Evaluation of Orange Peel as Eco-Friendly Additive: Impact of Concentration, Particle Size, and Temperature on Drilling Fluid Performance

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Abstract

Drilling fluids play a crucial role in petroleum drilling operations, serving to maintain wellbore pressure, cleanse the wellbore by transporting cuttings to the surface, cool the drill bit while reducing friction, and stabilize the geological formation. Despite their superior lubricity, salt tolerance, thermal stability, and shale inhibition properties, oil-based muds are subject to stringent regulatory constraints due to their environmental and health risks. Consequently, the industry is actively pursuing more environmentally friendly alternatives.

This paper presents the utilization of orange peel powder (OPP) as a biodegradable additive in water-based mud to improve rheological and filtration properties. OPP was tested in three particle sizes at 1%wt and in five concentrations (0.5-1.5%wt). Rheological experiments at three different temperatures employed Bingham Plastic, Power Law, and Hershel-Bulkley models. Smaller OPP particles reduced fluid volume by approximately 3% and fluid loss by up to 11% compared to the base sample. The Hershel-Bulkley model provided the best fit, indicating that higher additive concentrations (>1%wt) increased viscosity but improved fluid loss by up to 20% at 1.5%wt. Elevating temperature decreased viscosity but increased yield stress, enhancing cuttings transport. Consequently, higher flow index (n) values at elevated temperatures suggested a transition toward more Newtonian-like fluid behavior.

The study highlights the potential of OPP as a sustainable alternative to conventional chemical additives, contributing to reduced environmental impact in drilling operations. The comprehensive evaluation of OPP's performance across varying particle sizes and concentrations, combined with temperature effects, provides insights into its optimization for specific drilling conditions. Future work could explore the long-term stability of OPP-modified muds and their compatibility with other drilling fluid components, further solidifying the practical application of this green technology.

Introduction

Drilling fluids are critical to petroleum drilling, where they maintain wellbore pressure, clean the well hole by transport cuttings up to surface, cool and mitigate the friction applied on drill bit, and stabilize the formation (Sehly et al. 2015; Baltoiu et al. 2008). These muds are typically classified into water-based muds (WBMs) and oil-based muds (OBMs). Currently, about 80% of drilled wells use WBMs, whereas only 15% rely on OBMs composed of mineral oil or diesel suspended with polymers (Caenn et al. 2011). Although OBMs excel in lubricity, salt tolerance, thermal stability, and shale inhibition (Fornasier et al. 2017), their environmental and health hazards (Almudhhi 2016; Okoro et al. 2022; Pilgun and Aramelev 2013; Fornasier et al. 2017) have prompted strict regulatory limitations, motivating the industry to seek greener alternatives.

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WBMs are considered cost-effective and more environmentally benign. However, they often struggle in high-temperature or reactive shale environments and can lack sufficient cuttings suspension (Aftab et al. 2017). Conventional chemical additives—such as polyamines, chromium compounds, potassium-based salts, and other fluid-loss agents are typically expensive and pose environmental risks if not managed properly (Nguyen et al. 2023). Consequently, there is a growing focus on replacing these additives with sustainable bioproducts or waste-based materials to minimize ecological impact (Shafiq et al. 2024).

Table 1 summarizes recent research on natural additives for drilling fluids, including okra mucilage, banana peel, and potato peel. These studies highlight improvements in rheological measurement parameters, to some extent, in filtration and friction reduction. Among these additives, orange peel powder has shown promise in enhancing rheological properties and reducing fluid loss. With global orange production exceeding 60 million tons annually—and approximately 32 million tons of peel waste generated—orange peel presents a plentiful, low-cost resource. Nevertheless, previous investigations have not thoroughly examined how OP particle size and varying temperatures influence drilling fluid properties. Temperature stability is critical for high-temperature drilling, where polymer degradation can compromise fluid performance (Ali et al. 2022). This gap is especially pertinent for bentonite-based systems, where the interaction of OP and temperature on rheological behavior remains underexplored. As drilling extends into deeper, hotter formations, understanding OP's performance under such conditions becomes essential for maintaining fluid stability and efficiency.

Table 1— Current studies on natural additives for drilling fluid.

Additives	Findings	Limitations
Okra mucilage powder (Murtaza et al. 2021 and 2022)	- Acts as a shale swelling inhibitor. - Reduces bentonite swelling. - Improves viscosities. - Partially reduces filtration loss.	No mention of particle size or temperature effects on mud properties.
Banana peel powder (Al-saba et al. 2018)	- Improves rheological properties (PV and YP). - Partially reduces filtration.	
Potato peel powder (Al-Hameedi et al. 2019)	- Increases PV while reducing YP. - Reduces filtration loss.	
Citrus peel powder (Michael-Igolima et al. 2023; Le et al. 2023; Boruah et al. 2023; Idress and Hasan 2020; Dinh et al. 2024)	- Improves rheological properties. - Reduces fluid loss.	

This work explores the feasibility of utilizing orange peel as a sustainable additive in water-based mud. It details the preparation process of orange peel powder (OPP) and systematically evaluates its effects on drilling fluid performance. Specifically, the research investigates the effect of OP concentration, particle size, and temperature on rheological and filtration properties.

Materials and Method

Materials. **Figure 1** illustrates the step-by-step preparation of orange peel powder (OPP) and the subsequent particle size classification process. Raw orange peels were collected locally and thoroughly washed with distilled water to remove surface contaminants. The washed peels were dehydrated at 80 °C for 48 hours to ensure complete moisture removal. After drying, they were pulverized using a high-speed grinder. The resulting material was sieved to classify the OPP into three distinct particle size ranges: 100-150 µm, 45-100 µm, and particles smaller than 45 µm. These classified OPP particles were then used in further testing to assess their effects on drilling fluid performance.

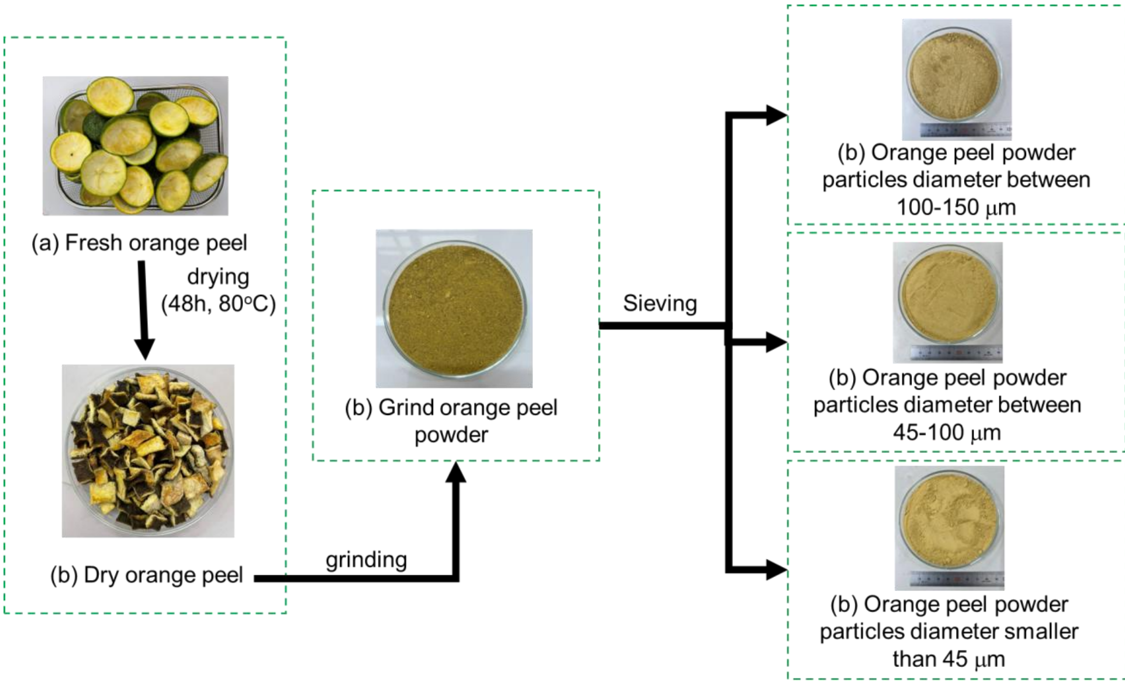

Figure 1— Preparation process and particle size classification of orange waste peel (OPP) powder.

Drilling Mud Preparation. 12 drilling fluid samples were prepared for this study. One base sample and eleven additional samples (labeled Mud 1 to Mud 11). Bentonite and distilled water were used as the base fluid, providing viscosity and suspension properties for the control sample. OPP was incorporated at specific concentrations and particle sizes, as detailed in **Table 2**. To investigate the effect of particle size, three samples (Mud 1, Mud 2, and Mud 3) were prepared with a fixed OPP concentration of 1%wt, using particle sizes of <45 µm, 45-100 µm, and 100-150 µm respectively. Five additional samples (Mud 4 to Mud 8) were formulated to examine the impact of varying OPP concentrations (0.5-1.5%wt) using a particle size of <45 µm. Lastly, three samples (Mud 9, Mud 10, and Mud 11) were prepared with 1%wt OPP (<45 µm) to evaluate the effects of various temperature at 25 °C, 50 °C, and 75 °C.

Table 2— Samples with various OPP concentrations, temperature and particle size.

Sample	OPP (%wt)	Temperature (°C)	Partical size (µm)
Base	0	50	-
MUD 1	1	50	100-150
MUD 2	1	50	45-100
MUD 3	1	50	< 45
MUD 4	0.5	50	< 45
MUD 5	0.75	50	< 45
MUD 6	1	50	< 45
MUD 7	1.25	50	< 45
MUD 8	1.5	50	< 45
MUD 9	1	25	< 45
MUD 10	1	50	< 45
MUD 11	1	75	< 45

All mud samples were prepared following a standardized procedure to ensure consistency. First, bentonite and distilled water were mixed using a high-speed mixer for approximately five minutes to form a uniform base fluid.

Next, a precise mass of OPP was gradually introduced under continuous mixing for an additional 25 minutes to ensure even dispersion. Finally, a few drops of defoamer were added as needed to control foam formation. After preparation, the rheological and filtration properties of each mud sample were determined. This systematic approach ensured reliable comparisons of the effects of OPP particle size, concentration, and temperature on drilling fluid performance.

Mud Density and pH Measurement. Mud density is an essential characteristic of drilling fluids, crucial for maintaining wellbore stability and regulating formation pressure. In this study, mud density and pH value were measured using a mud balance (**Figure 3**) and the inoLab equipment (**Figure 4**), respectively. These measurements ensured accurate assessment of the fluid's ability to maintain well integrity and drilling efficiency.

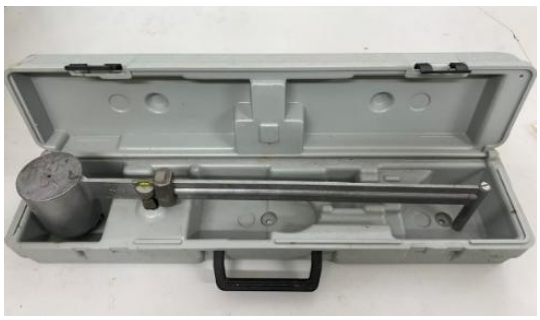

Figure 3— Mud balance.

Figure 4—inoLab pH7110.

Rheological Measurement. Twelve fluid samples were analyzed using an eight-speed rotational viscometer (**Figure 5**) to evaluate their rheological properties at different shear rates. Gel strength value was recorded at 10 seconds and 10 minutes to assess the interparticle forces that develop when circulation stops. To maintain consistent test conditions, a cup heater (**Figure 6**) was used to regulate the temperature at 25 °C, 50 °C, and 75 °C. The bellow equations were applied to estimate the rheological parameters (R600: reading at 600; R300: reading at 300 RPM,).

$$Apparent\ Viscosity\ (\mathrm{AV-cP}) = \mathrm{R600/2}, \quad (1)$$

$$Plastic\ Viscosity\ (PV - cP) = R600 - R300, \quad (2)$$

$$Yield\ Point\ (YP - \frac{lb}{100ft^2}) = R300 - PV, \quad (3)$$

Figure 5—8-speed rotational viscometer (OFITE).

Figure 6—Cup heater.

Rheological Models. Rheological models establish mathematical relationships between shear stress (τ) and shear rate (γ), providing insights into the flow rheological characteristic of drilling mud. In this study, three models were employed to interpret experimental data.

Bingham Plastic Model. A linear relationship between shear rate and shear stress is modeled once the fluid surpasses a critical yield point (τ_0). The plastic viscosity (μ_p) is derived from the slope of this relationship, while the intercept represents the yield stress,

$$\tau = \tau_0 + \mu_p\gamma, \qquad (4)$$

Where τ is shear stress, τ_0 is the yield point, μ_p is plastic viscosity, γ is shear rate

Power Law Model. It describes the non-Newtonian behavior using two parameters model, consistency (K) and flow behavior (n). The equation governing this model is,

$$\tau = \mathrm{K}\gamma^n, \qquad (5)$$

where n indicates the degree of flow behavior; and K reflects the fluid's consistency.

Herschel-Bulkley Model. It incorporates elements from both the Bingham Plastic and Power Law models. It accounts for both yield stress and non-Newtonian behavior, providing a more accurate representation of drilling fluid flow properties,

$$\tau = \tau_0 + \mathrm{K}\gamma^n, \qquad (6)$$

where τ represents shear stress; τ_0 is the yield stress; γ is shear rate; n indicates the degree of flow behavior; and K reflects the fluid's consistency.

Statistical Evaluation of Rheological Model Accuracy. To assess the accuracy of the predictive rheological models, two statistical metrics were used: the coefficient of determination (R^2) and the root mean square error (RMSE). These metrics quantify the degree of agreement between measured shear stress values and model-predicted values. The R^2 value represents the proportion of variance in measured shear stress (τ_{measured}) that is explained by the model.

$$R^2 = 1 - \frac{\sum(\tau_{measured} - \tau_{calculated})^2}{\sum(\tau_{measured} - (\tau_{measure})_{ave})^2}, \quad (7)$$

Root Mean Square Error (RMSE) estimates the mean deviation between the predicted and actual shear stress values, providing an overall measure of model accuracy.

$$RMSE = \sqrt{\frac{\sum(\tau_{measured} - \tau_{calculated})^2}{N}}, \quad (8)$$

where $\tau_{measured}$ is measured value; $\tau_{calculated}$ is calculated from model; $(\tau_{measure})_{ave}$ is the mean of measured value, N is the number of observations

Filtration Fluid Loss Measurement. Filtrate loss, or fluid loss, refers to the separation of water from the drilling mud and its infiltration into fractures and pores of the formation rock near the wellbore due to differential pressure (Novrianti et al. 2019). This process leads to the formation of a mud cake on the wellbore walls, which is essential for stabilizing the wellbore and preventing collapse or sloughing during drilling. However, excessive fluid loss can result in a thick, porous, and brittle mud cake, which may narrow the wellbore and increase the risk of drill string jamming. Additionally, excessive filtrate loss can destabilize the formation by inducing swelling and potentially damaging the reservoir zone (Dejtaradon et al. 2019). To mitigate these risks, it is crucial to maintain low filtrate loss while ensuring the formation of a thin, durable mud cake which contributes to hole stability and optimal drilling performance (Ali et al. 2020).

The fluid loss characteristics were assessed using a 100 psi filter press (**Figure 7**) in accordance with API standards (American Petroleum Institute 2017). This test quantifies the volume of water lost from the bentonite mud, replicating potential water invasion into the formation. To perform the test, mud sample was placed into a cylinderal chamber, and a pressure of 100 psi was applied. Fluid loss was recorded at multiple time intervals within 30 minutes. These measurements provided valuable insights into the fluid's ability to control filtration, ensuring minimal fluid invasion while facilitating the development of a stable mud cake (Le et al. 2023).

Figure 7—API filter press.

Results and Discussions

Effect of OPP particle size. Figure 8a illustrates the influence of OPP particle size on PV and YP for three tested mud samples (Mud 1, Mud 2, and Mud 3). The results shows that particle size 100-150 µm, 45-100 µm, and

<45 μm do not siginificantly impact PV or YP. Across 3 samples, PV remains constant at 6 cP, while YP fluctuates slightly between 5 and 6 lb/100 ft^2. This suggests that within the tested size range, OPP particle size has a minimal effect on flow resistance and cuttings suspension capability in the drilling fluid. **Figure 8b** presents the effect of particle size on gel strength values at two times of 10 seconds and 10 minutes. A slight reduction in gel strength values is recorded as particle size decreases. In Mud 1 (100-150 μm), Gel 10s and Gel 10m are recorded at 6 and 25 lb/100 ft^2, respectively. In Mud 3 (<45 μm), these values decrease slightly to 5 and 22 lb/100 ft^2. Despite this reduction, gel strength remains within the recommended range, ensuring effective cuttings suspension during static conditions.These findings suggest that smaller OPP particles (<45 μm) maintain adequate suspension capabilities while slightly improving flow characteristics, making them optimal for further evaluation of drilling fluid performance.

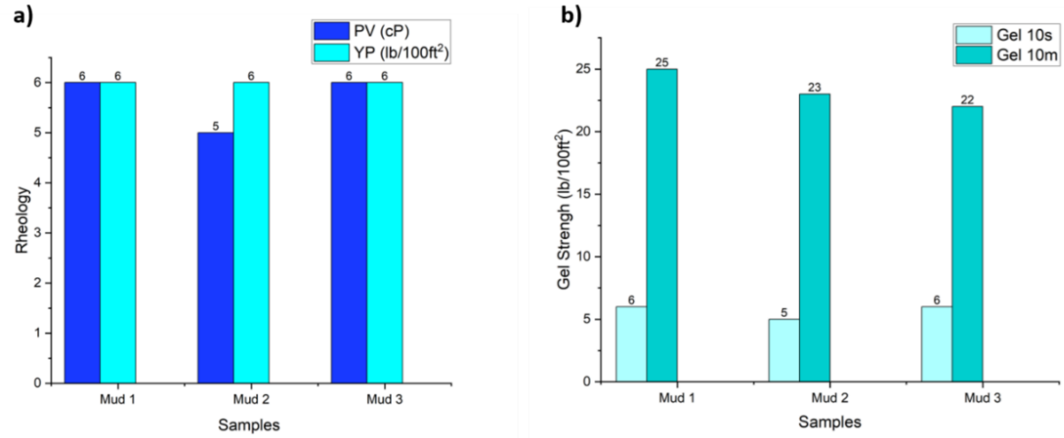

Figure 8—Influence of OPP particle size on (a) rheology parameters, (b) gel strength characteristic.

Figure 9a illustrates the fluid loss volume over time for the mud samples containing different OPP particle sizes (100-150 μm, 45-100 μm, and <45 μm). The data reveal that as the particle size decreases, the fluid loss volume slightly reduces. Specifically, the mud sample with the smallest particle size (<45 μm, Mud 3) exhibits the lowest fluid loss volume, reaching approximately 12.6 ml at 30 minutes, compared to 13.0 ml for the larger particle size samples (Mud 1 and Mud 2). The reduction in fluid loss with smaller particles is attributed to improved particle packing and reduced permeability of the filter cake, limiting water seepage into the formation. The images of mud cakes corresponding to the different particle sizes show that the thickness and visual distribution of the mud cakes are similar across all samples, with an average thickness of 2 mm (**Table 3**). Despite the slight reduction in fluid loss, the particle size does not significantly influence the mud cake structure. The mud cakes remain uniform and well-distributed, indicating effective particle bridging and filtration control across the tested particle sizes.

Table 3—Effect of OPP particle size on mud weight, fluid loss, ph and mudcake thickness.

Properties	100-150 μm	45-100 μm	< 45 μm
	Mud 1	**Mud 2**	**Mud 3**
Mud weight (ppg)	8.6	8.6	8.6
Filtration volume (ml)	13.0	13.0	12.6
pH	8.7	8.5	8.4
Mud cake (mm)	2	2	2

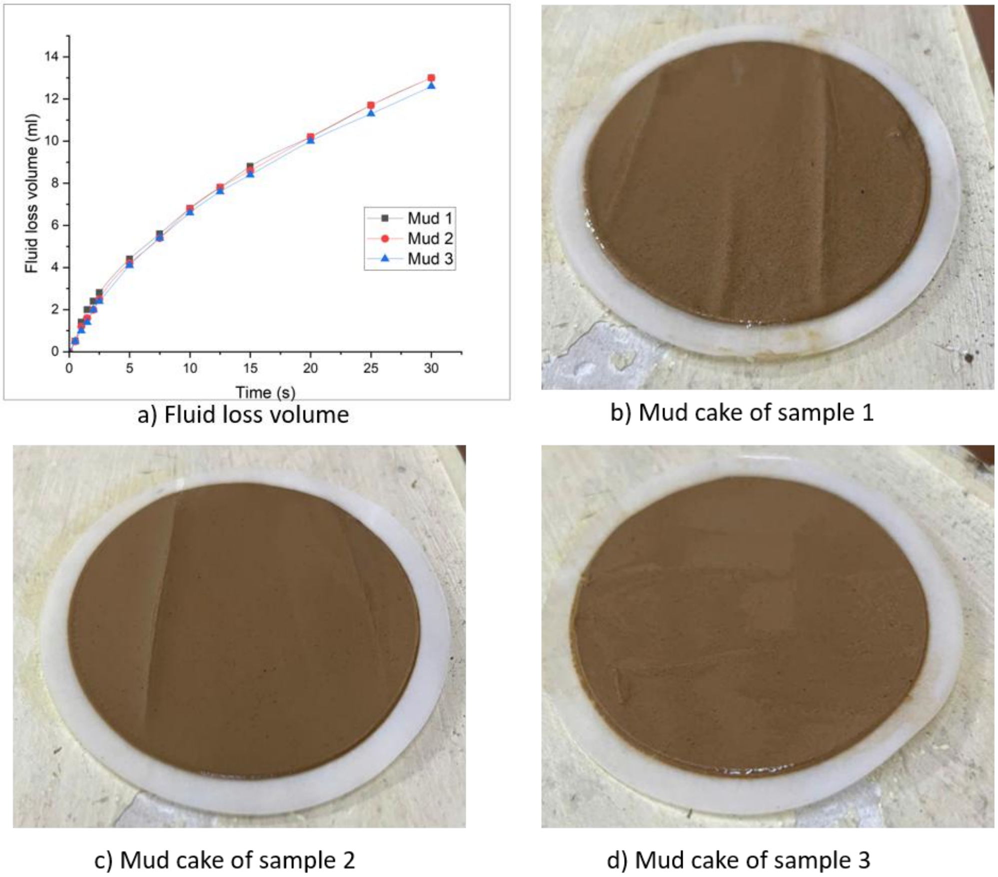

Figure 9—Fluid losses volume and mud cakes of different particle size samples.

These results indicate that OPP particles smaller than 45 µm provide the most effective reduction in fluid loss without while maintaining the structural integrity of the mud cake. Therefore, this particle size was selected for further investigation into OPP impact on drilling fluid performance.

Effect of OPP Concentrations. Figure 10a shows the variation in plastic viscosity PV and YP with increasing OPP concentration from 0.5%wt (Mud 4) to 1.5%wt (Mud 8). Compared to the base fluid, YP decreased significantly from 12 lb/100ft² to 6 lb/100ft² at Mud 5 (0.75%wt OPP). As the concentration increased to 1.5%wt, YP gradually recovered but remained lower than the base sample. PV initially increased slightly between Mud 4 and Mud 6, peaking at 7 cP before declining at higher concentrations. The drop in YP, coupled with minimal PV changes, suggests that OPP disrupts the fluid's initial structural integrity, but higher concentrations help stabilize suspension capabilities. **Figure 10b** illustrates the effect of OPP concentration on both gel strength values. As OPP concentration increased, gel strength showed a noticeable reduction. Gel 10s decreased by half, while Gel 10m dropped from 33 lb/100 ft² (base sample) to 23 lb/100 ft² at Mud 8 (1.5%wt OPP). The most significant drop occurred between the base sample and Mud 4 (0.5%wt OPP), with further increases in concentration having minimal additional impact. Despite these reductions, gel strength values across all OPP-modified samples remained within recommended limits, ensuring adequate cuttings suspension and wellbore stability during drilling operations.

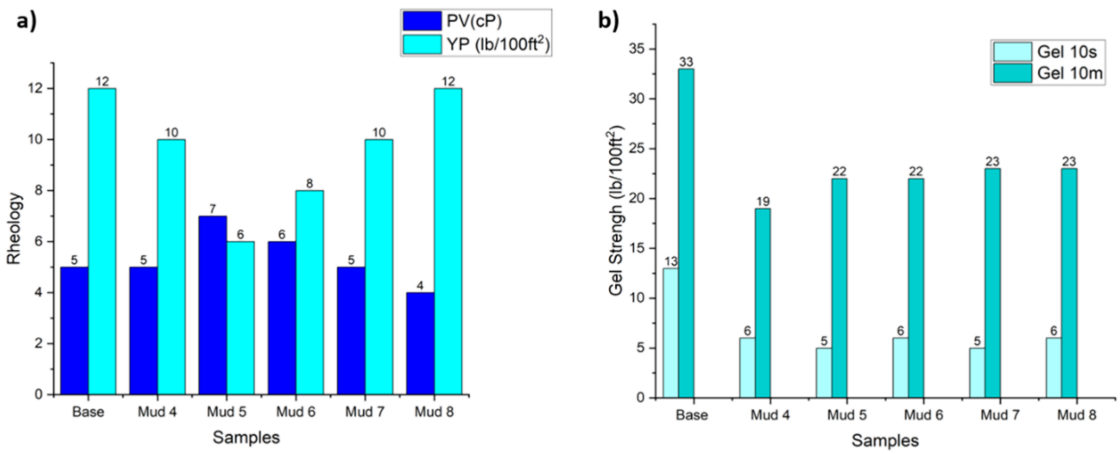

Figure 10—Influence of OPP concentrations on (a) Rheology parameters (b) Gel strength characteristic.

The rheological parameters for the three models are presented in **Table 4**. Among the models, the Bingham Plastic model exhibited the least accurate fit. The R^2 values ranged from 0.92 to 0.97, while RMSE values remained relatively high (1.2674-1.6799), indicating lower predictive accuracy. The Power Law model proved improved performance, with R^2 values between 0.9747 and 0.9878, and lower RMSE values compared to the Bingham model. However, this model did not entirely account for the nonlinear flow behavior of the fluid. Among the three models, the Herschel-Bulkley model provided the most precise fit, achieving R^2 values above 0.99 in most cases and RMSE values within an acceptable range. The flow behavior index (n) remained below 1, confirming that the fluid exhibited shear-thinning characteristics. The incorporation of OPP led to an increase in n up to 1%wt (Mud 6), but further increasing the concentration (Mud 7 and Mud 8) resulted in a decline, suggesting that excessive OPP slightly diminished the shear-thinning effect.

Table 4—Parameters of rheological models.

Model	Parameters	Base	Mud 4 (0.5% OPP)	Mud 5 (0.75% OPP)	Mud 6 (1% OPP)	Mud 7 (1.25% OPP)	Mud 8 (1.5% OPP)
Hershel Bulkley	K	0.5995	0.4357	0.1327	0.1841	0.5663	0.5009
	n	0.5051	0.5497	0.7137	0.6710	0.5133	0.5314
	τ_0	3.7431	1.8478	2.6059	2.2669	1.5607	1.9745
	RMSE	0.2939	0.4588	0.3758	0.7897	0.6528	0.6185
	R^2	0.9976	0.9941	0.9959	0.9830	0.9882	0.9896
Power Law	K	2.2079	0.9904	0.6457	0.6506	1.0800	1.1368
	n	0.3365	0.4410	0.4987	0.5005	0.4285	0.4237
	RMSE	0.8899	0.6619	0.9340	1.0784	0.7530	0.7921
	R^2	0.9824	0.9878	0.9747	0.9683	0.9843	0.9829
Bingham plastic	μ_p	0.0176	0.0178	0.0178	0.0181	0.0177	0.0178
	τ_0	7.2698	4.8131	4.0222	4.0507	4.9833	5.2021
	RMSE	1.2674	1.4985	0.8985	1.2857	1.6844	1.6799
	R^2	0.9274	0.9376	0.9765	0.9550	0.9214	0.9231

Figure 11 presents the fluid loss volume after 30 minutes for drilling fluid samples with varying OPP concentrations. The finding shows a notable decrease in fluid loss as OPP concentration increases, with the most

substantial decrease observed at 1.5%wt (Mud 8). The fluid loss volume dropped from 14.2 ml (base sample) to 11.4 ml, representing an overall 20% reduction. This suggests that OPP particles enhance cross-linking within the bentonite matrix, effectively lowering fluid permeability. **Table 5** shows that mud weight remained constant across all samples, indicating that OPP had no impact on overall density. However, pH levels gradually decreased from 9.1 to 8.2 as OPP concentration increased, though values remained within the acceptable range (8-12) for drilling operations.

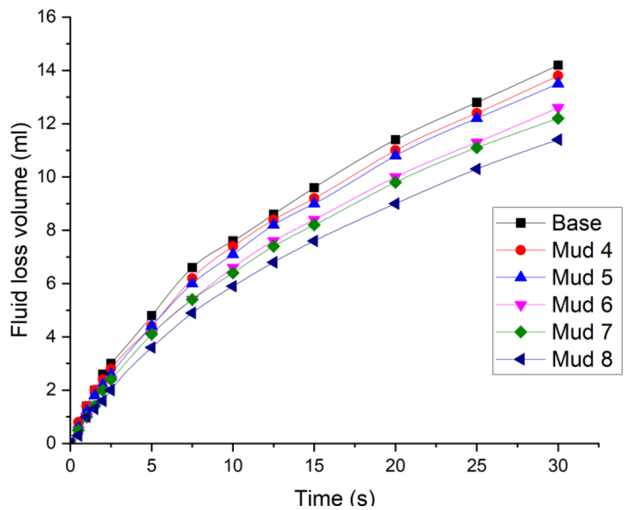

Figure 11—Fluid losses after 30 minutes for different OPP concentrations.

The formation of mud cakes, illustrated in **Figure 12**, confirms that mud cake thickness remained unchanged at 2 mm for all samples, irrespective of OPP concentration (**Table 5**). This demonstrates that while OPP effectively reduces fluid loss, it does not compromise mud cake structure or integrity. A thin, low-permeability mud cake is essential for preventing differential sticking and maintaining wellbore stability, making OPP a promising additive for filtration control in drilling fluids.

Table 5—Effect of OPP concentrations on mud weight, fluid loss, ph and mudcake thickness.

Properties	Base	Mud 4 (0.5% OPP)	Mud 5 (0.75% OPP)	Mud 6 (1% OPP)	Mud 7 (1.25% OPP)	Mud 8 (1.5% OPP)
Mud weight (ppg)	8.5	8.6	8.6	8.6	8.6	8.6
Filtration volume (ml)	14.2	13.8	13.5	12.6	12.2	11.4
pH	9.1	8.7	8.5	8.4	8.3	8.2
Mud cake (mm)	2	2	2	2	2	2

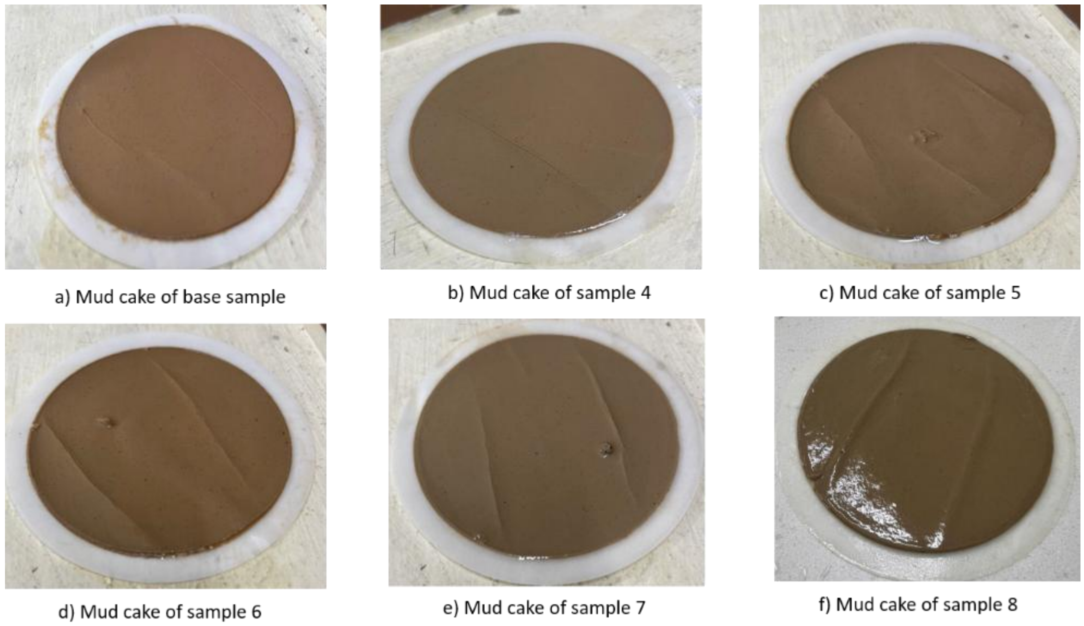

Figure 12—Mud cake formation for different OPP concentrations.

Effect of Temperature. When temperature increases, the primary chains of polymeric molecules break down, leading to a reduction in the network structure and a decline in the rheology of mud (Amani and Al-Jubouri 2012). However, the presence of additional additives such as OPP helps manage and mitigate these detrimental effects, making it essential to assess how temperature impacts OPP-modified drilling fluids (Quan et al. 2014). **Figure 13a** shows the impact of temperature on the apparent viscosity (AV) of the 1% OPP sample (Mud 9) at a 600 rpm shear rate using an eight-speed rotational viscometer. The temperature gradually rose from 25ºC to 75ºC in 5ºC increments. As indicated by **Eq. 9**, AV exhibited a consistent decline with rising temperatures. This relationship is quantified by an interpolation equation, which yields an R-squared value of 0.9929.

$$AV = 48.978\times T^{0.463} \qquad (9)$$

This strong correlation highlights the inverse relationship between AV and temperature, suggesting that the fluid becomes less viscous at higher temperatures due to thermal breakdown of its internal structure.

Figure 13b presents the variation in Herschel-Bulkley parameters, K, n, and τ_0 for the OPP-modified drilling mud at 25, 50, and 75°C. The following trends were observed: yield stress (τ_0) increased significantly from 0.7461 lb/100ft^2 at 25°C to 2.5967 lb/100ft^2 at 75°C—an increase of 2.5 times. This rise suggests enhanced cuttings suspension capacity at high temperatures, which is crucial for maintaining efficient drilling in deep wells. However, the elevated yield stress could also increase pressure losses, requiring careful monitoring. The flow behavior index, n, increased with temperature, indicating a reduction in the fluid's non-Newtonian characteristics. As temperature rose, the fluid became more Newtonian, suggesting lower resistance to flow under high shear conditions, which is beneficial for minimizing pressure losses during fluid circulation. The consistency index K decreased by 80%, from 0.5617 lb·s/100ft^2 at 25°C to 0.0995 lb·s/100ft^2 at 75°C. This decline implies reduced viscosity at high temperatures, contributing to improved flowability and reduced pumping effort.

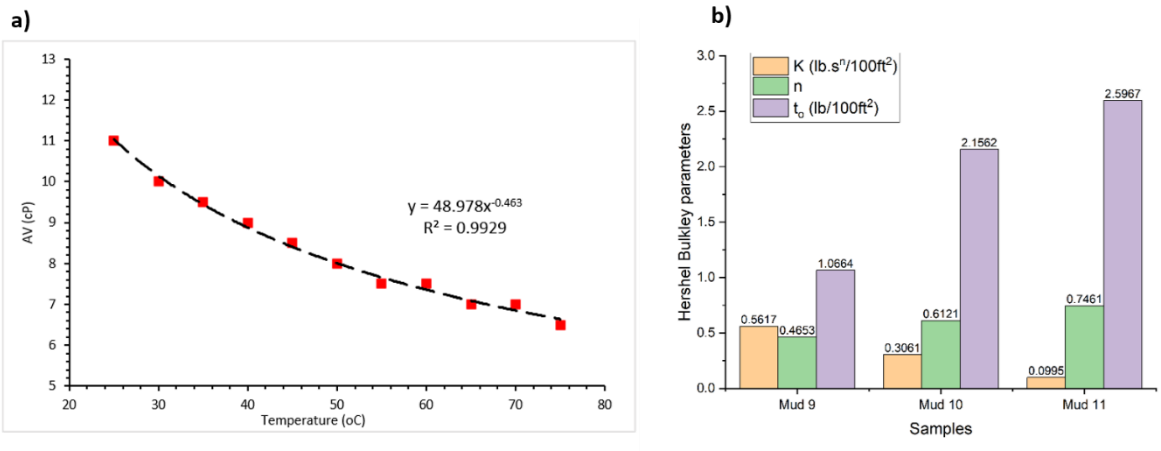

Figure 13—Impact of temperature on rheology behavior.

Conclusions

This study underscores the potential of OPP as a sustainable additive for water-based mud, demonstrating its efficacy in controlling fluid loss and enhancing overall drilling fluid performance. The integration of OPP markedly diminishes fluid loss, particularly when the particle size is less than 45 µm, thereby alleviating issues such as kick and formation contamination. OPP also reduces viscosity and gel strength, while ensuring that these parameters remain within the recommended ranges for effective cuttings suspension and wellbore stability. Furthermore, the study elucidates the influence of temperature in the presence of OPP. As drilling depth increases, temperature-induced alterations in the apparent viscosity were successfully modeled, offering a predictive framework for evaluating the behavior of drilling mud under bottom hole conditions. In summary, the findings corroborate the viability of OPP as a viable and cost-effective alternative to traditional chemical additives, contributing to environmentally responsible drilling practices.

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Conflicting Interest

The author(s) declare that they have no conflicting interests.

Reference

Aftab, A., Ismail, A, R., Ibupoto, Z. H., et al. 2017. Nanoparticles Based Drilling Muds a Solution to Drill Elevated Temperature Wells: A Review. *Renewable and Sustainable Energy Reviews* **76**(1):1301-1313.

Al-Hameedi, A. T., Alkinani, H. H., Dunn-Norman, S., et al. 2019. Environmental Friendly Drilling Fluid Additives: Can Food Waste Products Be Used as Thinners and Fluid Loss Control Agents for Drilling Fluid? Paper presented at the SPE Symposium: Asia Pacific Health, Safety, Security, Environment and Social Responsibility, 23-24 April. SPE-195410-MS.

Al-saba, M. T., Amadi, K. W., Al-Hadramy, K. O., et al. 2018. Experimental Investigation of Bio-Degradable Environmental

Friendly Drilling Fluid Additives Generated from Waste. Paper presented at the SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility, Abu Dhabi, UAE, 16-17 April. SPE-190655-MS.

Ali, I., Ahmad, M., Arain, A. H., et al. 2022. Utilization of Biopolymers in Water Based Drilling Muds. In *Drilling Engineering and Technology - Recent Advances New Perspectives and Applications*, ed. by Mansoor Zoveidavianpoor, Ch. 2, 36-58. Rijeka: IntechOpen.

Ali, M., Jarni, H. H., Aftab, A., et al. 2020. Nanomaterial-Based Drilling Fluids for Exploitation of Unconventional Reservoirs: A Review. *Energies* **13**(13): 1-31.

Almudhhi, S. M. 2016. Environmental Impact of Disposal of Oil-Based Mud Waste in Kuwait. *Petroleum Science and Technology* **34**(1): 91-96.

Amani, M. and Al-Jubouri, M. 2012. The Effect of High Pressures and High Temperatures on the Properties of Water Based Drilling Fluids. *Energy Science and Technology* **4**(1): 27-33.

American Petroleum Institute. 2017. Recommend Practice for Field Testing Water-Based Drilling Fluids-13B1. *API Publishing Services* **2008**(3): 121-132.

Baltoiu, L. V.,Warren, B.K., and Natras, T. A. 2008. State-of-the-Art in Coalbed Methane Drilling Fluids. *SPE Drilling & Completion* **23**(3): 250-57.

Boruah, A., Chowdhury, M., and Chowdhury, M. A. 2023. Application of Orange Peel Powder as an Environment Friendly Additive for Water-Based Drilling Fluids for Horizontal Wells in Parts of Upper Assam Oilfields. *Researchgate Net* **12**(9):1-12.

Caenn, R., Darley, H.C.H, and Gray, G.R. 2011. *Composition and Properties of Drilling and Completion Fluids*. Houston: Gulf Professional Publishing.

Dejtaradon, P., Hamidi, H., Chuks, M.H., et al. 2019. Impact of ZnO and CuO Nanoparticles on the Rheological and Filtration Properties of Water-Based Drilling Fluid. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **570**(12): 354-67.

Đinh, P., Tấn Phát Lê, Hữu Phước Trần, et al. 2024. Selecting an Appropriate Rheological Model for Environmentally Friendly Water-Based Drilling Fluid. *VNUHCM Journal of Engineering and Technology* **6**(1):1-10.

Fornasier, F. C., Campo, M., Djuric, A. et al. 2017. Designing Environmentally Conforming Drilling Fluids: Challenges and Considerations in Latin America. Paper presented at the SPE Latin America and Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina, 17-19 May. SPE-185492-MS.

Idress, M. and Hasan, M. L. 2020. Investigation of Different Environmental-Friendly Waste Materials as Lost Circulation Additive in Drilling Fluids. *Journal of Petroleum Exploration and Production Technology* **10**(2): 233-42.

Le, H. N. N., Hau, D. P., Hieu, L. T., et al. 2023. An Eco-Friendly Fluid Loss Control Additive for Water-Based Bentonite Drilling Fluid: Orange Peel Waste. *Chemical Engineering Transactions* **106**(7): 931-36.

Michael-Igolima, U., Samuel, J. A., Augustine, O. et al. 2023. Modified Orange Peel Waste as a Sustainable Material for Adsorption of Contaminants. *Materials* **16**(3):1-12.

Murtaza, M., Hafiz, M. A., Zhou, X., et al. 2022. Okra Mucilage as Environment Friendly and Non-Toxic Shale Swelling Inhibitor in Water Based Drilling Fluids. *Fuel* **320**(3): 123868.

Murtaza, M., Zeeshan, T., Zhou, X., et al. 2021. Okra as an Environment-Friendly Fluid Loss Control Additive for Drilling Fluids: Experimental & Modeling Studies. *Journal of Petroleum Science and Engineering* **204**(3): 108743.

Le, H. N. N., Phat, L.T., Phuoc, T. H., et al. 2024. Influence of Salt Contamination on the Rheological and Filtration Properties of Bentonite - Based Mud. *IOP Conference Series: Earth and Environmental Science* **1340**(1):1-12

Novrianti, I. K., Yuliastini, A., and Novriansyah, A. 2019. Experimental Analysis of Cassava Starch as a Fluid Loss Control Agent on Drilling Mud. *Materials Today: Proceedings* **39**(7): 1094-1098.

Okoro, E. E., Ochonma, C., Sanni, S. E., et al. 2022. Risk Assessment of Human Exposure to Radionuclides and Heavy Metals in Oil-Based Mud Samples Used for Drilling Operation. *International Journal of Environmental Health Research* **32**(5): 972-983.

Pilgun, S. and Aramelev, A. 2013. Environmentally Compatible Drilling Fluids. Paper presented at the SPE Arctic and Extreme Environments Technical Conference and Exhibition, Moscow, Russia, 15-17 October. SPE-166847-MS.

Quan, H., Li, H., Huang, Z., et al. 2014. Copolymer SJ-1 as a Fluid Loss Additive for Drilling Fluid with High Content of Salt and Calcium. *International Journal of Polymer Science* **2014**:1-15.

Sehly, K., Chiew, H., Li, H., et al. 2015. Stability and Ageing Behaviour and the Formulation of Potassium-Based Drilling Muds. *Applied Clay Science* **104**(1):309-17.

Shafiq, M. U., Viveganathan, D. N. Khan, M., et al. 2024. Experimental Investigation of Agricultural Wastes Effect on Drilling Mud Properties. *Improved Oil and Gas Recovery* **8**(1):1-18.

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