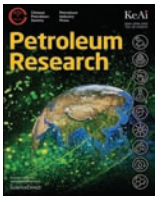
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Full Length Article

Experimental investigation of tea leaf extract as thinning agent and lubricity enhancer for water-based drilling fluid



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ABSTRACT

This study aims to develop a low-cost and environmentally friendly multifunctional thinning agent for water-based mud (WBM) from tea leaf extract (TLE). Matured tea leaves that are not used for tea production were collected, processed, and boiled in distilled water to release the extracts and prepare the liquid thinning agent. The resultant TLE was characterized using Fourier Transform Infrared spectroscopy (FTIR). Rheological properties were measured at two temperature conditions (35 °C and 70 °C) with varying concentrations of TLE, and the findings were compared with the widely used thinning agent potassium lignite (PL) under all test conditions. In addition, the density, pH, filtration control, and lubricating properties were evaluated under ambient conditions. The findings revealed that TLE, under all test conditions, exhibited better thinning performance than potassium lignite. At the temperature of 35 °C, when used at 1% concentration, TLE reduced apparent viscosity, plastic viscosity, yield point, initial and final gel strength by 23.94%, 21.57%, 27%, 76.99%, and 24.44%, respectively, compared to 12.89%, 16.34%, 8.44%, 39.82%, and 7.94% using the same concentration of potassium lignite. Compared to the ambient condition, the effectiveness of TLE in controlling rheology was found to be more pronounced at higher temperatures. Moreover, TLE at different concentrations significantly improved the filtration and lubricating properties of the mud. The addition of TLE reduced the mud cake thickness by a maximum of 44.44% and the coefficient of friction by a maximum of 40.7%. The comprehensive investigation and comparison with potassium lignite suggest that TLE can be effectively used as a multifunctional, non-toxic, and low-cost thinning agent for water-based drilling fluids.

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1. Introduction

Drilling fluid (DF) or mud is crucial for a safe, efficient, and successful drilling operation since it serves several important functions like rapid drilling, cutting transport, hole cleaning, wellbore stability, and contributes to reducing the overall cost of the well (Ahmed et al., 2020; Fadairo et al., 2021; Khan et al., 2024a; X.-L. Li et al., 2022; Maiti et al., 2021; Yi et al., 2023). Compared to the total expense of well drilling, DF shares only about 5–20%. However, if not designed properly, DF may significantly influence the overall cost of drilling, as well as production, by creating several operational complications, increasing non-productive drilling time, and damaging productive intervals (Ahmed et al., 2020; Hossain and Al-Majed, 2015). To obtain desired properties, drilling fluids are designed by blending different additives at varying concentrations (Yi et al., 2023, 2024).

Bentonite is the most commonly used additive in DF due to its affordability and diverse functional properties. The crystal lattice structure of bentonite can absorb water and swell approximately 10 times its original volume (Mitchell and Miska, 2011). However, the tendency of bentonite to flocculate at elevated temperatures leads to an unwanted and unpredictable rise in rheological properties, presenting challenges in maintaining the desired drilling fluid characteristics (Ghazali et al., 2018; Ismail et al., 2020). At lower temperatures, the particles are surrounded by a water film that prevents them from coming into close contact, thereby reducing the tendency for flocculation. However, flocculation accelerated with increasing temperatures as the protective water films gradually diminished (Heriot, 2005; Khan et al., 2024b). Flocculation is an undesirable phenomenon that leads to increased

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mud viscosity, gelation, fluid loss, and increased mud cake thickness. Highly viscous drilling fluids pose numerous challenges, including high pump pressure, formation damage, increased frictional pressure loss, lower penetration rates, and, in severe cases, well loss (Dehaghani and Elyaderani, 2023). Thinning agents or deflocculants are used in drilling fluid to reduce the flocculating tendency of bentonite and reduce mud viscosity. At the same time, various other additives are blended to enhance the lubrication and filtration properties (Caenn et al., 2017). Most of these products are either synthesized chemically or undergo modification, which can result in significant harm to the environment and biodiversity. Additionally, these additives often exhibit toxicity and incur substantial financial costs (Borah and Das, 2022; Ghazali et al., 2018.

Along with high viscosity, excessive torque generated by the rotating equipment poses a significant challenge during the drilling operation. It primarily arises from the friction between the wellbore, casing, and drill string (Sönmez et al., 2013). Drilling fluids must contain the lubrication property to minimize these excessive frictional forces. Generally, the lubricating properties of WBM are significantly lower compared to those of oil-based mud (OBM) (Zhao et al., 2022). However, the use of WBM is gradually increasing and has gained much popularity due to its low cost and environmentally friendly nature (Khan et al., 2024a; Yahya et al., 2024; Yi et al., 2024). Hence, a beneficial solution would involve designing an eco-friendly water-based fluid that is cost-effective and offers comparable lubricity to oil-based fluids.

Multiple research groups have attempted to develop a thinning agent for WBM from natural sources. Potato peel powder, palm tree leaf powder, oak seed extract, Rhizophora Mucronata bark waste, and dividivi tannin were some of the natural products investigated by several researchers (Al-Hameedi et al., 2020a, 2020b; Hafshejani et al., 2016; Ismail et al., 2020; Pérez and Colina, 2015). They reported that these natural products can control the rheology of drilling fluid as well as filtration loss to some extent. Despite several studies to develop alternative thinning agents from natural sources, none of them were compared with any industrial synergistic additives to explore their applicability in drilling fluid. The availability of these products also remains a concern. Moreover, the effect of these products on the lubricity of drilling fluid largely remains unexplored. However, a recent study by Khan et al. (2024b) showed that black tea waste (BTW) could be a promising alternative to industrial thinning agents due to its significant presence of tannin and other polyphenolic compounds. They also reported that polyphenols in BTW reduce the coefficient of friction (COF) of water-based drilling fluids. However, due to the insoluble nature of BTW, plastic viscosity was found to be increased for all concentrations.

This study aims to investigate the use of mature tea leaf extract as a novel source of thinning agent and lubricity enhancer for water-based mud. Matured tea leaves were selected in this study due to several compelling reasons. Aged tea leaves are widely accessible bio-resources with no commercial value. They are not used for tea production, whereas tea plants are regularly pruned for branching, resulting in a vast number of leaves being discarded as waste (Zhang et al., 2021). Tea leaves are rich in polyphenols (Tannin, catechin, epicatechin, epigallocatechin, epigallocatechin gallate, etc.), comprising about 36% of the dry weight, which is significantly higher than black tea or other plant materials (de Maat et al., 2000; Li et al., 2013; Liu et al., 2014; Sivakumaran and Amarakoon, 2018; Thummajitsakul et al., 2020; Čížková et al., 2008). The existence of numerous polyphenolic compounds in tea leaves can prevent bentonite flocculation, reduce viscosity and gelation, and also enhance the filtration and lubrication properties of drilling fluid. Moreover, the extract is free from insoluble cellulosic compounds that can prevent the increase of plastic viscosity observed in other studies. Unlike other studies, this study provides a thorough experimental comparison of the proposed thinning agent with a widely used industrial thinner, potassium lignite (PL). Along with the investigation of TLE as a thinning agent for water-based mud, other fundamental properties such as density, pH, filtration, and lubrication characteristics have been assessed at ambient conditions. The results reveal a promising prospect of TLE as a multipurpose additive, particularly as a thinner and lubricity enhancer for WBM, which may reduce the total cost of drilling operations while adopting eco-friendly practices within the industry.

2. Methodology

The methodology employed in this study is divided into the preparation of tea leaf extract (TLE), formulation of drilling fluid, and experimental section. The formulation and testing of drilling fluid samples were conducted following the specifications provided in API RP 13 B-1(API, 2009).

2.1. Preparation of tea leaf extract (TLE)

Mature leaves collected from the lower stems of tea plants were sun-dried for one week before grinding them into smaller particles. The ground leaves were then weighed and boiled in distilled water for 2 h with a water-leaves ratio of 20:1 to extract the polyphenolic compounds in the water. The water extract was then filtered using laboratory filter paper to separate the fibrous part and heated at 100 °C on a hot plate with a magnetic stirrer until the water-to-leaf ratio became 1:1. Finally, the extract was refrigerated at 5 °C for use as a tea leaf extract. The steps followed in the preparation of TLE are presented in Fig. 1, and the physical properties of TLE and PL are provided in Table 1.

2.2. Characterization of TLE

FTIR spectra of the dried ground tea leaves and extracts were obtained in the 500 to 4000 cm^{-1} wavenumber range using an FTIR spectrometer of Agilent Technologies (Cary 630, USA). Finely ground and dried samples were tested with an attenuated total reflectance (ATR) accessory to ensure direct contact between the sample and the crystal. The recorded absorbance spectra were processed to eliminate unwanted background noise and distortions. The processed data was then used for subsequent qualitative analysis and identification of characteristic functional groups.

2.3. Formulation of drilling fluid

Water, bentonite, sodium hydroxide, polyanionic cellulose (PAC-R), xanthan gum (XCD), and barite were used in the formulation of reference mud (RM). Tea leaf extract was added to the RM at concentrations of 0.5%, 1%, 1.5%, 2%, and 3% by volume of water. Similarly, potassium lignite was added at the same concentrations to the RM separately by weight of water. A single-spindle Hamilton Beach Mixer (*HMD 200R, USA*) was used for homogenous mixing of all the additives. Table 2 provides a detailed overview of the composition and formulation process of the drilling fluid samples.

2.4. Experimental section

Each mud sample underwent a series of tests to assess its rheological properties, density, filtration characteristics, and lubricity. Rheological properties were measured at two different

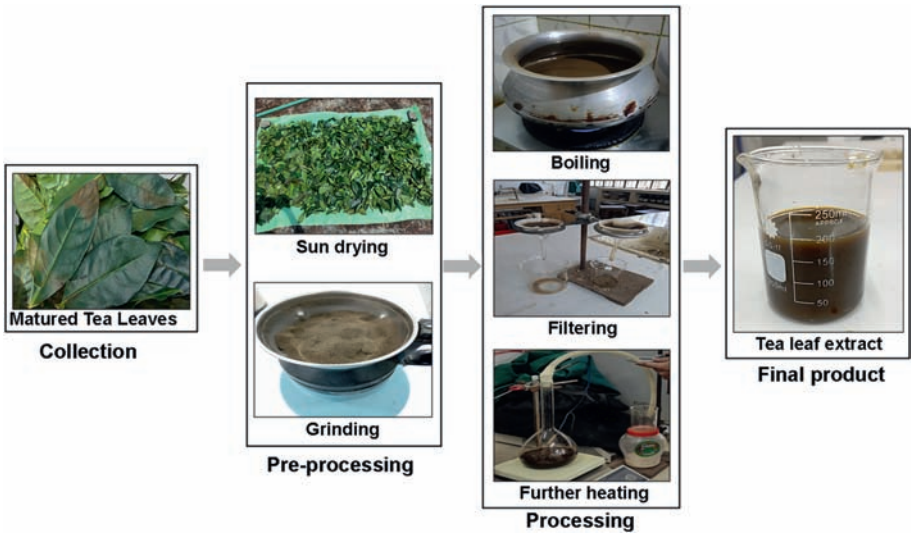


Fig. 1. Preparation of tea leaf extract.

Table 1
Physical properties of tea leaf extract and potassium lignite.

Properties	Tea leaf extract (TLE)	Potassium lignite (PL)
Physical state	Liquid	Solid
Physical appearance	Dark	Black powder
Specific gravity	1.4	1.7
Water solubility	100%	Partially soluble
pH	4.77	9.52

temperatures, 35 °C and 70 °C, using a rotational viscometer (*Fann RheoVARD, USA*). The viscometer automatically recorded the 10S and 10 M gel strengths. At the same time, the six-speed data were used to determine apparent viscosity (AV), plastic viscosity (PV), yield point (YP), and development of rheological diagrams. The following formulae were employed to determine the AV, PV, and YP, and the calculations of shear stresses and shear rates (Agwu et al., 2021):

$$\mathrm{AV} = \theta_{600}/2\ (\mathrm{cp}) \tag{1}$$

$$\mathrm{PV} = \theta_{600} - \theta_{300}\ (\mathrm{cp}) \tag{2}$$

$$\mathrm{YP} = \theta_{300} - \mathrm{PV}\ \left(\mathrm{lb_f} \Big/ 100\ \mathrm{ft^2}\right) \tag{3}$$

$$\text{Shear Rate}\ (\gamma) = 1.7023 \times \mathrm{RPM}\ \left(\mathrm{s^{-1}}\right) \tag{4}$$

$$\text{Shear Stress}\ (\tau) = 1.067 \times \text{Dial Reading}\ \left(\mathrm{lb} \Big/ 100\mathrm{ft^2}\right) \tag{5}$$

Where, θ_{600} and θ_{300} denotes the dial readings obtained at 600 and 300 RPM respectively.

The flow characteristics of the fluids were analyzed using both the Bingham Plastic and Power Law models to determine the most suitable rheological model. The shear stress-shear rate relationships described by these models are as follows (Andaverde et al., 2019):

$$\text{Bingham Plastic model (BPM)}: \tau = \tau_y + \mu_p \gamma \tag{6}$$

$$\text{Power Law model (PLM)}: \tau = K\gamma^n \tag{7}$$

Model validation was performed through regression analyses to quantify the agreement between the obtained experimental data and the data calculated from the fitted models. The goodness of fit was evaluated using the Coefficient of Determination (R^2) and the Root Mean Square Error (RMSE), calculated as follows:

$$R^2 = \left(\frac{\sum(\tau_{measured} - \tau_{mean\ measured})(\tau_{calculated} - \tau_{mean\ calculated})}{\sqrt{\sum(\tau_{measured} - \tau_{mean\ measured})^2 \sum(\tau_{calculated} - \tau_{mean\ calculated})^2}} \right)^2 \tag{8}$$

$$RMSE = \sqrt{\frac{\sum(\tau_{measured} - \tau_{calculated})^2}{N}} \tag{9}$$

Where N represents the number of shear stress values.

The density and pH of each sample were measured using a mud balance (Fann 140, USA) and a multiparameter (Hanna HI 9829, Romania), respectively.

API Low pressure-low temperature (LPLT) filter press (Fann 300 series, USA) was used to determine the filtration characteristics of each sample. The test was conducted at ambient temperature using a pressure of 100 psi applied by CO_2 gas. A filter paper was placed inside the cell, and 350 ml of the fluid sample was poured into the chamber. Filtrate volume was recorded over a 30-min period, and the thickness of the filter cake was measured afterward to assess fluid loss control performance.

Table 2
Formulation of drilling fluid samples.

Components	Quantity					
	RM	Mixing time (min)	TLE Mud	Mixing time (min)	PL mud	Mixing time (min)
Water	350 ml	0	350 ml	0	350 ml	
Bentonite	17.5 g	10	17.5 g	10	17.5 g	10
Sodium hydroxide	0.2 g	3	0.2 g	2	0.2 g	2
Xanthan gum	0.50 g	5	0.50 g	4	0.50 g	4
Polyanionic cellulose	0.75 g	5	0.75 g	4	0.75 g	4
Tea leaf extract (TLE)	–	–	0.5%, 1%, 1.5%, 2%, 3%	5	–	–
Potassium lignite (PL)	–	–	–	–	0.5%, 1%, 1.5%, 2%, 3%	5
Defoamer	As required	–	As required	–	As required	–
Barite	50 g	12	50 g	10	50 g	10

The lubricity was determined using an EP lubricity tester (Haitongda EP-C, China). The test was conducted at a rotational speed of 60 RPM with an applied torque of 150 in-lb. The instrument measured the coefficient of friction between a rotating steel ring and a stationary block, simulating downhole metal-to-metal contact conditions. The instrument provides a lubrication factor that serves as an indicator of the lubricating efficiency exhibited by drilling fluid. The lubricity tester was calibrated with distilled water before each test, and a correction factor (CF) was introduced if the freshwater did not exhibit the typical lubrication factor of 34. The following formulae have been employed to determine the coefficient of friction (COF) for the mud samples (Khandaker et al., 2023):

$$\mathrm{COF} = \frac{\text{lubrication factor} \times \mathrm{CF}}{100} \tag{10}$$

$$\mathrm{CF} = \frac{34}{\text{Meter reading during calibration}} \tag{11}$$

3. Results and discussion

3.1. Fourier Transform Infrared spectroscopy

When comparing the dried leaf sample and its extract, noticeable differences in polyphenolic and cellulosic content are clear (Fig. 2). The dried tea leaf spectrum (top) displays prominent absorption bands at 3340 cm^{-1}, which correspond to O–H stretching (hydroxyl groups) from polyphenols and cellulose. The peaks at 2916 cm^{-1} and 2852 cm^{-1} correspond to C–H stretching vibrations of methyl and methylene groups from lipids and other aliphatic compounds. Peaks at 1723 cm^{-1} indicate C=O stretching, likely from carboxylic acids, esters, or aldehydes. C=C stretching in aromatics can be observed at 1622 cm^{-1}, and peaks at 1150 cm^{-1} and 1025 cm^{-1} indicate polysaccharides and cellulose in the sample (Esteki et al., 2023; Li et al., 2015; Thummajitsakul et al., 2020).

In contrast, the spectrum of the tea leaf extract (bottom) shows broad and strong absorption at 3293 cm^{-1} due to O–H stretching from water-soluble polyphenols like catechins, and a peak at 1634 cm^{-1} corresponding to C=C aromatic ring stretching (Li et al., 2015). The absence of peaks around 2900 cm^{-1} and below 1200 cm^{-1} indicates the successful removal of cellulosic and lignin-related compounds during filtration. Comparatively, the dried tea leaves contain both polyphenolic compounds and structural biopolymers, such as cellulose and lignin, whereas the filtered extract contains primarily soluble polyphenolic compounds. The absence of cellulose-related peaks in the extract confirms the effective separation of insoluble plant matter. These results are consistent with the known water solubility of tea polyphenols and suggest the extract is rich in catechins, flavonoids, and other phenolic acids (Thummajitsakul et al., 2020).

3.2. Flow behavior characterization

A proper understanding of drilling fluid rheology is crucial for minimizing frictional pressure loss, achieving a higher penetration rate, and enhancing hole-cleaning ability during drilling operations. A single mathematical model cannot adequately describe the complex system of drilling fluids. Among numerous rheological models, BPM and PLM are widely used to analyze the flow characteristics and hydraulic calculations due to their simplicity and reasonable consistency in describing the shear stress-shear rate relationships (Kelessidis et al., 2006). Fig. 3a and b presents the shear stress response of the DF samples for different shear rates at temperatures of 35 °C and 70 °C, respectively. The slope of the SS vs SR curve represents a qualitative measure of mud viscosity. In both cases, it can be observed that the slope of the mud samples with different concentrations of TLE and PL is lower than that of the RM. However, compared to lower temperatures, the effect of thinner (TLE, PL) is more pronounced at a higher temperature of 70 °C. At higher temperatures, bentonite flocculation increases the viscosity of the RM; however, the incorporation of thinners like TLE and PL effectively prevents these tendencies.

Table 3 presents the parameters of the Bingham Plastic Model (BPM) and Power Law Model (PLM), along with statistical measures (R^2 and RMSE), to assess the fit of each model to the experimental data. It also illustrates the influence of temperature and

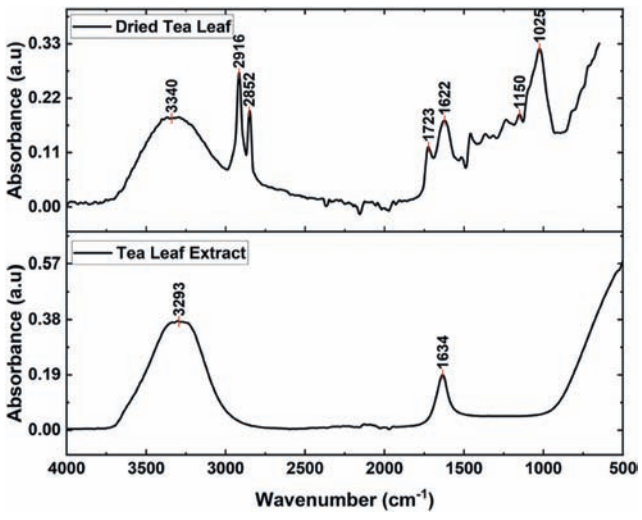


Fig. 2. FTIR analysis of tea leaf and tea leaf extract.

thinner concentration on the rheological properties of the drilling fluids.

The shear stress-shear rate data exhibits superior agreement with the PLM compared to the BPM. This agreement is further strengthened by the lower root mean square error (RMSE) and higher correlation coefficient (R^2) of the Power Law model. Across all samples and both temperatures, the R^2 values for the Power Law Model (PLM) are consistently higher, typically above 0.990. In contrast, the Bingham Plastic Model (BPM) shows slightly lower R^2 values, ranging from approximately 0.916 to 0.975. The higher R^2 value demonstrated by the PLM suggests the reliability of this model in representing the data across a wide range of shear rates. Similarly, the RMSE values are consistently lower for the PLM compared to the BPM, reinforcing the superior predictive performance of the PLM. For instance, at 35 °C, the PLM RMSE values for most samples remain close to or below 1.5, while BPM RMSE values are generally higher. The same trend is observed at 70 °C, where PLM again outperforms BPM with notably smaller RMSEs (as low as 0.79 in some cases), suggesting better accuracy in describing the fluid behavior under thermal variation. The flow behavior index ($n < 1$) of the fluid samples, as calculated in Table 3, indicates pseudoplastic flow at both temperature conditions (Guo and Liu, 2011). At lower temperatures, the impact of thinners on the flow behavior index (n) is minimal, with values ranging from 0.45 to 0.50. However, at the elevated temperature of 70 °C, a consistent increase in the 'n' value is observed with higher concentrations of both TLE and PL, suggesting a gradual transition toward more Newtonian flow behavior. This also indicates that the concentrations of thinner in DF must be optimized carefully for better hole-cleaning efficiency.

In contrast to the flow behavior index, the consistency index (K), presented in Table 3, provides a quantitative representation of mud thickness, which is similar to mud viscosity (Hossain and Al-Majed, 2015). Table 3 clearly shows a consistent decline in the "K" values as concentrations of both TLE and PL increase, suggesting lower viscosity of the TLE and PL-based muds. For example, at 35 °C, the consistency index of the RM drops from 10.13 to 6.05 at 3.0% TLE. A similar decreasing trend is observed for potassium lignite-treated muds. However, compared to PL, TLE-based muds consistently exhibit lower consistency index values across all concentrations and temperatures. This highlights the superior viscosity control characteristics and thinning behavior of tea leaf extract.

3.3. Rheological properties

The rheological properties considered in this section include apparent viscosity (AV), plastic viscosity (PV), yield point (YP), initial gel strength (10S GS), and final gel strength (10 M GS).

Fig. 4 presents the comparative changes in rheological properties for varying concentrations of TLE and PL at temperatures of 35 °C and 70 °C, while Tables 4 and 5 provide the quantitative results with relative changes at both temperatures. A consistent decline in AV, PV, YP, and GSs has been observed with increasing concentrations of TLE and PL at both temperatures. However, TLE exhibited better performance in controlling rheological properties compared to PL. For instance, at 35 °C, the addition of TLE at different concentrations reduced AV by a minimum of 17.13% to a

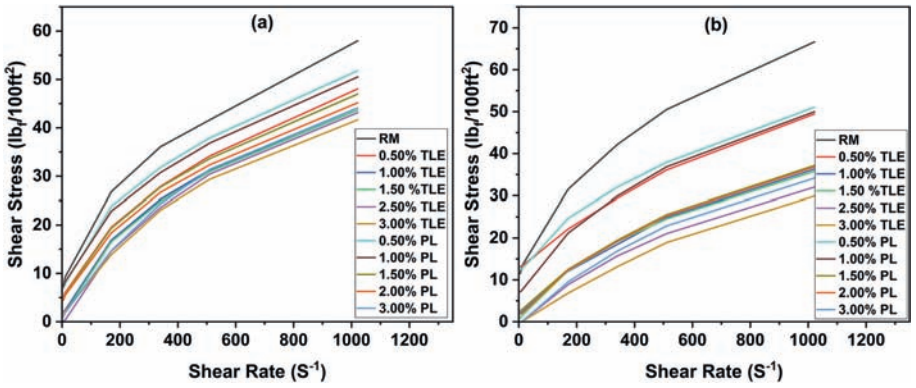


Fig. 3. Shear stress-shear rate relationship of fluid samples. a) assessed at 35 °C, b) assessed at 70 °C.

Table 3
Calculated parameters of rheological models.

Drilling fluid samples	Model parameters at 35 °C								Model parameters at 70 °C							
	Bingham Plastic Model				Power Law Model				Bingham Plastic Model				Power Law Model			
	PV (CP)	YP (lb_f/100 ft^2)	R^2	RMSE	n	K (dyne.sec/cm^2)	R^2	RMSE	PV (CP)	YP (lb_f/100 ft^2)	R^2	RMSE	n	K (dyne.sec/cm^2)	R^2	RMSE
RM	15.3	23.7	0.916	10.13	0.48	10.13	0.999	2.04	15.1	32.20	0.918	13.44	0.40	19.95	0.997	1.88
0.50% TLE	13.0	19.0	0.936	8.99	0.49	7.60	0.999	0.82	12.5	21.30	0.973	6.19	0.45	10.16	0.975	4.63
1.00% TLE	12.0	17.3	0.920	9.88	0.50	6.81	0.999	1.10	10.7	12.60	0.957	7.06	0.54	3.97	0.996	0.90
1.50% TLE	11.9	17.1	0.919	10.01	0.50	6.71	0.999	1.32	10.5	12.50	0.939	7.55	0.54	3.97	0.999	0.98
2.00% TLE	11.9	16.6	0.924	10.76	0.50	6.29	0.998	2.32	10.3	9.40	0.957	6.34	0.61	2.28	0.999	1.27
3.00% TLE	11.5	16.0	0.935	9.51	0.50	6.05	0.997	1.57	10.3	7.40	0.975	5.23	0.66	1.46	0.996	1.27
0.50% PL	13.0	22.5	0.916	10.03	0.45	10.93	0.999	1.09	12.3	23.20	0.947	7.44	0.43	12.45	0.990	3.87
1.00% PL	12.8	21.7	0.925	9.35	0.46	10.29	0.999	1.42	12.3	22.20	0.932	10.13	0.44	11.32	0.995	1.24
1.50% PL	12.5	19.0	0.929	9.16	0.48	7.94	0.999	0.60	10.9	13.00	0.956	7.02	0.54	4.15	0.997	0.79
2.00% PL	12.0	18.3	0.929	8.91	0.48	7.68	0.999	0.53	10.8	12.90	0.949	7.41	0.54	4.12	0.998	0.89
3.00% PL	11.9	17.5	0.930	10.76	0.49	7.04	0.997	2.12	10.6	10.80	0.953	7.31	0.58	2.92	0.998	1.62

maximum of 28.18%. In contrast, PL reduced the AV by a minimum of 10.68% to a maximum of 23.94%. Likewise, a steady reduction in PV, YP, and GSs was observed with incremental concentrations of TLE and PL. The addition of 3% TLE reduced the PV, YP, 10S GS, and 10 M GS by 24.84%, 32.49%, 94.695%, and 34.60%, respectively, compared to 22.22%, 26.16%, 85.84%, and 26.35%, using PL of the same concentration.

Higher temperature provides a better representation of the mud rheological properties at downhole wellbore conditions and is thus considered in this study, along with the initial condition of the fresh mud samples. Bentonite clay tends to flocculate at higher temperatures, giving rise to rheological properties compared to low-temperature conditions. This is evident from the measured properties of RM in Table 5.

A similar decreasing trend in the rheological properties was observed with the addition of TLE and PL at higher temperatures. However, the effect of both thinners is more pronounced at higher temperatures than at lower temperatures. For instance, at 70 °C, the addition of 3% TLE reduced AV, PV, YP, 10 S GS, and 10 M GS by 55.13%, 31.79%, 77.02%, 100%, and 52.14%, respectively, compared to 48.72%, 29.80%, 66.46%, 100%, and 43.21% using PL of the same concentration. This demonstrates the effectiveness of TLE as a thinning agent, even in high-temperature conditions.

Apparent viscosity (AV) is a measure of a drilling fluid's resistance to flow at a specific shear rate. Apparent viscosity reflects the combined effect of both the plastic and the yield point in the drilling fluid. The reduction in AV viscosity is due to the corresponding decrease in PV and YP. Unlike AV, Plastic viscosity is a measure of flow resistance that results from friction between the liquid and solid phases in drilling mud. High plastic viscosity reduces the penetration rate and may also increase the equivalent circulating density (ECD) resulting from high pump pressure

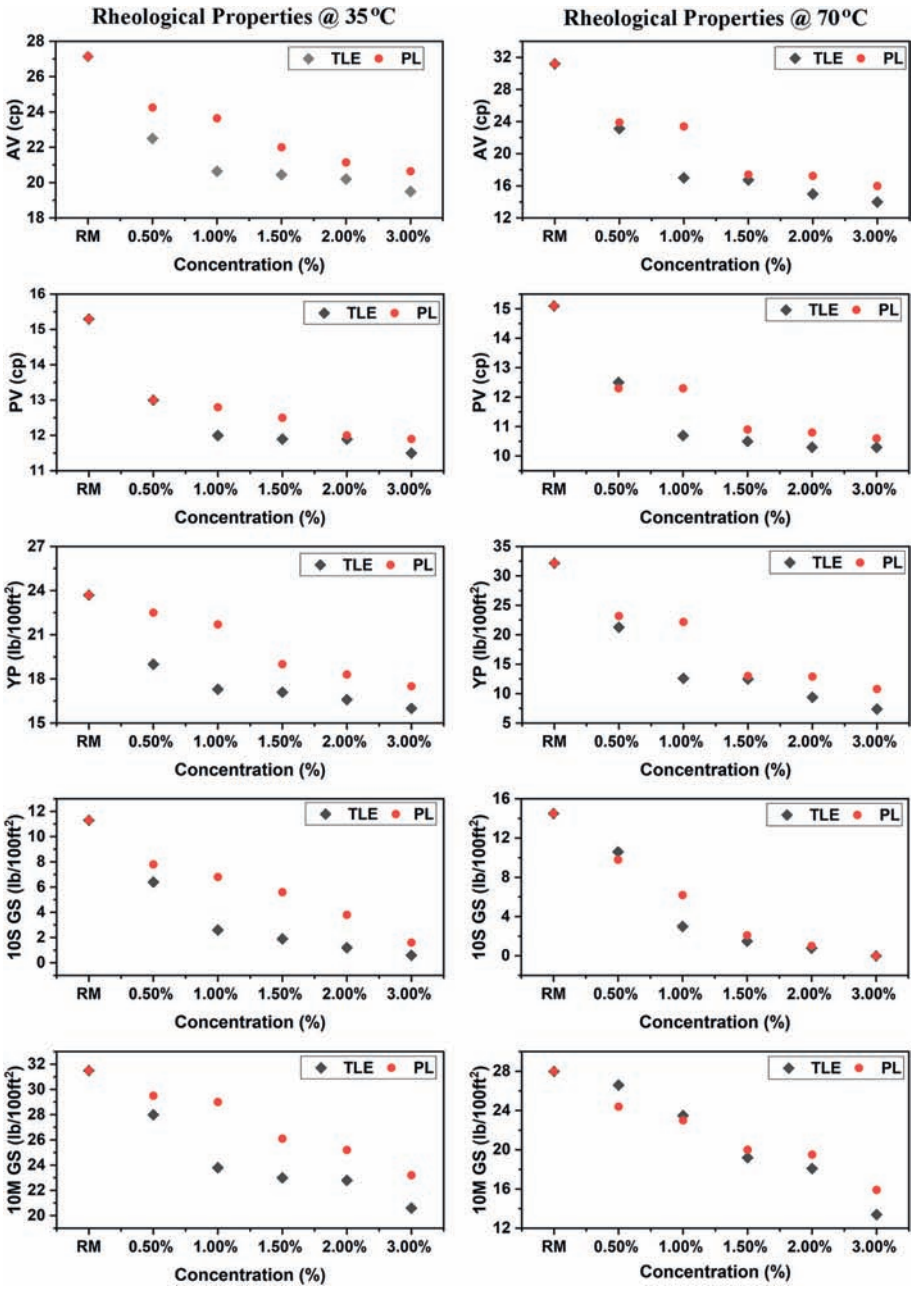


Fig. 4. Rheological properties of DF samples with varying concentrations of tea leaf extract and potassium lignite.

Table 4
Rheological properties of mud samples at 35 °C and relative reduction with varying concentrations of TLE and PL.

Mud samples	AV (CP)	Relative Reduction (%)	PV (CP)	Relative Reduction (%)	YP (lb_f /100 ft^2)	Relative Reduction (%)	10S Gel (lb_f/100 ft^2)	Relative Reduction (%)	10 M Gel (lb_f/100 ft^2)	Relative Reduction (%)
RM	27.15	0.00	15.30	0.00	23.70	0.00	11.30	0.00	31.50	0.00
0.50% TLE	22.50	17.13	13.00	15.03	19.00	19.83	6.40	43.36	28.00	11.11
1.00% TLE	20.65	23.94	12.00	21.57	17.30	27.00	2.60	76.99	23.80	24.44
1.50% TLE	20.45	24.68	11.90	22.22	17.10	27.85	1.90	83.19	23.00	26.98
2.00% TLE	20.20	25.60	11.90	22.22	16.60	29.96	1.20	89.38	22.80	27.62
3.00% TLE	19.50	28.18	11.50	24.84	16.00	32.49	0.60	94.69	20.60	34.60
0.50% PL	24.25	10.68	13.00	15.03	22.50	5.06	7.80	30.97	29.50	6.35
1.00% PL	23.65	12.89	12.80	16.34	21.70	8.44	6.80	39.82	29.00	7.94
1.50% PL	22.00	18.97	12.50	18.30	19.00	19.83	5.60	50.44	26.10	17.14
2.00% PL	21.15	22.10	12.00	21.57	18.30	22.78	3.80	66.37	25.20	20.00
3.00% PL	20.65	23.94	11.90	22.22	17.50	26.16	1.60	85.84	23.20	26.35

Table 5
Rheological properties of mud samples at 70 °C and relative reduction with varying concentrations of TLE and PL.

Mud samples	AV (CP)	Relative Reduction (%)	PV (CP)	Relative Reduction (%)	YP (lb_f /100 ft^2)	Relative Reduction (%)	10S Gel (lb_f/100 ft^2)	Relative Reduction (%)	10 M Gel (lb_f/100 ft^2)	Relative Reduction (%)
RM	31.20	0.00	15.10	0.00	32.20	0.00	14.50	0.00	28.00	0.00
0.50% TLE	23.15	25.80	12.50	17.22	21.30	33.85	10.60	26.90	26.60	5.00
1.00% TLE	17.00	45.51	10.70	29.14	12.60	60.87	3.00	79.31	23.50	16.07
1.50% TLE	16.75	46.31	10.50	30.46	12.50	61.18	1.50	89.66	19.20	31.43
2.00% TLE	15.00	51.92	10.30	31.79	9.40	70.81	0.80	94.48	18.10	35.36
3.00% TLE	14.00	55.13	10.30	31.79	7.40	77.02	0.00	100.00	13.40	52.14
0.50% PL	23.90	23.40	12.30	18.54	23.20	27.95	9.80	32.41	24.40	12.86
1.00% PL	23.40	25.00	12.30	18.54	22.20	31.06	6.20	57.24	23.00	17.86
1.50% PL	17.40	44.23	10.90	27.81	13.00	59.63	2.10	85.52	20.00	28.57
2.00% PL	17.25	44.71	10.80	28.48	12.90	59.94	1.00	93.10	19.50	30.36
3.00% PL	16.00	48.72	10.60	29.80	10.80	66.46	0.00	100.00	15.90	43.21

requirements (Beck et al., 1995; Nicora et al., 2001). Deflocculation and the resulting dispersion of mud solids are probable causes for the lowered plastic viscosity (Akpan et al., 2019).

The yield point (YP) in drilling mud is the result of electrochemical attractive forces among the colloidal particles in the aqueous system. The surface charges of the scattered particles in the fluid phase are what generate this electrochemical force. A higher yield point also contributes to a rise in ECD and frictional pressure losses (Agwu et al., 2021). In contrast to YP, gel strength (GS) is a measurement of the attractive forces under static circumstances in proportion to the time that reveals the thixotropic qualities of a drilling fluid. 10-second and 10-min measurements of GSs provide an idea of the amount of gelation that will occur once circulation ceases and the mud becomes stagnant. As the mud gels more during downtime periods, the amount of pump pressure required to restart circulation will increase and may surpass the formation breakdown pressure (Agwu et al., 2021). Thinners control mud rheology by minimizing the electrical interaction of the active clay particles and thus ensuring a homogeneous dispersion of the clay platelets in the aqueous system (Steiger, 1982). Likewise, TLE limits the electrochemical attractive forces of solid particles by creating a negatively charged film surrounding them. The repulsive forces among the particles aid in maintaining an effective distribution of solids, which in turn destroys the flocculation tendency of the active clays and reduces YP and gel-forming abilities.

3.4. Deflocculation mechanism

The flocculation behavior of bentonite and possible deflocculation in the presence of tea leaf extracts is schematically represented in Fig. 5. Bentonite particles possess a layered structure in which a silica octahedral sheet is nestled between two tetrahedral layers of aluminum. In the presence of water, an isomorphous substitution occurs, wherein the tetravalent silica (Si^{4+}) in the tetrahedral sheet is partially replaced by trivalent aluminum (Al^{3+}). Within the octahedral sheet, Al^{3+} can be substituted with bivalent ions like Fe^{2+} and Mg^{2+}. Consequently, this substitution creates a shortage of positive charge at the surfaces, while positive charge predominates at the edges (Hafshejani et al., 2016; Khan et al., 2024b; Salles et al., 2007). The oppositely charged edges and faces attract each other, leading to a face-to-edge interaction that creates a “house-of-cards” arrangement known as flocculation. At lower temperatures, the particles are surrounded by a water film that prevents them from coming closer, reducing the tendency of flocculation. However, flocculation accelerated with increasing temperatures as the protective water films gradually diminishes (Heriot, 2005; Khan et al., 2024b).

Tea leaves are rich in various phenolic compounds, which are mostly released into water during the boiling process and preparation of TLE. These phenolic compounds include catechins, epicatechin, epicatechin gallate, and epigallocatechin gallate, all of which contain a long chain of phenolic hydroxyl groups (Abudureheman et al., 2022; Sivakumaran and Amarakoon, 2018; Zhang et al., 2021). The abundance of phenolic hydroxyl groups from TLE neutralizes the positive edges of clay particles, which in turn inhibits the face-to-edge association. In addition, phenolic compounds may adsorb onto the faces of bentonite particles, surrounding them with a protective layer of hydroxyl groups and creating a net negative charge (Ghazali et al., 2018; Zhang and Yin, 1999). Once the edges are neutralized, the negative faces of bentonite particles repel each other, which in turn maintains a well-dispersed clay particle suspension in water.

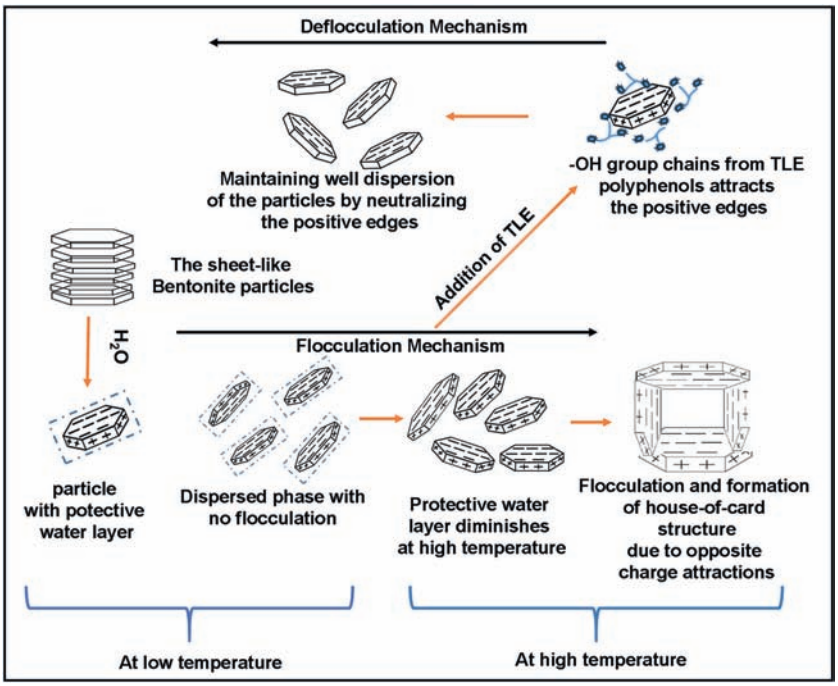


Fig. 5. Schematic representation of bentonite flocculation and possible deflocculation mechanism in the presence of TLE.

3.5. Lubricity

The lubricity of the reference mud (RM) and the tea leaf extract (TLE) muds was measured with an extreme pressure lubricity tester at ambient temperature and 150 in-lb torque. The COF registered by the instrument signifies excellent lubricating characteristics of TLE-based muds, as presented in Fig. 6.

It has been observed that TLE at all concentrations significantly reduced the COF, reaching a maximum of 40.7%. Even the smallest dose of 0.50% TLE reduces the COF by 21.54%. This demonstrates the clear effectiveness of tea leaf extract in enhancing the lubricity of water-based mud. Typically, lubricants create a protective film between surfaces that is sufficiently thick to smooth out surface roughness and withstand substantial compressional forces. This film reduces the contact area, thereby diminishing friction and torque (Sönmez et al., 2013). The reduction in COF in this study is attributed to the presence of catechol and aglycone groups within the polyphenolic compounds found in tea. The arrangement of phenolic hydroxyl groups greatly impacts the lubrication and wear resistance characteristics of drilling mud systems (Yang et al., 2023). A key characteristic of polyphenol-rich materials is their ability to form an adhesive coating on metal surfaces due to the presence of hydroxyl groups (Halake et al., 2018; Zhao et al., 2022). The hydroxyl groups located at different sites of aglycone show robust interactions with metal surfaces, and catechol is recognized for its versatile binding properties (Halake et al., 2018). Fig. 7 illustrates the potential coordination of the catechol group with metal ions that form a polyphenol coating on metal surfaces.

Catechol interacts with metal ions through various mechanisms, including chelation, coordination, and oxidation, resulting in the formation of metal-catechol complexes. Catechol's two hydroxyl groups allow it to coordinate wth metal ions, forming strong complexes. The strength of these bonds can be comparable to covalent bonds, depending on the metal and the specific coordination state (Zou et al., 2024). Tea leaf extract is rich in catechol and aglycone compounds (Melak et al., 2013; Rha et al., 2019). Through a bidentate metal-ligand bond, the catechol structure in tea polyphenols, featuring adjacent hydroxyl groups, can produce a robust film on the metal surface exceeding 100 nm in thickness (Yang et al., 2023). As a result, the friction between surfaces is greatly reduced with the addition of TLE in the mud system.

3.6. Filtration properties

Mitigating the loss of water from the drilling fluid and achieving a thin mud cake on the wall of the permeable formations offers significant benefits, as they contribute to minimizing formation damage and alleviating issues related to differential sticking problems (Caenn et al., 2017). Fig. 8 illustrates the total filtration loss after 30 min, along with the thickness of the mud cakes obtained.

It has been observed that TLE at almost all concentrations reduces filtration loss slightly, reaching a maximum of 6.8% at a 3% TLE concentration. An exception was observed with 2% TLE, which indicates no change in filtrate loss volume compared to the

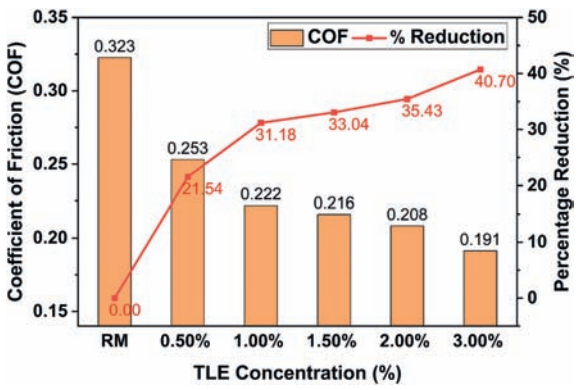


Fig. 6. Lubricating characteristics of mud samples with varying concentrations of tea leaf extract.

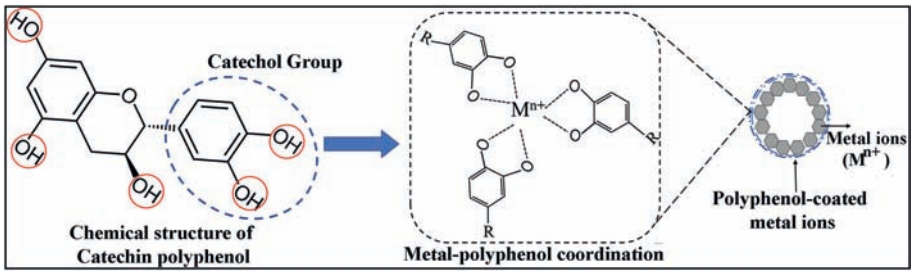


Fig. 7. Schematic representation of catechol group's interaction with metal surfaces. The red circles denote possible chemical reaction sites.

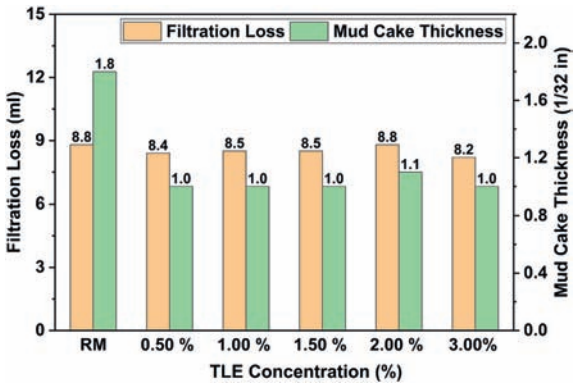


Fig. 8. Filtrate loss and mud cake thickness with varying concentration of tea leaf extract.

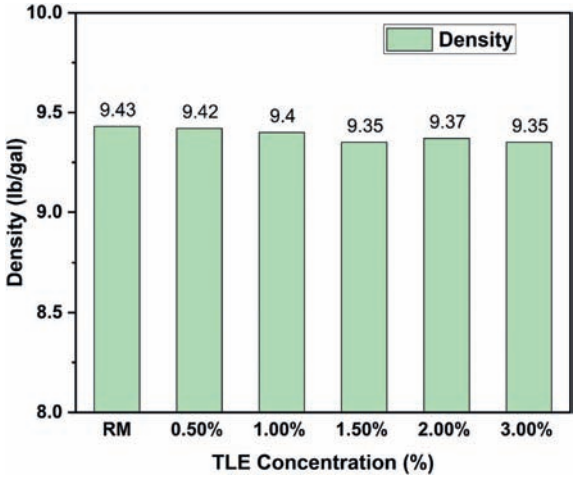


Fig. 9. Effect of tea leaf extract on mud density.

reference mud. However, a significant improvement was observed in mud cake thickness compared to the total filtration loss. TLE at all concentrations reduced the thickness of the mud cake, with the maximum reduction being 44.44%. The lowest improvement was found with 2% TLE, which is 38.88%. The formation of larger particles through the aggregation and flocculation of bentonite leads to a thicker mud cake and increased fluid loss (Altun et al., 2015). Tea leaf extract prevented bentonite flocculation, ensuring a well-dispersed system where particles remain excellently distributed in the solution. This effective dispersion allows clay particles to plug the small pores and form a thinner cake on the formation wall, resulting in a subsequent reduction in filtration loss (Mitchell and Miska, 2011).

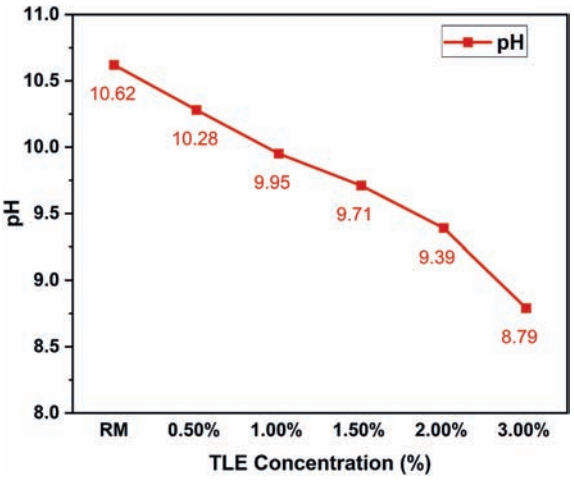


Fig. 10. Effect of tea leaf extract on mud pH.

3.7. Density and pH

The density and pH of the reference mud (RM) and the mud samples with tea leaf extract are shown in Figs. 9 and 10, respectively. A declining and inconsistent trend in mud weight is observed for varying concentrations of TLE.

Despite having a higher specific gravity of TLE compared to RM, the reduced weight in TLE-based muds is attributed to the foaming effect generated by the organic non-ionic surfactants, saponins, that are present in tea leaves (Yu and He, 2018). Complete elimination of foam is often difficult due to the dynamic and complex nature of drilling mud systems. However, the effect was found to be insignificant, as the foaming ability and stability of foams generated by saponins are weaker compared to other similar surfactants (Yu and He, 2018).

In contrast to mud density, a consistent decline in mud pH was observed for TLE-based mud samples. The pH of the mud samples with 3% TLE was found to be 17% lower than the RM. The pH of TLE was measured to be 4.77**,** which is substantially lower compared to the RM. Tea leaves contain various organic acids, including citric acid, malic acid, oxalic acid, and tartaric acid, which is the primary reason for the low pH of TLE and the steady reduction in mud pH with increasing concentrations of TLE (Chen et al., 2023). Since the pH of drilling fluids is typically maintained at a higher level to inhibit corrosiveness, additional caustic treatment may be necessary if TLE is used at higher concentrations.

4. Conclusion

The effect of tea leaf extract on different properties of water-based mud was investigated in this study. Under the tested

concentrations and temperature conditions, TLE presents a promising prospect in controlling the rheological properties of WBM. At the same time, a comprehensive comparison with the widely used industrial thinner potassium lignite further supports the excellent effectiveness of TLE. At ambient conditions, even at a lower concentration of 1%, TLE reduced the YP and final GS by 27% and 24.44%, respectively, compared to 21.70% and 7.94% for PL. Significant improvements were achieved in reducing the mud cake thickness and coefficient of friction (COF) with all concentrations of TLE, reaching a maximum of 44.44% and 40.7%, respectively. The phenolic hydroxyl groups present in the TLE were responsible for controlling the rheological properties by neutralizing the edges of bentonite particles, while the catechol compounds enhanced the lubricity by forming a dense layer on the metal surfaces. Considering the performance, availability, environmental, and economic acceptance, the incorporation of tea leaf extract into drilling mud presents an opportunity to curtail the reliance on expensive and environmentally hazardous additives while addressing several operational challenges.

In this study, all tea leaf samples were sourced from the same garden to maintain consistency across experiments. The variability across different origins or production years was not analyzed in this study. While our findings provide promising preliminary evidence, a deeper rheological characterization focusing on the viscoelastic behavior of the fluid, detailed economic analysis, efficient preservation techniques, and assessment of compatibility under varying field conditions are necessary for large-scale field applications. Future research should address these areas to fully establish the viability of TLE as a sustainable alternative in drilling fluid systems.

CRediT authorship contribution statement

Majedul Islam Khan: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **M. Farhad Howladar:** Writing – review & editing, Supervision, Methodology. **Ahsanul Hoque Emon:** Writing – review & editing, Investigation, Formal analysis. **Md. Omar Faruk Nadim:** Investigation, Formal analysis, Data curation. **Pranta Das:** Software, Formal analysis, Conceptualization. **Md. Omar Faruque:** Investigation, Formal analysis.

Declaration of competing interest

There are no conflicts of interest, as confirmed by the authors.

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Abbreviations

API	American Petroleum Institute
AV	Apparent viscosity
COF	Coefficient of friction
DF	Drilling fluid
GS	Gel strength
LPLT	Low pressure low temperature
PV	Plastic viscosity
PL	Potassium lignite.
TLE	Tea leaf extract
YP	Yield point
WBM	Water based mud
n	Flow behavior index
K	Consistency index
μ_p	Plastic viscosity
γ	Shear rate
τ_y	Yield stress
τ	Shear stress

References

Abudureheman, B., Yu, X., Fang, D., Zhang, H., 2022. Enzymatic oxidation of tea catechins and its mechanism. Molecules 27 (3), 942. https://doi.org/10.3390/molecules27030942.

Agwu, O.E., Akpabio, J.U., Ekpenyong, M.E., Inyang, U.G., Asuquo, D.E., Eyoh, I.J., Adeoye, O.S., 2021. A critical review of drilling mud rheological models. J. Petrol. Sci. Eng. 203, 108659. https://doi.org/10.1016/j.petrol.2021.108659.

Ahmed, N., Alam, Md.S., Salam, M.A., 2020. Experimental analysis of drilling fluid prepared by mixing iron (III) oxide nanoparticles with a KCl–Glycol–PHPA polymer-based mud used in drilling operation. J. Pet. Explor. Prod. Technol. 10 (8), 3389–3397. https://doi.org/10.1007/s13202-020-00933-1.

Akpan, E.U., Enyi, G.C., Nasr, G., Yahaya, A.A., Ahmadu, A.A., Saidu, B., 2019. Water-based drilling fluids for high-temperature applications and water-sensitive and dispersible shale formations. J. Petrol. Sci. Eng. 175, 1028–1038. https://doi.org/10.1016/j.petrol.2019.01.002.

Al-Hameedi, A.T., Alkinani, H.H., Dunn-Norman, S., Al-Alwani, M.A., Al-Bazzaz, W. H., Alshammari, A.F., Albazzaz, H.W., Mutar, R.A., 2020a. Experimental investigation of bio-enhancer drilling fluid additive: can palm tree leaves be utilized as a supportive eco-friendly additive in water-based drilling fluid system? J. Pet. Explor. Prod. Technol. 10 (2), 595–603. https://doi.org/10.1007/s13202-019-00766-7.

Al-Hameedi, A.T., Alkinani, H.H., Dunn-Norman, S., Alkhamis, M.M., Al-Alwani, M.A., Mutar, R.A., Salem, E., 2020b. Proposing a new biodegradable thinner and fluid loss control agent for water-based drilling fluid applications. Int. J. Environ. Sci. Technol. 17 (8), 3621–3632. https://doi.org/10.1007/s13762-020-02650-y.

Altun, G., Osgouei, A.E., Ozyurtkan, M.H., Serpen, U., 2015. Sepiolite based muds as an alternate drilling fluid for hot environments. In: World Geothermal Congress 2015.

Andaverde, J.A., Wong-Loya, J.A., Vargas-Tabares, Y., Robles, M., 2019. A practical method for determining the rheology of drilling fluid. J. Petrol. Sci. Eng. 180, 150–158. https://doi.org/10.1016/j.petrol.2019.05.039.

APl, 2009. Recommended practice for field testing water-based drilling fluids. In: *API RECOMMENDED PRACTICE 13B-1* (Fourth). American Petroleum Institute.

Beck, F.E., Powell, J.W., Zamora, M., 1995. The effect of rheology on rate of penetration. All Days. https://doi.org/10.2118/29368-MS.

Borah, B., Das, B.M., 2022. A review on applications of bio-products employed in drilling fluids to minimize environmental footprint. Environ. Chall. 6, 100411. https://doi.org/10.1016/j.envc.2021.100411.

Caenn, Ryen., Darley, H.C.H., Gray, G.R., 2017. Composition and Properties of Drilling and Completion Fluids, seventh ed. Gulf professional publishing.

Chen, H., Yu, F., Kang, J., Li, Q., Warusawitharana, H.K., Li, B., 2023. Quality chemistry, physiological functions, and health benefits of organic acids from tea (Camellia sinensis). Molecules 28 (5), 2339. https://doi.org/10.3390/molecules28052339.

Čížková, H., Voldřich, M., Mlejnecká, J., Kvasnička, F., 2008. Authenticity evaluation of tea-based products. Czech J. Food Sci. 26 (4), 259–267. https://doi.org/10.17221/10/2008-CJFS.

de Maat, M., Pijl, H., Kluft, C., Princen, H., 2000. Consumption of black and green tea has no effect on inflammation, haemostasis and endothelial markers in smoking healthy individuals. Eur. J. Clin. Nutr. 54 (10), 757–763. https://doi.org/10.1038/sj.ejcn.1601084.

Dehaghani, A.H.S., Elyaderani, S.M.G., 2023. Experimental investigation of the impact of sugarcane molasses on the properties of colloidal gas aphron (CGA) drilling fluid. Petroleum 9 (2), 199–204. https://doi.org/10.1016/j.petlm.2021.07.004.

Esteki, M., Memarbashi, N., Simal-Gandara, J., 2023. Classification and authentication of tea according to their harvest season based on FT-IR fingerprinting using pattern recognition methods. J. Food Compos. Anal. 115, 104995. https://doi.org/10.1016/j.jfca.2022.104995.

Fadairo, A., Adeyemi, G., Ogunkunle, T., Ling, K., Rasouli, V., Effiong, E., Ayoo, J., 2021. Study the suitability of neem seed oil for formulation of eco-friendly oil based drilling fluid. Petrol. Res. 6 (3), 283–290. https://doi.org/10.1016/j.ptlrs.2021.02.003.

Ghazali, N.A., Naganawa, S., Masuda, Y., Ibrahim, W.A., Bakar, N.F.A., 2018. Eco-Friendly drilling fluid deflocculant for drilling high temperature well: a review. Polar Arctic Sci. Technol. Petrol. Technol. 8. https://doi.org/10.1115/OMAE2018-78149.

Guo, B., Liu, G., 2011. Mud hydraulics fundamentals. In: Applied Drilling Circulation Systems. Elsevier, pp. 19–59. https://doi.org/10.1016/B978-0-12-381957-4.00002-4.

Hafshejani, K.S., Moslemizadeh, A., Shahbazi, K., 2016. A novel bio-based deflocculant for bentonite drilling mud. Appl. Clay Sci. 127–128, 23–34. https://doi.org/10.1016/j.clay.2016.03.037.

Halake, K., Cho, S., Kim, J., Lee, T., Cho, Y., Chi, S., Park, M., Kim, K., Lee, D., Ju, H., Choi, Y., Jang, M., Choe, G., Lee, J., 2018. Applications using the metal affinity of polyphenols with mussel-inspired chemistry. Macromol. Res. 26 (2), 93–99. https://doi.org/10.1007/s13233-018-6051-x.

Heriot, W., 2005. Drilling Engineering. Heriot Watt University. Institute of Petroleum Engineering, UK.
Hossain, M.E., Al-Majed, A.A., 2015. Fundamentals of Sustainable Drilling Engineering. Wiley. https://doi.org/10.1002/9781119100300.
Ismail, A.R., Mohd Norddin, M.N.A., Latefi, N.A.S., Oseh, J.O., Ismail, I., Gbadamosi, A.O., Agi, A.J., 2020. Evaluation of a naturally derived tannin extracts biopolymer additive in drilling muds for high-temperature well applications. J. Pet. Explor. Prod. Technol. 10 (2), 623–639. https://doi.org/10.1007/s13202-019-0717-7.
Kelessidis, V.C., Maglione, R., Tsamantaki, C., Aspirtakis, Y., 2006. Optimal determination of rheological parameters for Herschel–Bulkley drilling fluids and impact on pressure drop, velocity profiles and penetration rates during drilling. J. Petrol. Sci. Eng. 53 (3–4), 203–224. https://doi.org/10.1016/j.petrol.2006.06.004.
Khan, M.I., Das, P., Mogira, Md.A., Howladar, M.F., Chnapa, S.S., Chowdhury, M.S.J., 2024b. Drilling mud contamination effect on wellbore cement strength: an experimental investigation. Heliyon 10 (15), e35622. https://doi.org/10.1016/j.heliyon.2024.e35622.
Khan, M.I., Howladar, M.F., Das, P., Hossain, Md.N., Yasin, Md., 2024a. Application of black tea waste as eco-friendly deflocculant and rheology stabilizer for water-based mud. Geoenergy Sci. Eng. 239, 212956. https://doi.org/10.1016/j.geoen.2024.212956.
Khandaker, A.B.M.A.B., Ahmed, N., Alam, M.S., 2023. Rheology and lubricity characteristics study at different temperatures using synthesized SnO2 nanoparticles in KCl free bentonite water base mud. Petrol. Res. 8 (4), 541–549. https://doi.org/10.1016/j.ptlrs.2023.03.003.
Li, N., Zhao, Y., Liang, Y., 2013. Cardioprotective effects of tea and its catechins. Health 5 (4), 23–30. https://doi.org/10.4236/health.2013.54A004.
Li, X., Sun, C., Luo, L., He, Y., 2015. Determination of tea polyphenols content by infrared spectroscopy coupled with iPLS and random frog techniques. Comput. Electron. Agric. 112, 28–35. https://doi.org/10.1016/j.compag.2015.01.005.
Li, X.-L., Jiang, G.-C., Xu, Y., Deng, Z.-Q., Wang, K., 2022. A new environmentally friendly water-based drilling fluids with laponite nanoparticles and polysaccharide/polypeptide derivatives. Pet. Sci. 19 (6), 2959–2968. https://doi.org/10.1016/j.petsci.2022.07.003.
Liu, C.-Y., Huang, C.-J., Huang, L.-H., Chen, I.-J., Chiu, J.-P., Hsu, C.-H., 2014. Effects of green tea extract on insulin resistance and glucagon-like peptide 1 in patients with type 2 diabetes and lipid abnormalities: a randomized, double-blinded, and placebo-controlled trial. PLoS One 9 (3), e91163. https://doi.org/10.1371/journal.pone.0091163.
Maiti, M., Bhaumik, A.K., Mandal, A., 2021. Performance of water-based drilling fluids for deepwater and hydrate reservoirs: designing and modelling studies. Pet. Sci. 18 (6), 1709–1728. https://doi.org/10.1016/j.petsci.2021.09.001.
Melak, F., Redi, M., Tessema, M., Alemayehu, E., 2013. Electrochemical determination of catechol in tea samples using anthraquinone modified carbon paste electrode. Nat. Sci. 5 (8), 888–894. https://doi.org/10.4236/ns.2013.58107.
Mitchell, R.F., Miska, S.Z., 2011. Fundamentals of drilling engineering. Society of Petroleum EngineersRichardson. https://doi.org/10.2118/9781555632076. Texas, USA.
Nicora, L.F., Pirovano, P., Blomberg, N., Taugbøl, K., 2001. High-density invert-emulsion system with very low solids content to drill ERD and HPHT Wells. All Days. https://doi.org/10.2118/65000-MS.
Pérez, M.A., Colina, R.A., 2015. Rherological behavior of water-based drilling fluids contaminated with gypsum (CaSO4) using unmodified dividivi tannins (Caesalpinia coriaria) as deflocculant agent. In: SPE Latin American and Caribbean Petroleum Engineering Conference. https://doi.org/10.2118/177032-MS.
Rha, C.-S., Jeong, H.W., Park, S., Lee, S., Jung, Y.S., Kim, D.-O., 2019. Antioxidative, anti-inflammatory, and anticancer effects of purified flavonol glycosides and aglycones in green tea. Antioxidants 8 (8), 278. https://doi.org/10.3390/antiox8080278.
Salles, F., Bildstein, O., Douillard, J.-M., Jullien, M., Van Damme, H., 2007. Determination of the driving force for the hydration of the swelling clays from computation of the hydration energy of the interlayer cations and the clay layer. J. Phys. Chem. C 111 (35), 13170–13176. https://doi.org/10.1021/jp0719762.
Sivakumaran, K., Amarakoon, S., 2018. Bioactivity of fruit teas and tisanes - a review. J. Pharmacogn. Phytochem. 7 (1), 323–327.
Sönmez, A., Verşan Kök, M., Özel, R., 2013. Performance analysis of drilling fluid liquid lubricants. J. Petrol. Sci. Eng. 108, 64–73. https://doi.org/10.1016/j.petrol.2013.06.002.
Steiger, R.P., 1982. Fundamentals and use of potassium/polymer drilling fluids to minimize drilling and completion problems associated with hydratable clays. J. Petrol. Technol. 34 (8), 1661–1670. https://doi.org/10.2118/10100-PA.
Thummajitsakul, S., Samaikam, S., Tacha, S., Silprasit, K., 2020. Study on FTIR spectroscopy, total phenolic content, antioxidant activity and anti-amylase activity of extracts and different tea forms of Garcinia schomburgkiana leaves. Lebensm. Wiss. Technol. 134, 110005. https://doi.org/10.1016/j.lwt.2020.110005.
Yahya, M.N., Norddin, M.N.A.M., Ismail, I., Rasol, A.A.A., Salahudeen, N., Oseh, J.O., Muhammad, M., Shahid, M., Omar, S.B., 2024. Influence of triton-assisted coconut shell derived graphene nanoplatelets in water-based drilling fluid lubricity and shale inhibition application. Petrol. Res. https://doi.org/10.1016/j.ptlrs.2024.06.002.
Yang, X., Jiang, G., Liu, F., He, Y., Liu, R., Dong, T., 2023. Lubricity and mechanism of catechol-based biomimetic lubricant in water-based drilling fluid. Tribol. Int. 188, 108862. https://doi.org/10.1016/j.triboint.2023.108862.
Yi, S., Xu, Y., Cao, Y., Mao, H., He, G., Shi, H., Li, X., Dong, H., 2024. The decisive role of filtration reducers' surface charge in affecting drilling fluid filtration performance. J. Mol. Liq. 409, 125505. https://doi.org/10.1016/j.molliq.2024.125505.
Yi, S., Zhong, X., Mao, H., Li, H., Zhang, J., Dong, H., 2023. Poly(acrylamide-co-acrylic acid) grafted graphene oxide for improving the filtration performance of drilling fluids. Geoenergy Sci. Eng. 228, 212014. https://doi.org/10.1016/j.geoen.2023.212014.
Yu, X.-L., He, Y., 2018. Tea saponins: effective natural surfactants beneficial for soil remediation, from preparation to application. RSC Adv. 8 (43), 24312–24321. https://doi.org/10.1039/C8RA02859A.
Zhang, L., Li, M., Li, X., Yan, P., Zhang, L., Han, W., 2021. Summer pruning improves the branch growth and tea quality of tea trees (Camellia sinensis). Acta Physiol. Plant. 43 (4), 65. https://doi.org/10.1007/s11738-021-03226-0.
Zhang, L.-M., Yin, D.-Y., 1999. Novel modified lignosulfonate as drilling mud thinner without environmental concerns. J. Appl. Polym. Sci. 74 (7), 1662–1668.
Zhao, X., Li, D., Zhu, H., Ma, J., An, Y., 2022. Advanced developments in environmentally friendly lubricants for water-based drilling fluid: a review. RSC Adv. 12 (35), 22853–22868. https://doi.org/10.1039/D2RA03888A.
Zou, Y., Wang, X., Li, Y., Cheng, Y., 2024. Design of metal ion-catecholate complexes towards advanced materials. Mater. Today 79, 112–133. https://doi.org/10.1016/j.mattod.2024.07.010.