposure rather than a direct effect of wood ash addition. Thermal-induced density changes associated with fluid loss at elevated temperatures have been documented in bentonite-based mud systems [8]. The limited variation in density under both ambient and thermal conditions suggests that wood ash does not compromise density control and may be incorporated without adversely affecting weighting performance.

Importantly, wood ash did not adversely affect mud density across the evaluated concentration range, confirming its compatibility with hydrostatic pressure control requirements (**Figure 1**).

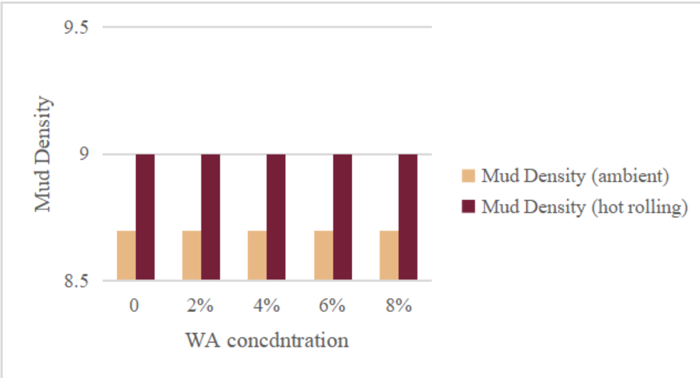

Figure 1. Drilling Mud Density Results.

3.2. Plastic viscosity (PV)

Plastic viscosity decreased progressively with increasing wood ash concentration up to 6% under ambient conditions, followed by a slight increase at 8%. The initial reduction can be attributed to improved dispersion of bentonite particles promoted by the alkaline environment introduced by wood ash, which enhances electrostatic repulsion and reduces interparticle resistance. Similar dispersion-induced reductions in viscosity have been reported in clay-based drilling mud systems under alkaline conditions [16,17].

After hot rolling, a general decrease in plastic viscosity was observed across all samples, reflecting thermal thinning associated with weakening of bentonite structural interactions at elevated temperature. However, the improvement observed at moderate concentrations under ambient conditions was less pronounced after thermal exposure. This diminished benefit at higher concentrations may be associated with increased solid loading and ionic strength effects under elevated temperature, which can partially promote particle association. Temperature-induced rheological reduction in water-based mud systems has been widely documented [17,18].

Despite this overall thermal thinning caused by the hot rolling process, the fundamental relationship between concentration and viscosity remained unchanged; the fluid continued to exhibit the same opposite effects at 8% concentration. Therefore, even though the hot rolling process succeeded in lowering the overall viscosity profile compared to ambient conditions, the 8% addition level persisted in causing a relative increase in viscosity, reinforcing the conclusion that the rheological benefits of wood ash are strictly dose-dependent and that exceeding the optimal range negates the thinning benefits, regardless of the thermal environment, see **Figure 2**.

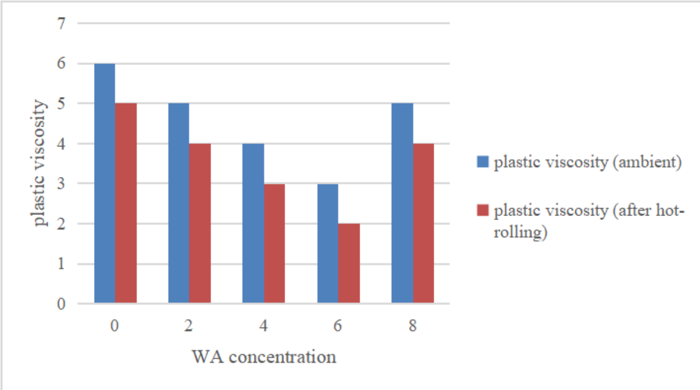

Figure 2. Plastic Viscosity Results.

3.3. Yield point (YP)

Yield point exhibited a concentration-dependent response under ambient conditions, where moderate wood ash additions reduced interparticle attractive forces within the bentonite system, resulting in improved dispersion and controlled yield behavior. This behavior reflects reduced structural resistance between clay platelets under alkaline conditions. Similar reductions in yield strength under alkaline dispersion environments have been reported in water-based mud systems [7, 18].

Following hot rolling, a noticeable reduction in yield point was observed, indicating weakening of the gel structure due to thermal degradation of interparticle interactions. Elevated temperature reduces the strength of the clay network, leading to lower resistance to flow. However, at higher wood ash concentrations, the reduction in performance benefit became less pronounced, which may be attributed to increased solid loading and ionic strength effects under thermal conditions. Temperature-sensitive yield behavior has been documented in bentonite-based drilling fluids [8, 19] (**Figure 3**).

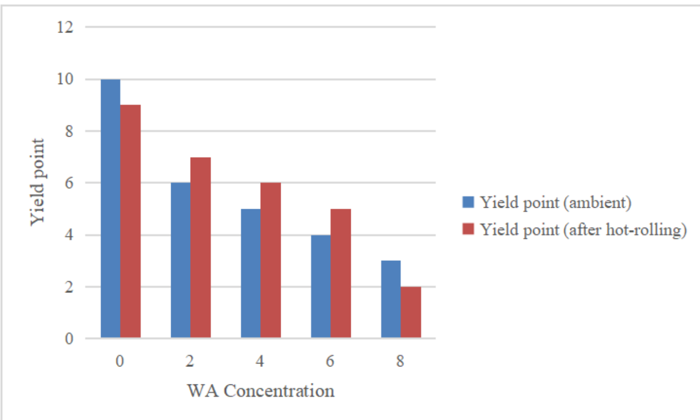

Figure 3. Yield Point vs. WA Concentration.

3.4. Gel strength (10 s and 10 min)

Gel strength measurements (10 s and 10 min) exhibited a concentration-dependent behavior under ambient conditions. Both initial and progressive gel strengths decreased as wood ash concentration increased from 2% to 6%, indicating reduced structural buildup and weaker interparticle association within the bentonite network. This behavior reflects enhanced particle dispersion under alkaline conditions. Similar reductions in gel strength under dispersive environments have been reported in clay-based drilling mud systems [7,20] (**Figure 4**).

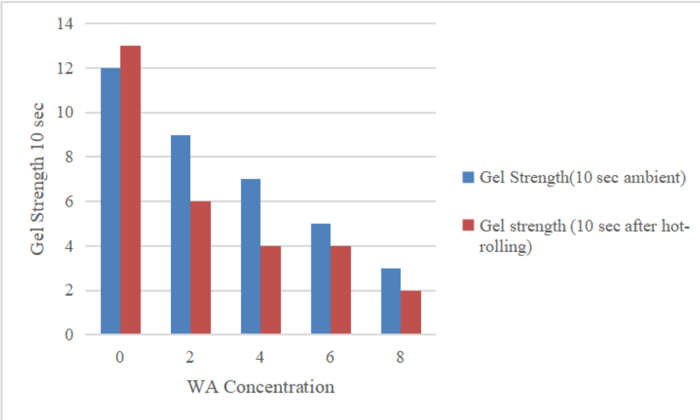

Figure 4. 10 s Gel Strength of Drilling Mud.

However, at 8% concentration, both 10 s and 10 min gel strengths increased, indicating partial structural rebuilding. This reversal suggests that excessive wood ash may introduce increased solid loading and ionic effects that promote particle interaction rather than dispersion.

After hot rolling, gel strength values generally decreased compared to ambient conditions, reflecting thermal weakening of the bentonite structural network. Elevated temperature reduces interparticle bonding and limits the ability of the system to rebuild structure during static periods. Nevertheless, at 8% concentration, the thermal reduction was less pronounced, indicating diminished dispersion efficiency under elevated temperature at high additive loading. Temperature-sensitive gel behavior in bentonite-based systems has been widely documented [8] (**Figure 5**).

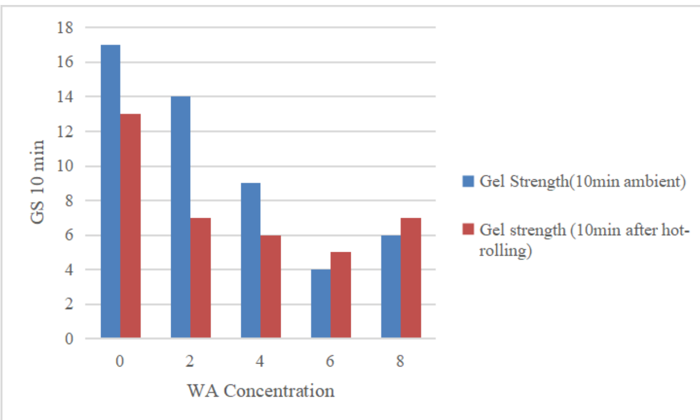

Figure 5. 10 min Gel Strength of Drilling Mud.

3.5. Mud cake thickness

Mud cake thickness decreased at moderate wood ash concentrations (2–6%) under ambient conditions, indicating improved particle packing and enhanced filtration control. The alkaline environment promotes better dispersion of bentonite particles, leading to the formation of a thinner and more compact filter cake. Similar improvements in filtration behavior under dispersive conditions have been reported in water-based drilling fluids [7,21] (**Figure 6**).

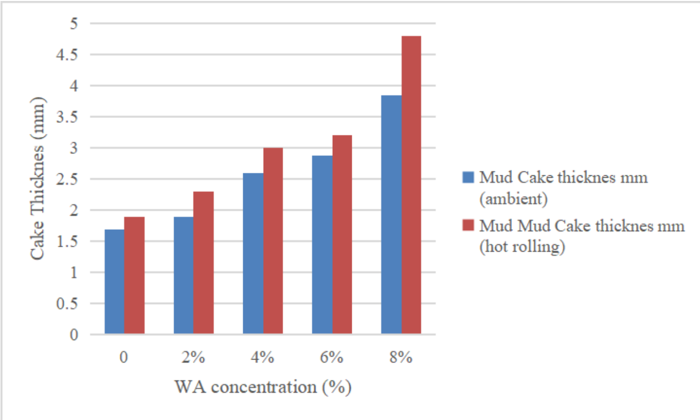

Figure 6. Drilling Mud Cake Thickness.

However, at 8% concentration, mud cake thickness increased, suggesting that excessive solid loading may alter particle arrangement and promote thicker cake formation. While a thinner mud cake is generally desirable for minimizing fluid loss, excessively thick cake can increase the risk of differential sticking during drilling operations. Therefore, an optimal concentration range must balance filtration performance and operational safety.

After hot rolling, variations in mud cake characteristics reflected thermal modification of the bentonite structure. Elevated temperature may alter particle interactions and cake compaction behavior. Although moderate concentrations maintained relatively favorable cake properties under thermal conditions, the performance benefit at higher concentrations was reduced. Temperature-dependent filtration behavior in bentonite-based systems has been widely documented [8].

3.6. PH

Wood ash addition significantly increased the pH of the mud formulations under ambient conditions, showing a clear concentration-dependent trend as wood ash content increased. All treated samples achieved the targeted alkaline operational range, while the control sample remained below this level (**Figure 7**).

At 8% concentration, the highest pH value was recorded (11.7), reflecting increased availability of alkaline constituents. While elevated alkalinity supports mud stability and additive activation, excessively high pH levels may require careful monitoring to avoid over-treatment and potential compatibility issues with other drilling fluid components. Excessively high pH may also accelerate corrosion in susceptible drilling equipment and alter formation mineral interactions, particularly in clay-rich or reactive formations where elevated alkalinity can modify surface chemistry and stability.

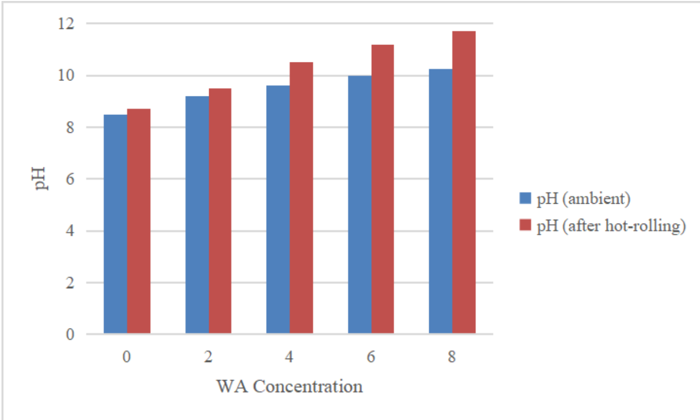

Figure 7. Drilling Mud pH Values.

Following hot rolling, pH values increased further across all samples. This behavior is attributed to enhanced dissolution of alkaline components under elevated temperature and mechanical agitation, promoting greater release of reactive species into the fluid phase.

3.7. Comparison

A comprehensive comparison between ambient and hot rolling conditions demonstrates that thermal exposure significantly influences the rheological and filtration characteristics of the bentonite-based mud system. Under ambient conditions, moderate wood ash concentrations improved dispersion, optimized rheological parameters, and contributed to more favorable mud cake characteristics. However, after hot rolling, a general reduction in rheological stability was observed due to thermal thinning associated with weakening of interparticle forces and partial breakdown of the bentonite structural network at elevated temperature.

Thermal aging modifies clay platelet interactions and reduces the strength of the structured gel network, which explains the observed decreases in plastic viscosity, yield point, and gel strength after hot rolling. Additionally, while moderate wood ash additions retained part of their dispersion-enhancing effect under thermal conditions, higher concentrations exhibited reduced performance benefits. This behavior is attributed to increased solid loading and ionic strength, which become more influential at elevated temperatures and may promote partial particle association.

In terms of filtration behavior, variations in mud cake characteristics under thermal conditions further reflect temperature-induced structural adjustments within the system. These findings collectively highlight the importance of evaluating additive performance under both ambient and thermal environments to ensure operational reliability and minimize wellbore risks during drilling operations.

4. Discussion

Environmental impact and sustainability of wood ash in water-based drilling fluids

The behavior of wood ash observed in the present study can be interpreted in relation to its alkaline nature and reported composition, which typically includes calcium- and potassium-bearing compounds capable of increasing system pH and modifying particle interactions within bentonite-based mud systems [7,8]. The results demonstrate that wood ash effectively elevated pH while influencing rheological and filtration characteristics in a concentration-dependent manner [21].

The increasing regulatory focus on environmentally responsible drilling operations has encouraged the development of alternative additives for water-based mud systems. In this context, the utilization of wood ash, a byproduct of biomass combustion, presents a potential pathway for reducing reliance on conventional synthetic alkaline agents. Traditional additives such as caustic soda are widely used for pH control; however, they require careful handling and may pose environmental and occupational considerations. Wood ash, due to its inherent alkalinity, demonstrated the ability to achieve and maintain the desired pH range required for mud stability in the present study [22].

From a sustainability standpoint, the use of wood ash aligns with resource recovery and waste valorization principles by repurposing an industrial byproduct [23]. This approach may reduce landfill disposal and partially offset the demand for manufactured chemical additives. In addition, the observed improvements in filtration performance at moderate concentrations suggest potential operational benefits that could contribute to reduced fluid loss during drilling [24].

The behavior of wood ash observed in this study can also be interpreted from an electrochemical perspective. The increase in alkalinity enhances the dissociation of clay particles, promoting electrostatic repulsion and reducing particle aggregation at moderate concentrations. However, at higher concentrations, the increase in ionic strength and solid content may compress the electrical double layer surrounding clay particles, reducing repulsive forces and facilitating partial flocculation. This dual effect explains the observed transition from improved dispersion at moderate wood ash loading to rheological reversal at higher concentrations. Such behavior is characteristic of clay-based suspensions subjected to varying ionic environments.

However, the environmental suitability of wood ash-based systems depends on proper sourcing and characterization, as biomass-derived ash may contain trace elements that require monitoring. Therefore, while the present findings support the technical feasibility of wood ash as an alternative additive, comprehensive environmental assessment and compositional control remain essential for field-scale implementation [25].

5. Conclusion

This study evaluated the performance of wood ash as an alkaline additive and rheological modifier in bentonite-based water-based drilling mud systems across a concentration range of 2–8 wt% under both ambient and thermal (hot rolling) conditions.

The results demonstrated a clear concentration-dependent response. Moderate wood ash concentrations (4–6 wt%) provided the most balanced performance, reducing plastic viscosity, yield point, and gel strength while improving mud cake characteristics. These concentrations promoted improved dispersion without compromising structural stability. Importantly, mud density remained stable across all tested concentrations, confirming that wood ash does not adversely affect hydrostatic pressure control within the evaluated range.

At higher concentration (8 wt%), partial reversal of rheological improvements was observed, including increases in gel strength and mud cake thickness, indicating that excessive solids loading may counteract dispersion benefits. Additionally, pH values approached the upper alkaline range at this concentration, suggesting that dosage control is necessary to avoid excessive alkalinity.

Thermal aging through hot rolling generally reduced rheological parameters due to weakening of the bentonite structural network. While moderate concentrations maintained relatively stable performance under thermal conditions, higher additive loading showed diminished benefits.

Despite these promising findings, several limitations must be acknowledged. API filtration loss, permeability assessment, and filter cake friction properties were not evaluated due to equipment limitations during the experimental phase. Furthermore, detailed mineralogical and trace element characterization of wood ash was not conducted, which limits a comprehensive environmental and compositional assessment. The rheological analysis was based on the Bingham model; alternative constitutive models were not examined and may provide additional insight into non-Newtonian behavior.

Future research should therefore include comprehensive filtration testing, permeability and friction evaluation, detailed compositional analysis, application of alternative rheological models, and pilot-scale validation to confirm field applicability and long-term performance.

The observed rheological trends highlight the importance of concentration control when incorporating particulate additives into bentonite-based systems. The transition from dispersion-dominated behavior at moderate concentrations to partial structural rebuilding at higher loading reflects the balance between electrochemical repulsion and increased solids interaction within the fluid. This behavior is consistent with the known sensitivity of clay-based suspensions to ionic strength and particle concentration, particularly under alkaline conditions. Therefore, the effectiveness of wood ash as a functional additive is governed not only by its contribution to alkalinity but also by its influence on interparticle forces and system structure.

Author contributions: Conceptualization, AE and AB; methodology, AB; software, AB; validation, AE and AB; formal analysis, AB; investigation, AB; resources, AE; data curation, AE; writing original draft preparation, AB; writing review and editing, AE; visualization, AE; supervision, AE; project administration, AE; funding acquisition, AE and AB. 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(2): 1721. doi: 10.59400/mtr1721
2. Amanullah M, Yu L. Environment 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. doi: 10.1016/j.petrol.2005.06.013
3. Abdelgawad K, Elkatatny S, Moussa T, et al. Real-Time Determination of Rheological Properties of Spud Drilling Fluids Using a Hybrid Artificial Intelligence Technique. Journal of Energy Resources Technology. 2019; 141(3): 032908. doi: 10.1115/1.4042233
4. Caenn R, Darley HCH, Gray GR. Introduction to Drilling Fluids. In: Composition and Properties of Drilling and Completion Fluids. Elsevier; 2017. pp. 1–34. doi: 10.1016/B978-0-12-804751-4.00001-8
5. Bland R, Jones T, Tibbitts GA. Reducing Drilling Costs by Drilling Faster. In: Proceedings of the SPE Annual Technical Conference and Exhibition; 5 October 1997; San Antonio, TX. doi: 10.2118/38616-MS
6. Siddique R. Waste Materials and By-Products in Concrete. Springer; 2008. doi: 10.1007/978-3-540-74294-4
7. Etiégni L, Campbell AG. Physical and chemical characteristics of wood ash. Bioresource Technology. 1991; 37(2): 173–178. doi: 10.1016/0960-8524(91)90207-Z
8. Siddique R. Utilization of wood ash in concrete manufacturing. Resources, Conservation and Recycling. 2012; 67: 27–33. doi: 10.1016/j.resconrec.2012.07.004
9. Ghasemi K, Akbari A, Jahani S, et al. A critical review of life cycle assessment and environmental impact of the well drilling process. The Canadian Journal of Chemical Engineering. 2025; 103(6): 2499–2526. doi: 10.1002/cjce.25539
10. 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. doi: 10.1016/j.petrol.2019.106424
11. Hossain ME, Al-Majed AA. Fundamentals of Sustainable Drilling Engineering, 1st ed. Wiley; 2015. doi: 10.1002/9781119100300
12. 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.
13. 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. doi: 10.3390/ma14154171
14. 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. doi: 10.1007/s12182-016-0083-8
15. 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. doi: 10.3390/pr12102180
16. Fink J. Petroleum Engineer's Guide to Oil Field Chemicals and Fluids. Elsevier; 2012.
17. Rafieepour S, Ghotbi C, Pishvaie MR. The Effects of Various Parameters on Wellbore Stability During Drilling Through Shale Formations. Petroleum Science and Technology. 2015; 33(12): 1275–1285. doi: 10.1080/10916466.2011.606253
18. Ahmed A, Alsaihati A, Elkatatny S. An Overview of the Common Water-Based Formulations Used for Drilling Onshore Gas Wells in the Middle East. Arabian Journal for Science and Engineering. 2021; 46(7): 6867–6877. doi: 10.1007/s13369-020-05107-z
19. Samavati R. Use of Cassava Derivative in Water Based Drilling Mud [PhD Thesis]. Universiti Putra Malaysia; 2016.

20. Martínez-García R, Jagadesh P, Zaid O, et al. The Present State of the Use of Waste Wood Ash as an Eco-Efficient Construction Material: A Review. Materials. 2022; 15(15): 5349. doi: 10.3390/ma15155349
21. Al-Hameedi AT, Alkinani HH, Dunn-Norman S, et al. Insights into Eco-Friendly and Conventional Drilling Additives: Applications, Cost Analysis, Health, Safety, and Environmental Considerations. In: Proceedings of the SPE Symposium: Asia Pacific Health, Safety, Security, Environment and Social Responsibility; 19 April 2019; Kuala Lumpur, Malaysia. doi: 10.2118/195398-MS
22. Fan W, Zhuang G, Li Q, et al. Review of Nanoparticles in Water-Based Drilling Fluids: Innovations, Challenges, and Future Directions. Energy & Fuels. 2025; 39(19): 8800–8826. doi: 10.1021/acs.energyfuels.5c00700
23. Zhou Z, Scales PJ, Boger DV. Chemical and physical control of the rheology of concentrated metal oxide suspensions. Chemical Engineering Science. 2001; 56(9): 2901–2920. doi: 10.1016/S0009-2509(00)00473-5
24. Pitman RM. Wood ash use in forestry—A review of the environmental impacts. Forestry. 2006; 79(5): 563–588. doi: 10.1093/forestry/cpl041
25. Azevedo MLS, Balaban RC, Souza EA, et al. Biomass ashes as a new additive for eco-friendly drilling fluids: chemical characterization and evaluation of rheological and filtration properties. Petroleum Science and Technology. 2026; 44(11): 1653–1667. doi: 10.1080/10916466.2025.2464032