

Optimum Selection of H₂S Scavenger in Light-Weight and Heavy-Weight Water-Based Drilling Fluids

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Cite This: *ACS Omega* 2021, 6, 24919–24930

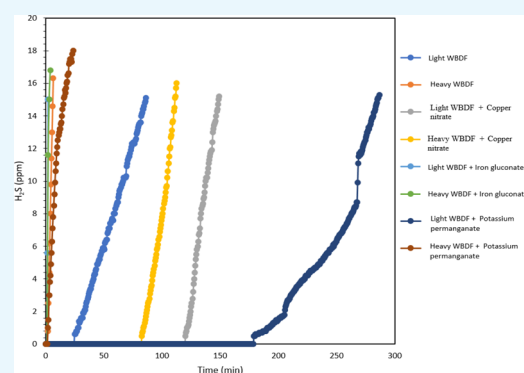
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ABSTRACT: During hydrocarbon drilling operations, the presence of hydrogen sulfide (H₂S) gas could cause serious health and safety issues. Scavenging this gas and eliminating its impact are essential requirements for a safe drilling operation. This study investigated the impact of three H₂S scavenger additives (copper nitrate, iron gluconate, and potassium permanganate) on water-based drilling fluids (WBDFs). The additives were tested on two actual field drilling mud samples that differ mainly in their weight. The scavengers' impact on drilling muds was investigated by measuring their scavenging capacity and their effect on rheology, fluid loss, and pH. Potassium permanganate outperformed the other scavengers when added to the lighter (lower density) WBDF. However, it did not impact the scavenging capacity of the heavier mud system. Copper nitrate outperformed the other scavengers in the heavier drilling mud system. Also, the addition of copper nitrate in the lighter mud system increased its H₂S-scavenging capacity greatly, while for iron gluconate, it did not perform very well. Overall, all the scavenger-containing drilling muds did not have any significant harmful impact on the plastic viscosity or the fluid loss properties of the drilling muds. Furthermore, all the tested drilling mud samples showed an excellent ability to clean wellbores and suspend drill cuttings evident by the high carrying capacity with the exception of iron gluconate or potassium permanganate with the heavy mud system.



1. INTRODUCTION

Hydrogen sulfide (H₂S) gas can be encountered during the different oil and gas well development stages. Reservoir fluids (oil and gas) may contain a considerable amount of H₂S gas. H₂S gas can migrate through the drilling fluid to the surface during drilling operations due to the lack of a hydrostatic head. In addition to drilling operations, H₂S can be produced during the well test operations, production operations due to the leak in the casing, or channeling in the cement behind the casing. The migration/leak of H₂S to the surface may cause severe health and safety issues in high-pressure, high-temperature oil and gas wells.¹ H₂S gas presents a severe hazard during drilling operations. It is a major health and safety issue in the oil and gas industry for the devastating harm it could cause to the workforce and equipment of the drilling operation. H₂S is a very lethal and toxic gas to the workforce, and it has to be dealt with and controlled carefully at any cost.^{2,3} Dealing with it is considered as the riskiest and most challenging operation during the wellbore development.

Drilling fluids are weighted with different weighting materials to control the formation fluids and perform other jobs such as cutting transport and lubrication and cooling the drilling equipment downhole. The essential function of the drilling

fluid is to control the formation and prevent the influx of the formation fluids, especially gas, from entering the wellbore and migrate upward to the surface, which may lead to a surface blowout.^{4–7} Drilling fluids are formulated to possess specific rheological properties in addition to the required weight. Drilling additives should have a low or minimal impact on the drilling fluid rheology to avoid the deficiency in the drilling fluid performance. Several other additives are required during the drilling process, such as H₂S scavengers, shale inhibitors, stabilizers, and so forth. These additives should carry the necessary function, and at the same time, they should not impact the rheology, which is vital for cutting transport and wellbore cleanup during the drilling operations.^{8,9}

It is common to encounter H₂S gas during drilling oil and gas wells. H₂S is a very toxic and flammable gas with a density higher than that of air (H₂S specific gravity is 1.18).^{10–12} The risk of

Received: July 16, 2021

Published: September 15, 2021

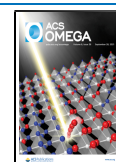


Table 1. Different H₂S Scavengers Used during Drilling Oil and Gas Wells

Scavenger type	solid/liquid	method of work	comments
metal-based ^{14–23}	solid	reacts with H ₂ S in the mud to produce solid/insoluble sulfides	low cost, efficient, no risk
copper-based (copper carbonate) ^{24–27}	solid	reacts with H ₂ S in the drilling fluid and produces copper sulfide, stable/insoluble materials	efficient, low cost, issues of corrosion by spontaneous copper plating
zinc-based ^{27–31}	solid	dissolves in drilling fluid to a solution that can capture H ₂ S	efficient, no risk of corrosion compared to copper-based, may affect mud rheology above pH 11
iron-based (the common type is magnetite) ^{32–37}	solid	reacts with H ₂ S to form iron sulfide (different types, depending on the abundance of iron and H ₂ S) may form a 1:1 or 1:2 Fe:S ratio.	some iron sulfide species may affect the mud rheology, such as pyrite
oxidizers such as potassium permanganate, calcium hypochlorite, hydrogen peroxide, and potassium oxydisulfate ^{18,15,24,38}	liquid	oxidize H ₂ S to elemental sulfur or sulfate	efficient, high solubility in drilling fluids
copper nitrate ^{31,39,40}	solid	reacts with H ₂ S and produces copper sulfide and nitric acid	efficient, nitric acid may add scavenging capacity

H₂S gas comes from the fact that when it mixes with air in a wide range of concentrations (4.3–45 wt %) at high temperatures, it can cause explosions.¹³ Gas kicks and blowouts during drilling operations are considered very dangerous, and this risk will increase if the gas is H₂S gas. In addition to the health and safety issues, H₂S can damage drilling equipment, and it can form scales and plug the moving parts of the drilling rig.

Corrosion problems due to H₂S contamination in the drilling fluid are a prevalent issue. In addition to drilling, H₂S can cause corrosion to all metallic equipment in the well and surface pipelines.^{2,3} H₂S should be controlled carefully during drilling operations; even low concentrations of H₂S, as low as 50 ppm, can cause severe damage and corrosion to the wellbore tubular. It is reported that 0.1 ppm H₂S gas could also impact the efficiency and durability of the equipment.¹⁴

H₂S causes serious health, economic, and safety issues during drilling operations, which demands an essential need to scavenge this gas and eliminate its impact on the drilling operations. H₂S scavengers are considered the primary additives in wells with potential production of H₂S. H₂S scavengers that are added to the drilling muds during the drilling operation are required to eliminate the harmful impacts of H₂S gas by performing proper scavenging, while avoiding any harmful impact on the drilling mud rheology and its fluid loss properties. Optimal H₂S scavengers are required to provide the maximum scavenging capacity with minimal or no impact on the drilling mud properties.

The following table (Table 1) shows the different types of H₂S scavengers and their impact on the drilling fluid performance.

Based on the literature review, several studies have investigated the use of H₂S scavengers to control H₂S in drilling muds. Previous studies did not show the effect of mud density on the H₂S-scavenging capacity. This study tested the impact of WBDF density on three types of H₂S scavengers: copper nitrate, iron gluconate, and potassium permanganate. Light (low density) and heavy (high density) WBDFs were used in this study. The scavengers' impact on WBDFs was investigated by measuring their scavenging capacity and their effect on rheology, fluid loss properties, and pH values. The ultimate objective of this study is to identify the optimal type of H₂S scavengers for light and heavy WBDFs that provides the maximum scavenging capacity with minimal or no impact on the drilling mud properties.

2. MATERIALS AND METHODS

2.1. Drilling Mud Preparation. Two different mud systems, light-weight mud (LWM) and heavy-weight mud (HWM), were utilized to investigate the performance of three various scavengers. Both mud systems have different weights, as shown in Table 2. The LWM has a lower density (88 lb/ft³) than

Table 2. Properties of the Two Mud Systems (LWM and HWM)

property	unit	LWM	HWM
mud weight	lb/ft ³	88	105
funnel viscosity	sec/qt	58	60
solid content	%	24	30

HWM, 105 lb/ft³. The funnel viscosity of both systems is almost identical, with a slight difference. The solid content of HWM is higher than that of LWM.

The mud systems were composed of several additives: viscosifier, fluid loss controller, shale inhibitor, hardness removal, pH controller, defoamer, bridging agent, and cement contamination removal and weighting agents. Both mud systems were prepared with the same additives but with slightly varied concentrations.

The two drilling mud systems are collected from real field mud, and then, the three different H₂S scavengers are added to both mud systems in the lab. The investigated scavengers in this study are copper nitrate (Cu(NO₃)₂·3H₂O), iron gluconate (FeC₁₂H₂₂O₁₄), and potassium permanganate (KMnO₄). Ultimately, 10 different samples are prepared, with five samples for each WBDF system. Odd sample numbers are for LWM, and even sample numbers are for HWM. The details on the concentration of each scavenger are given in Table 3. LWM and HWM are samples of base drilling muds without scavengers. LWM/Cu and HWM/Cu had copper nitrate, LWM/Fe and HWM/Fe had iron gluconate, LWM/K and HWM/K had potassium permanganate, and LWM/Cu + K and HWM/Cu + K had a mixture of copper nitrate and potassium permanganate to portray their synergistic effect. The concentrations of the scavengers used (in pounds per barrel, ppb) are based on the common practice in field drilling operations. All the scavengers have been added with a concentration of 2 ppb to the drilling mud. The drilling fluid samples and the scavengers were supplied by Petrogistics, a service company based in Saudi Arabia.

2.2. Methodology. The different scavengers' effects on mud systems' properties are investigated by conducting various tests,

Table 3. Scavenger Type and Concentrations Used for all 10 Samples

sample #	sample components				
	LWM, lab barrel	HWM, lab barrel	copper nitrate, ppb	iron gluconate, ppb	potassium permanganate, ppb
LWM	350				
HWM		350			
LWM/Cu	350		2		
HWM/Cu		350	2		
LWM/Fe	350			2	
HWM/Fe		350		2	
LWM/K	350				2
HWM/K		350			2
LWM/Cu + K	350		1		1
HWM/Cu + K		350	1		1

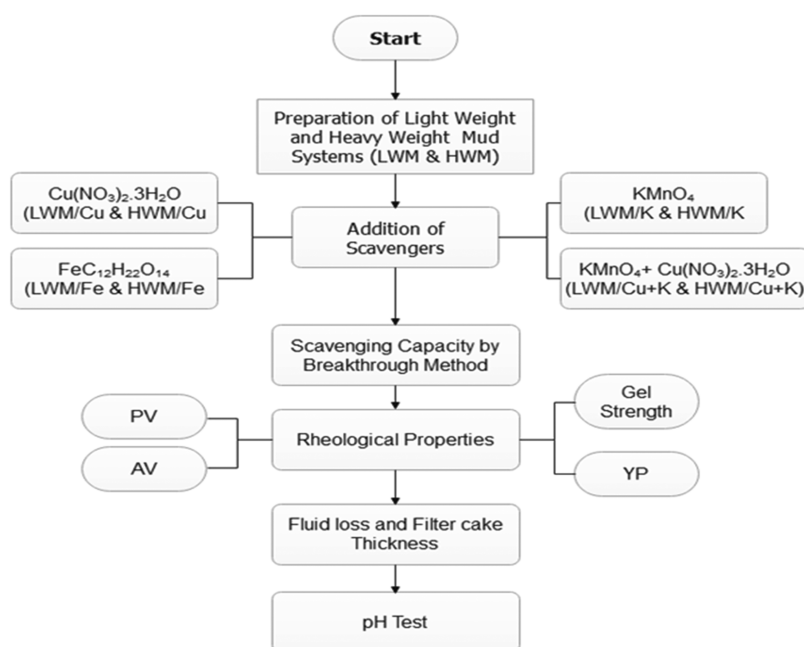


Figure 1. Flowchart of the methodology.

including H₂S-scavenging capacity, rheology, fluid loss, and pH tests. The flowchart provided in Figure 1 shows the outlook of the methodology adopted in conducting this study.

2.2.1. H₂S-Scavenging Capacity Test. The H₂S-scavenging capacity (at a breakthrough time) of each drilling mud was obtained as follows. First, 10 mL of the drilling mud of interest was carefully placed into a column, which was kept in the upright position throughout the test. The lower end of the column was connected to a gas cylinder, while the upper end was connected to an H₂S detector (minimum detection limit = 0.5 ppm H₂S). The H₂S detector was calibrated regularly using a standard gas mixture in order to ensure the accuracy of the collected data. The gas mixture in the cylinder contained 101.1 ppm (mole basis) methane. A flow controller was installed at the bottom of the column in order to control the inlet gas flowrate. At the beginning of each experiment, the valve at the bottom of the column was opened, and the inlet gas flowrate was fixed at 80 mL/min. The gas was bubbled into the bottom of the column, penetrated through the drilling mud, and left from the top of the column. Before sending the outlet gas to the detector for measuring the H₂S concentration in the existing stream, the entrained liquid in the outlet gas was removed using a demister, which was installed at the top of the column. The concentration

of H₂S in the outlet gas stream was continuously measured till the concentration of H₂S in the outlet stream reached 15 ppm. Then, the experiment was stopped.

In order to quantitatively compare the performance of the 10 drilling mud samples examined in this work, the scavenging capacity at breakthrough time (when H₂S in the exiting gas stream was detected) of each scavenger was calculated using the following expression (eq 1)

$$\text{Scavenging capacity (mg H}_2\text{S/L mud)} = \frac{\rho_{\text{H}_2\text{S}} \cdot Q \int_0^{t_b} (C_{\text{in}} - C_{\text{out}}) dt}{V \cdot f} \quad (1)$$

where $\rho_{\text{H}_2\text{S}}$ is the density of H₂S (=1.391 mg/mL) at the temperature (25 °C) and pressure (1 atm) of the test, Q is the volumetric flowrate of the gas (=80 mL/min), t_b is the breakthrough time in min, which was taken as the time when H₂S was detected in the exiting gas, V is the utilized volume of the mud (=10 mL), f is a conversion factor (=10⁶), and C_{out} and C_{in} are, respectively, the outlet and inlet concentrations (in ppm) of H₂S in the gas stream.

2.2.2. Rheology Test. The rheology of drilling mud is critical for determining flow behavior under various shear rates so that

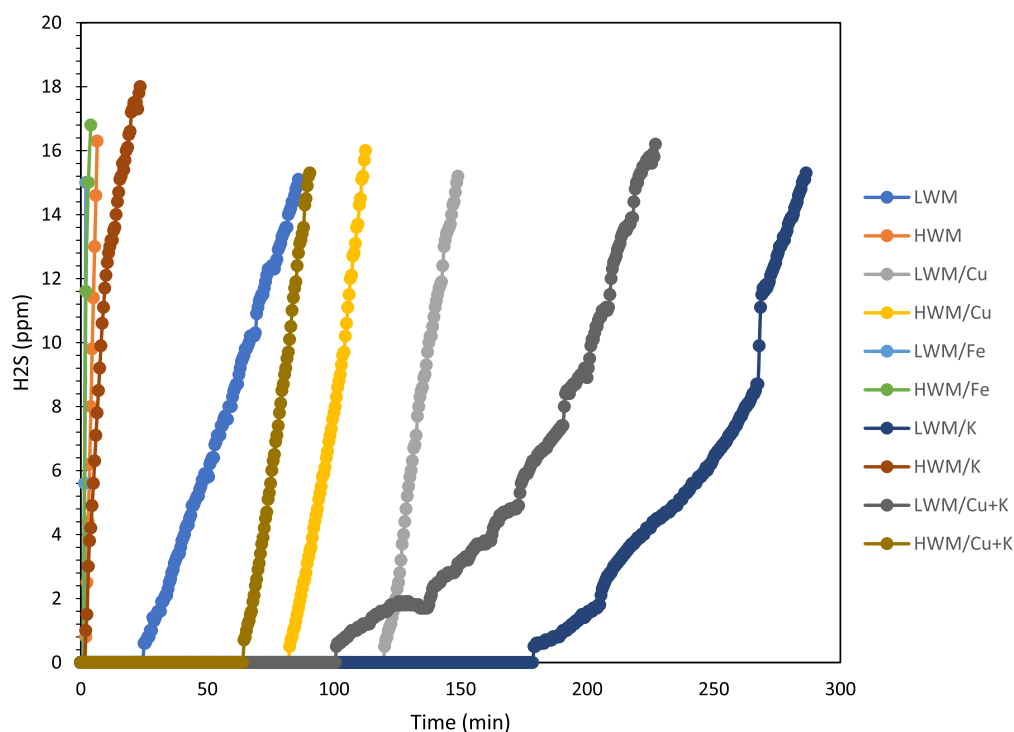


Figure 2. H₂S scavenging using the base and scavenger-containing drilling muds. The flow rate of the inlet gas feed is 80 mL/min. The scavenging experiments were conducted at room temperature and atmospheric pressure.

drilling operations can run smoothly. The plastic viscosity (PV), yield stress (YP), and gel strength are all rheological parameters that are crucial for drilling mud circulation. A M900 digital viscometer from OFITE was used in this study to measure the rheological parameters of drilling muds. A total of 10 samples based on two different mud systems were tested for rheology. The rheological characteristics in the presence of three various H₂S scavengers were investigated. The test was conducted under 120 °F temperature and atmospheric pressure conditions. The viscometer reading was taken at various shear rates as recommended by the API.

Standard eqs 2 and 3 were used to calculate PV and YP. Each drilling mud sample's gel strength was measured at two different time intervals, as suggested by API, such as 10 s and 10 min. Each drilling mud was given a 10 s static time before being subjected to a low shear rate at 3 rpm to measure the 10 s gel strength. The maximum deflection determined the gel strength of the drilling muds at 3 rpm. In the same way, 10 min gel strength was determined by retaining the drilling mud sample for 10 min before applying a low shear rate at 3 rpm. The apparent viscosity (AV) was measured as well for all the samples using a digital viscometer. The rheological parameters were calculated using equations of the Bingham plastic model

$$PV \text{ (cP)} = \phi_{600\text{rpm}} - \phi_{300\text{rpm}} \quad (2)$$

$$YP \left(\frac{\text{lb}}{100 \text{ ft}^2} \right) = \phi_{300\text{rpm}} - PV \quad (3)$$

where ϕ_{600} is shear stress reading at 600 rpm shear rate and ϕ_{300} is shear stress reading at 300 rpm shear rate.

2.2.3. Fluid Loss Test. The amount of fluid loss and the thickness of the filter cake resulting from the filtration process can be used to measure the fluid loss-controlling characteristics of drilling mud. A Fann filter press was used to determine the

fluid loss in this study. The procedure of conducting a fluid loss test was mentioned in our previous publication.⁴¹ A Whatman filter paper no. 40 was inserted at the bottom of the filter cup assembly, followed by filling a filter cup with 350 ml of drilling mud to carry out the filtration experiment. The filter cup was snugly fastened in place, and the filtration experiment began using compressed air at 100 psi. After finishing the 30 min filtration experiment, the filtrate liquid was collected, and its total volume was measured. The filter cake was carefully removed and rinsed with distilled water to remove any remaining drilling mud. A FANN scale was used to determine the filter cake thickness (1/32 in.).

2.2.4. pH Measurements. pH is a value that indicates the concentration of hydrogen ions in a liquid and is used to determine the acidity or alkalinity of drilling muds. The pH has a significant effect on the rheological and fluid loss properties of the drilling muds.⁴² The pH value is expressed numerically (0–14), indicating an inverse measurement of the hydrogen ion concentration in the fluid. The pH of drilling fluids was measured using a digital pH meter from Mettler Toledo under room conditions (21 °C). The pH meter is the most precise instrument available for measuring pH. It is an electrical device that uses glass electrodes to detect a potential difference and instantly indicates the pH of a sample.

The pH of the drilling muds was measured by applying the API-13B standard procedure.⁴³ Before taking a pH measurement, the meter must be calibrated using a buffer solution with a known pH, such as 4, 7, or 10 pH. After removing the electrode from its storage cap, it was washed with distilled water. It is then dipped into the drilling mud sample. The drilling mud is stirred for a few seconds with the pH electrode before starting the measurement. The meter begins logging immediately, and the pH gradually changes before stabilizing after a while. The stable pH reading indicates the drilling mud's pH.

3. RESULTS AND DISCUSSION

3.1. H₂S-Scavenging Capacity. The scavenging performance of the drilling muds was determined by a breakthrough method. The concentration level of H₂S in the outlet gas stream was continuously monitored until it reached 15 ppm. The change in H₂S concentration in the outflow gas stream as a function of time is depicted in Figure 2 (i.e., breakthrough curves). The scavenging capacities of all samples are given in Table 4.

Table 4. Breakthrough Times and Scavenging Capacities of the Drilling Mud Samples

sample #	breakthrough time (min)	scavenging capacity at breakthrough time (mg of H ₂ S/L of mud)
LWM	25	28.1
HWM	2	2.2
LWM/Cu	120	135.0
HWM/Cu	82.5	92.8
LWM/Fe	1.5	1.7
HWM/Fe	1	1.1
LWM/K	179	201.3
HWM/K	2	2.2
LWM/Cu + K	101	113.6
HWM/Cu + K	64.5	72.5

The first two samples (LWM and HWM) were treated as base drilling muds. LWM and HWM showed low scavenging capacity, as there were no scavengers. In comparison to LWM, HWM demonstrated a lower scavenging capacity. The time required for a breakthrough was only 2 min, implying that less than 2.2 g/mL H₂S was scavenged per ml of drilling mud at breakthrough. At saturation (when the H₂S concentration in the outlet gas stream reaches 15 ppm), the total amount of H₂S scavenged was estimated to be approximately 2.2 g/mL of the HWM drilling mud. In contrast, LWM demonstrated a higher scavenging capacity of 28.1 g/mL.

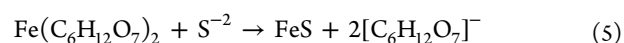
Copper nitrate (Cu(NO₃)₂·3H₂O) was added to LWM and HWM at 2.10 g/1000 mL of drilling mud concentration. The H₂S breakthrough time was 120 and 82.5 min in the presence of copper nitrate in LWM/Cu and HWM/Cu, respectively. Therefore, the H₂S-scavenging capacity in the presence of copper nitrate in LWM/Cu and HWM/Cu is 135.0 mg of H₂S/L of mud and 92.8 mg of H₂S/L of mud, respectively. The ability to scavenge H₂S increased greatly when compared to base mud samples (LWM and HWM).

Numerous researchers have investigated the use of copper nitrate-containing drilling mud for H₂S scavenging.^{30,39,44} Copper nitrate effectively removed H₂S from a sour gas stream, with a scavenging capacity nearly three times that of a commercial triazine-based scavenger. Copper compounds have a major drawback, which is their tendency to accelerate equipment corrosion. Therefore, copper-based scavengers are not commonly used in the industry and have been largely replaced with scavengers based on iron or zinc compounds. The detailed scavenging capacity of copper nitrate was discussed in our previous study by Onaizi et al.⁴⁵ Furthermore, to address the corrosion issue, during the drilling of an H₂S-containing formation, the drilling fluids are combined with a corrosion inhibitor to protect the metals from the severe effects of H₂S. These corrosion inhibitors can be useful in mitigating the adverse effects of other acidic compounds produced during the scavenging process.

The proposed reaction equation between copper nitrate and H₂S is as follows (eq 4)³⁹



Davidson⁴⁶ introduced iron gluconate as an environment-friendly H₂S scavenger and found that iron gluconate removed the sulfide from drilling fluids with a pH of 9 and above without having adverse effects on the rheological properties of drilling fluids. Similarly, Amosa et al.⁴⁷ investigated it as a scavenger and proposed a reaction (eq 5) of iron gluconate with H₂S.

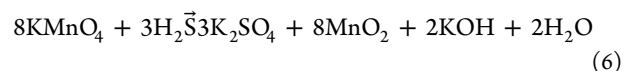


Ferrous gluconate + sulfide → ferrous sulfide + gluconate.

Iron gluconate was added to LWM and HWM at 5.71 g/1000 mL of drilling mud concentration to make LWM/Fe and HWM/Fe, respectively. The H₂S breakthrough time was decreased upon the addition of iron gluconate. It was 1.5 and 1 min in LWM/Fe and HWM/Fe, respectively. Therefore, the H₂S-scavenging capacity in the presence of iron gluconate was reduced compared to that of the base mud systems without scavengers.

Potassium permanganate was added to LWM and HWM at 2.10 g/1000 mL of drilling mud concentration to make LWM/K and HWM/K, respectively. The H₂S breakthrough times for LWM/K and HWM/K were 179 and 2 min in the presence of potassium permanganate, respectively. Therefore, the H₂S-scavenging capacity of LWM/K and HWM/K is 201.3 mg of H₂S/L of mud and 2.2 mg of H₂S/L of mud, respectively. The scavenging capacity of LWM was increased by seven times. On the other hand, the scavenging capacity of HWM/K was compromised, and the potassium permanganate addition did not bring any change in the scavenging capacity of HWM. The amount of H₂S scavenged (201.3 mg/g) up to the breakthrough time using potassium permanganate-containing drilling mud LWM/K was higher than the corresponding values obtained using copper nitrate-containing drilling mud LWM/Cu. Potassium permanganate showed a higher H₂S-scavenging capacity than copper nitrate and iron gluconate for the LWM mud system. However, it did not impact the scavenging capacity of the HWM mud system and was outperformed as compared to copper nitrate (HWM/Cu).

Potassium permanganate scavenges H₂S according to the following reaction (eq 6)⁴⁸



Furthermore, the synergistic impact of copper nitrate and potassium permanganate as scavengers was investigated. Both additives were mixed in base mud systems at a concentration of 1.05 g/1000 mL of mud. The scavenging capacities of LWM and HWM increased greatly due to the addition of the two scavengers in LWM/Cu + K and HWM/Cu + K. Nonetheless, the scavenging capacities of the mixed two scavengers underperformed the scavenging capacities when each of the scavengers is added alone. The scavenging capacities of LWM/Cu (135.0 mg of H₂S/L of mud) and LWM/K (201.3 mg of H₂S/L of mud) are higher than the scavenging capacity of LWM/Cu + K (113.6 mg of H₂S/L of mud). Also, the scavenging capacity of LWM/K is higher than that of LWM/Cu + K (201.3 and 113.6 mg of H₂S/L of mud, respectively). The only exception is in the HWM with potassium permanganate (HWM/K), as it shows much less scavenging capacity than

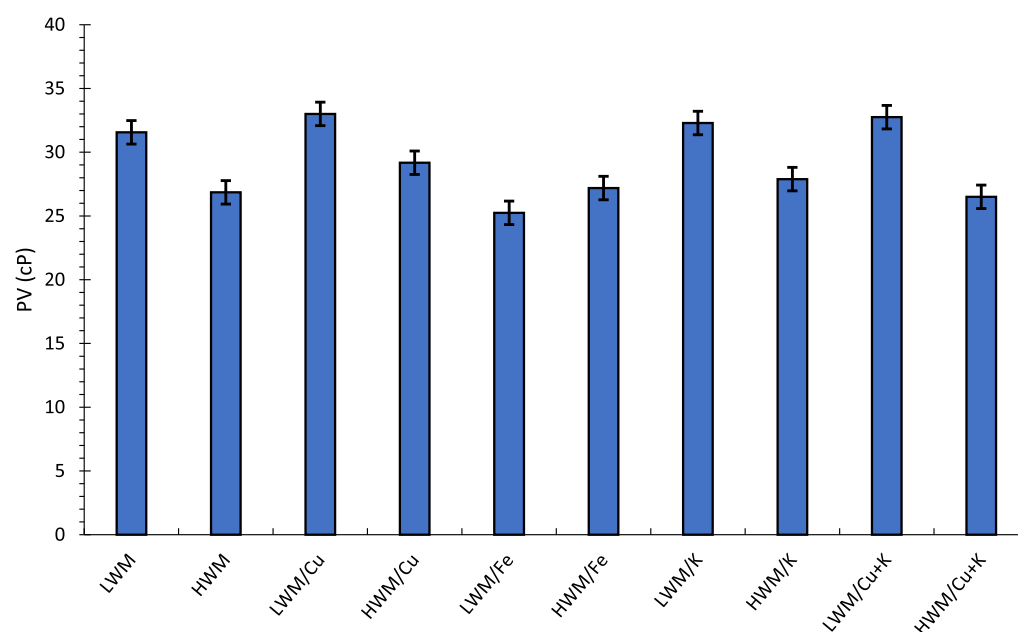


Figure 3. PV of base and scavenger-containing drilling muds.

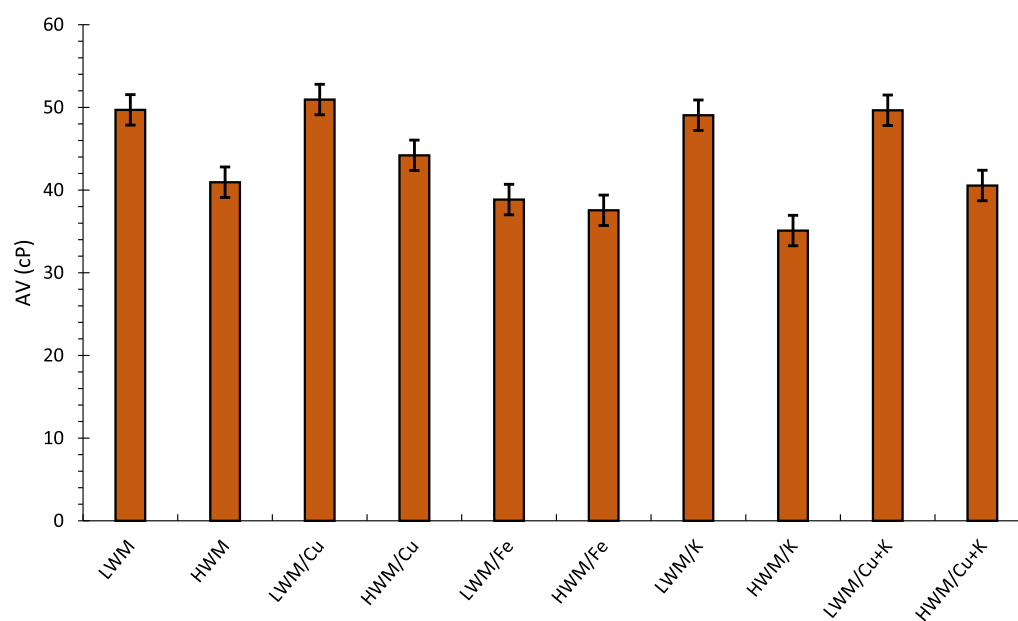


Figure 4. AV of base and scavenger-containing drilling muds.

HWM/Cu + K (2.2 and 72.5 mg of $\text{H}_2\text{S}/\text{L}$ of mud, respectively). Overall, mixing the two scavengers did not result in any desired improvements in terms of scavenging capacity.

In terms of scavenging capacity, potassium permanganate (LWM/K) had the highest scavenging capacity (201.3 mg of $\text{H}_2\text{S}/\text{L}$ of mud at breakthrough time) for the lighter drilling mud system (LWM) and overall as well. For the heavier drilling mud system (HWM), potassium permanganate (HWM/K) did not impact the scavenging capacity of the base mud, while copper nitrate (HWM/Cu) provided the highest scavenging capacity in the heavier (HWM) mud system (92.8 mg of $\text{H}_2\text{S}/\text{L}$ of mud). Also, in the lighter base mud system (LWM) copper nitrate increased the H_2S -scavenging capacity of the base drilling mud greatly (from 28.1 to 135.0 mg of $\text{H}_2\text{S}/\text{L}$ of mud). The mixing of the two scavengers (copper nitrate and potassium permanganate) worked very well in both drilling systems in terms of

scavenging capacity by increasing the scavenging capacity of the base drilling muds greatly. Iron gluconate did not perform very well; the H_2S -scavenging capacity in the presence of iron gluconate was reduced compared to that of the base mud systems without scavengers.

3.2. Rheological Properties. After measuring the scavenging potential of the additives, the first thing that is considered is the pumpability of the scavenger-containing drilling muds. It is an essential requirement that the H_2S scavenger should not damage the drilling mud's rheological properties if it is to be used in drilling mud compositions. To evaluate the scavenger impact on rheology, a series of rheological tests on drilling muds were conducted in the presence of copper nitrate, iron gluconate, and potassium permanganate, comparing the results with the standard drilling mud system (LWM and HWM) results.

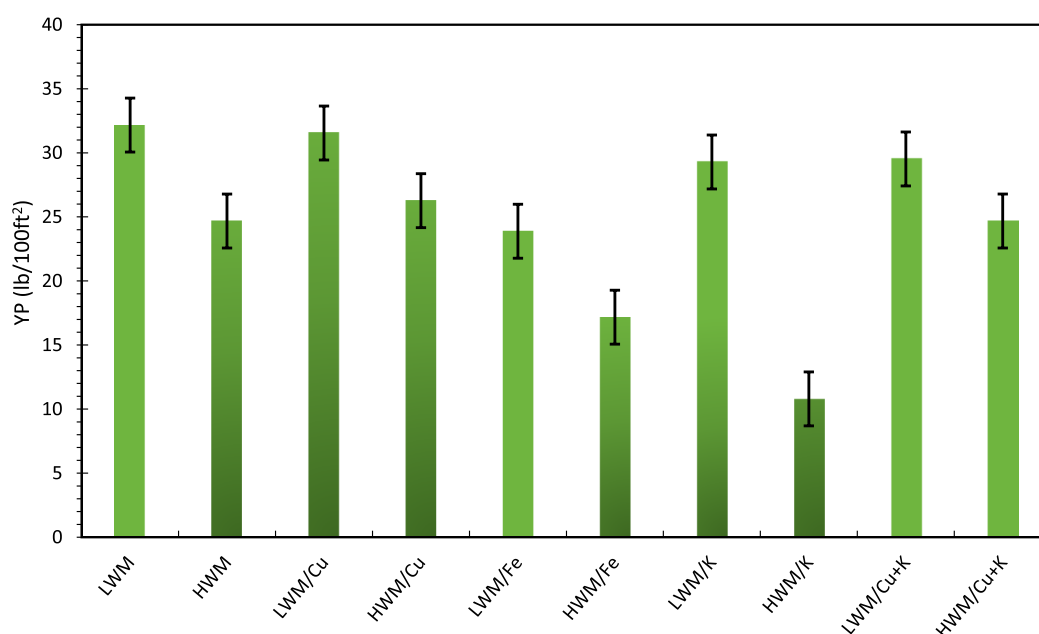


Figure 5. YP of base and scavenger-containing drilling muds.

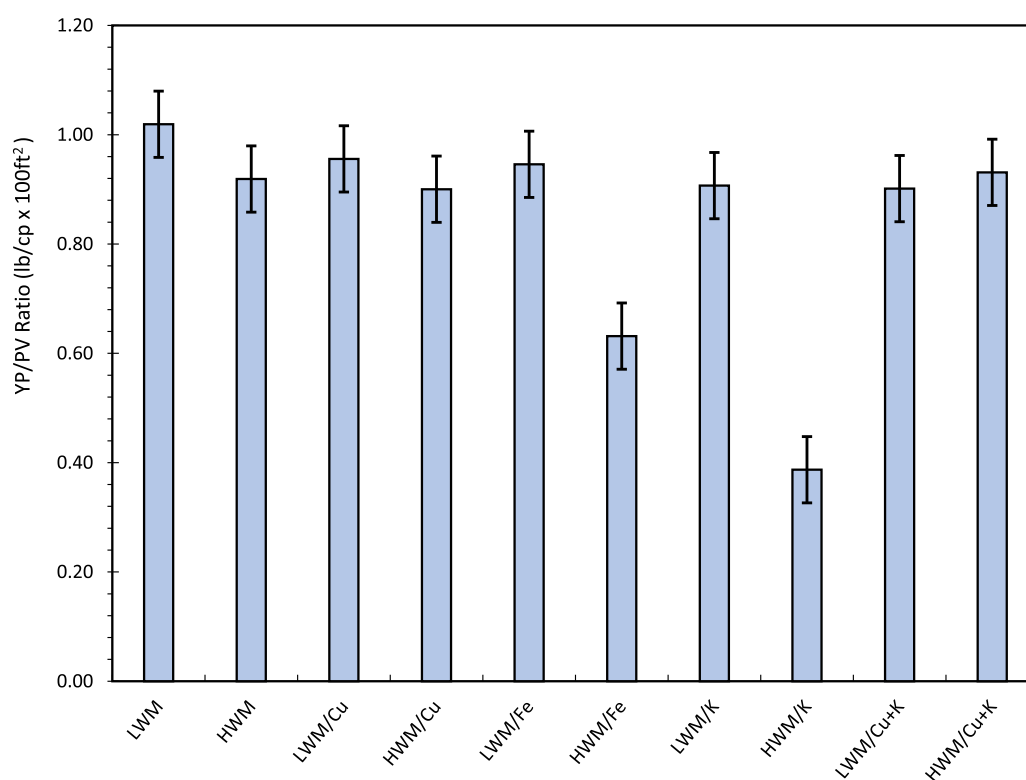


Figure 6. Carrying capacity (YP/PV ratio) of base and scavenger-containing drilling muds.

Various rheological parameters were measured, including PV, YP, and gel strengths. The carrying capacity of the drilling muds was investigated by calculating the ratio (YP/PV). Figures 3–6 provide results of rheological parameters.

PV is an essential rheological property of drilling muds. It offers flow resistance to drilling muds, and it is affected by the number of solids in the mud system. Increased PV is linked to higher flow resistance and vice versa. As a result, low-PV drilling muds are preferable in terms of pumping costs. Therefore, the drilling muds' PV range must be kept within a specific value. The

PV values of the base and scavenger-containing drilling muds are shown in Figure 3. The PV values of the base drilling muds LWM and HWM were 31.6 and 26.9 cP, respectively. The PV was slightly increased when copper nitrate was added to the base drilling muds as PV of LWM rose from 31.6 to 33 cP as observed in LWM/Cu. The increase in PV by the addition of copper nitrate was shown in previous work in the literature where Elkhatny et al.⁴⁰ observed that copper nitrate increased the PV by 20%. Similarly, PV of HWM was slightly increased by the addition of copper nitrate in HWM/Cu. The addition of iron

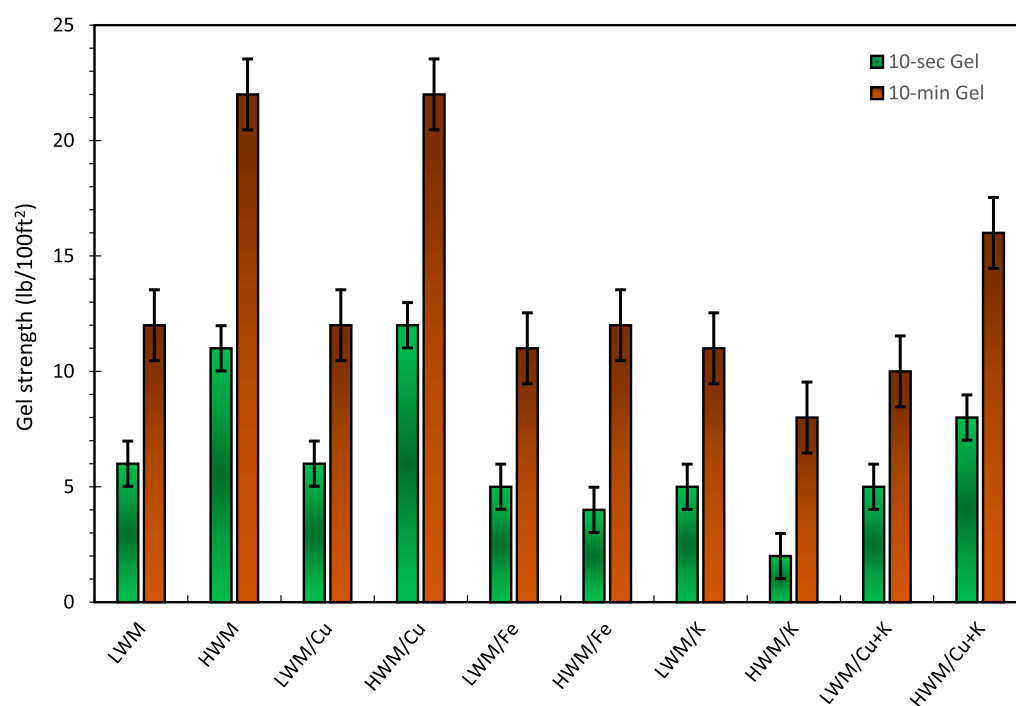


Figure 7. Gel strengths (10 s and 10 min) of base and scavenger-containing drilling muds.

gluconate in LWM/Fe brought down the PV values of the base mud sample LWM from 31.6 to 25.2 cP. Iron gluconate did not affect the second base mud sample (HWM), as demonstrated with the HWM/Fe PV results.

However, when potassium permanganate was added to the base drilling muds, the PV of both mud systems increased, as demonstrated in LWM/K and HWM/K. This increase in PV is observed in the literature as well. For instance, Onaizi et al.⁴⁵ investigated that potassium permanganate increased the PV of WBDFs. The addition of copper nitrate and potassium permanganate as a synergist slightly increased the PV of LWM, as shown in LWM/Cu + K. The PV of HWM stayed the same. Overall, all the scavenger-containing drilling muds did not have any significant harmful impact on the PV of the drilling base muds. Also, the PV value of all tested WBDFs met the recommended PV range (10–60 cP) for biodiesel-based drilling muds by Li et al.⁴⁹ The AV was measured for all the samples, as shown in Figure 4; the AV results showed similar trends as those of PV.

The YP is another critical characteristic of drilling muds. It is defined as the shear stress required to initiate fluid flow. It is caused by the electrochemical attraction of the drilling mud's additives. The YP is proportional to the ability of the drilling mud to lift the drill cuttings out of the wellbore; drilling muds with a higher YP have better lifting characteristics. However, higher YP values are associated with increased mud viscosity, which increases the amount of energy required for circulation. Thus, an optimal value is needed that is both high enough to ensure efficient lifting of the drill cuttings and low enough to avoid excessive pump pressure. As illustrated in Figure 5, the addition of copper nitrate in LWM/Cu and HWM/Cu had little effect on the YP of the base drilling muds (LWM and HWM). However, by adding iron gluconate in LWM/Fe and HWM/Fe, the YPs of the base drilling muds were decreased significantly from 32.17 to 23.88 lb/100 ft² and 24.68 to 17.17 lb/100 ft² for LWM and HWM, respectively. This reduction in the YPs of the

base drilling muds in the presence of iron gluconate indicates that electrochemical forces decrease among particles. The addition of potassium permanganate brought a slight change in the base mud LWM and badly impacted HWM, as shown in LWM/K and HWM/K. The YP of HWM was decreased from 24.68 to 10.80 lb/100 ft².

The carrying capacity of drilling muds (YP/PV) is another critical rheological property. It is related to the drilling mud's ability to suspend drill cuttings and, thus, to remove them from the wellbore. The carrying capacity (YP/PV) values for the base drilling mud and the scavenger-containing drilling muds are shown in Figure 6. According to the literature, an YP/PV value of ≥ 0.75 is associated with a high carrying capacity of drilling muds, resulting in improved wellbore-cleaning performance.⁵⁰ All three scavenger-containing drilling muds (in addition to the base drilling mud) have an excellent ability to clean wellbores and suspend drill cuttings in both drilling mud systems except for the iron gluconate and potassium permanganate impact on the base mud sample (HWM). The YP/PV ratio of HWM was decreased, with a significant impact noticed in the presence of potassium permanganate in HWM/K.

Additionally, the effect of the scavengers on the gel strength of the drilling muds was evaluated. The gel strength of a drilling mud indicates its ability to suspend drill cuttings and solid ingredients (e.g., weighting agent) when mud circulation is ceased. Figure 7 illustrates the gel strengths of the base and scavenger-containing drilling muds after 10 s and 10 min. The gel strength at 10 min for all drilling muds is significantly greater than the gel strength at 10 s, demonstrating the time effect on the gel strength of these muds. First of all, LWM showed less gel strength values compared to HWM. The addition of scavengers in LWM did not affect its gel strengths at 10 s and 10 min. Almost all the scavengers resulted in the same results as the base mud sample. For HWM, the addition of scavengers changed the gel strengths with a higher impact on the 10 min gel strength. The addition of copper nitrate did not alter the gel strengths of

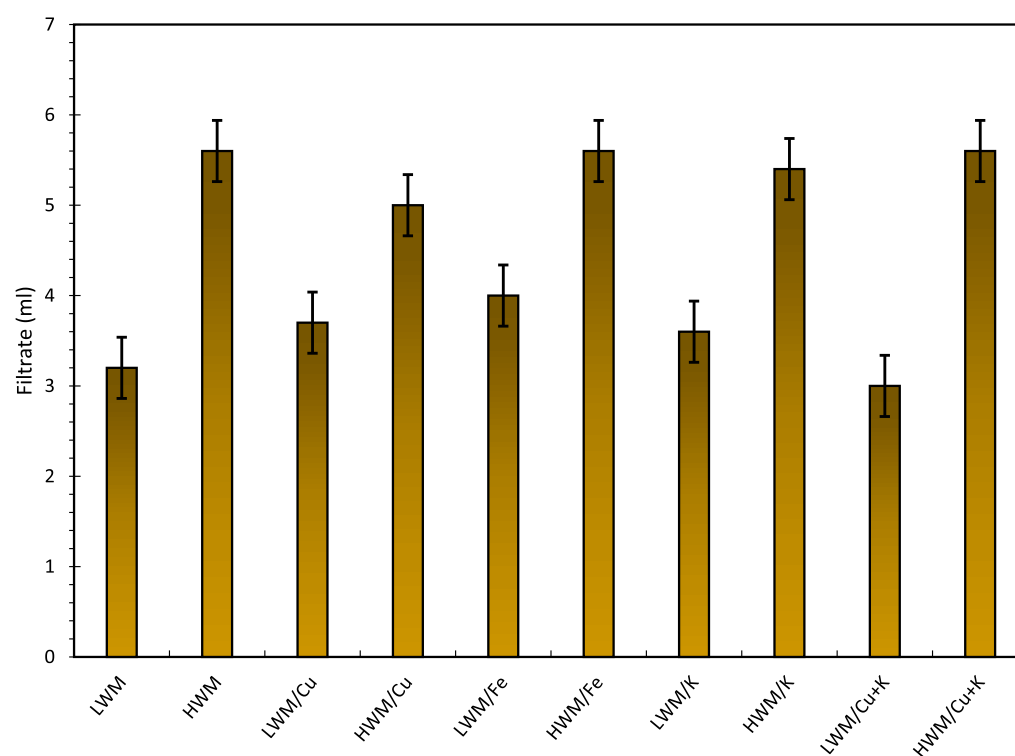


Figure 8. API fluid loss after 30 min of base and scavenger-containing drilling muds.

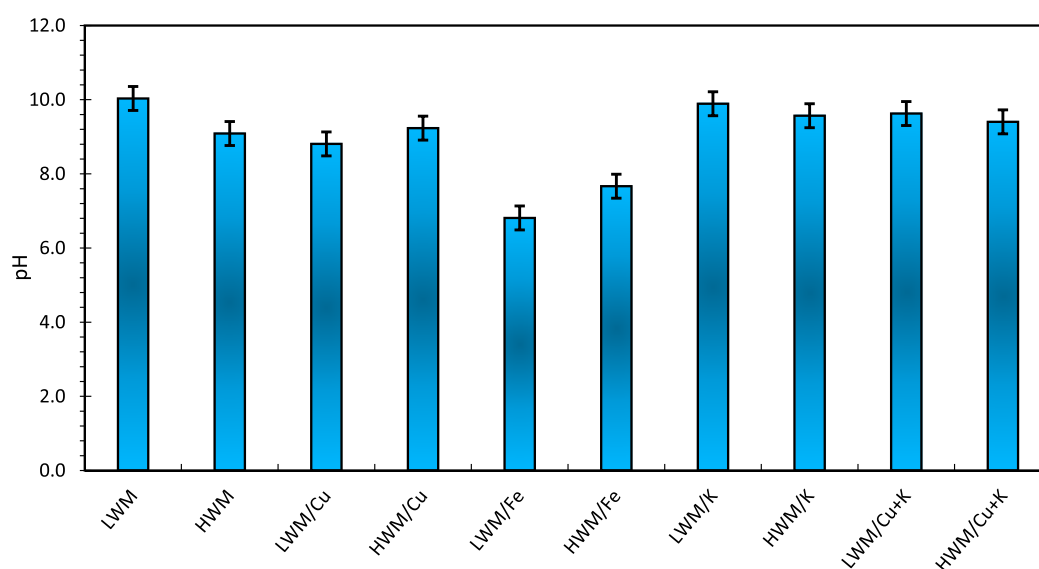


Figure 9. pH values of base and scavenger-containing drilling muds.

LWM and HWM. Iron gluconate showed a significant effect on HWM, as depicted in HWM/Fe. The 10 s and 10 min gel strengths reduced from 11 to 4 lb/100 ft² and 22 to 12 lb/100 ft², respectively. Similarly, potassium permanganate affected both base mud systems (LWM and HWM), significantly impacting HWM. This could be due to the interaction between the scavenger and the weighting materials (i.e., calcium carbonate) in the heavier mud system (HWM). The combined addition of copper nitrate and potassium permanganate brought a little change in gel strengths from the base values in the LWM, as depicted by LWM/Cu + K. In the HWM, the gel strength was reduced greatly, as depicted by HWM/Cu + K. This could also

be due to the interaction between potassium permanganate and the weighting materials.

3.3. Fluid Loss Properties. Fluid loss tests were conducted to gain insights into the base drilling mud's fluid loss-controlling characteristics and how the addition of H₂S scavengers affects these characteristics. As illustrated in Figure 8, the fluid loss from the base drilling mud samples, LWM and HWM, after 30 min was approximately 3.2 and 5.6 mL, respectively. Copper nitrate slightly changed the fluid loss of both LWM and HWM. The fluid losses from the copper nitrate-containing drilling muds, LWM/Cu and HWM/Cu, were 3.7 and 5.0 mL, respectively. This shows copper nitrate's negligible effect on the base mud's fluid loss-controlling properties. Iron gluconate in LWM/Fe

increased the fluid loss of LWM from 3.2 to 4 mL, and in HWM/Fe, it showed no effect on HWM, as the fluid loss was maintained at 5.6 mL after its addition. A similar response was observed in potassium permanganate-containing drilling muds. Onaizi et al.⁴⁵ observed a similar response that the addition of copper nitrate and potassium permanganate increased the fluid loss as noticed in this study with the light-weight drilling muds, LWM/Cu and LWM/K. For LWM/Cu + K and HWM/Cu + K, no change in the fluid loss volume was observed compared to base drilling muds. It showed that the synergistic effect of copper nitrate and potassium permanganate maintained the fluid loss. It was observed that the fluid losses from the base and scavenger-containing drilling muds remained in the limit of 15 mL/30 min when subjected to standard API test conditions.⁵¹ Overall, all the scavenger-containing drilling muds did not have any significant harmful impact on the fluid loss properties of the drilling base muds. The thickness of the filter cakes acquired at the end of the fluid loss test was measured. It was found that the base drilling mud, LWM and HWM, filter cake thicknesses were 0.80 and 1.60 mm, respectively. The addition of scavengers did not change the filter cake thickness of both LWM and HWM. Both values remained relatively constant for all tested scavengers.

3.4. pH Effect. pH is a value that determines the acidity or alkalinity of drilling muds. The pH value is expressed numerically (0–14), indicating an inverse measurement of the hydrogen ion concentration in the fluid. The mud system with a pH of above 7 is basic, and the mud sample with a pH of below 7 is considered acidic. Figure 9 provides the pH values of the base and scavenger-containing drilling muds. The pH of the base mud systems, LWM and HWM, was 10.03 and 9.09, respectively. The addition of scavengers slightly changed the pH of the base drilling muds. Copper nitrate slightly reduced the pH, and potassium permanganate brought a minor change in the pH of the drilling muds. However, significant differences were noticed upon the addition of iron gluconate, which reduced the pH of LWM and HWM to 6.81 and 7.61, respectively, in LWM/Fe and HWM/Fe. Davidson et al.⁵² used iron gluconate as a scavenger and observed that it reduced the pH of the drilling muds. The reduction in pH by iron gluconate is due to the high H^+ in the drilling mud and can be attributed to the production of ferrous sulfide that may interact with the drilling mud solids. The resulting low pH values by the addition of iron gluconate could be very corrosive, potentially leading to a very poor efficiency in both drilling mud systems.

4. CONCLUSIONS

This study investigated the scavenging capacity and rheological properties of three different H_2S scavenger additives on WBDFs. The three types of H_2S scavengers are copper nitrate, iron gluconate, and potassium permanganate. Also, a mixture of copper nitrate and potassium permanganate in the drilling mud was studied too. These additives were tested on two actual field drilling mud samples. The two base drilling muds (LWM and HWM) differ in their weight and solid content. The scavengers' impact on drilling muds was investigated by measuring their scavenging capacity and their effect on rheology, fluid loss properties, and pH values. These tests were performed to ultimately provide the optimal type and concentration of the H_2S scavenger for a WBDF that provides the maximum scavenging capacity with minimal or no impact on the drilling mud properties. The following are the conclusions for the work presented in this study.

Overall, copper nitrate worked very well and outperformed the other scavengers in the heavier (higher density) drilling mud system (HWM), while in the lighter (lower density) drilling mud system (LWM), potassium permanganate outperformed the other scavengers.

For potassium permanganate, the efficiency of the heavier drilling mud (HWM) was degraded. This could be due to the interaction between potassium permanganate and the weighting materials (i.e., calcium carbonate) in the heavier drilling mud system (HWM).

Iron gluconate did not perform very well in terms of scavenging capacity. The H_2S -scavenging capacity in the presence of iron gluconate was reduced compared to that in the base mud systems without scavengers.

The scavenging capacities of the mixed two scavengers (copper nitrate and potassium permanganate) underperformed the scavenging capacities when each of the scavengers is added alone. Overall, mixing the two scavengers did not result in any desired improvements in terms of scavenging capacity.

All the scavenger-containing drilling muds did not have any significant harmful impact on the fluid loss properties of the drilling base muds.

All the scavenger-containing drilling muds (in addition to the base drilling mud) have an excellent ability to clean wellbores and suspend drill cuttings in both drilling mud systems ($YP/PV \geq 0.75$). The only exception is when iron gluconate or potassium permanganate is added to the heavy mud system; they both tend to reduce the carrying capacity of the heavy drilling mud greatly.

The lighter mud base (LWM) showed less gel strength values compared to heavier mud base (HWM). Also, all the scavengers resulted in a similar effect on the gel strength when added to the lighter base mud sample (LWM). For the heavier base mud sample (HWM), iron gluconate and potassium permanganate reduced its gel strengths significantly.

Copper nitrate and potassium permanganate brought a minor change in the pH of the drilling muds. However, a significant reduction in pH values is noticed upon the addition of iron gluconate in both base mud systems. The resulting and potentially corrosive low pH values (6.81 and 7.67) could be caused due to the production of ferrous sulfide that may interact with the drilling mud solids, leading to a very poor efficiency in both drilling mud systems.

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<https://pubs.acs.org/10.1021/acsomega.1c03792>

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors of this article would like to acknowledge the support provided by the King Fahd University of Petroleum and Minerals (KFUPM) to publish this work.

NOMENCLATURE

- AV, apparent viscosity
cP, inlet concentration, ppm
 C_{in} , outlet concentration, ppm
 C_{out} , density, mg/mL
 ρ , viscometer dial reading at different speeds
 ϕ , dimensionless
PV, plastic viscosity
cP, inlet concentration, ppm
Q, breakthrough time
 t_B , minutes
V, volume, mL
YP, yield point, lb/100 ft²

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