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Innovations in Non-Damaging Mud Systems for Enhanced Wellbore Stability in Saudi Arabia's Ghawar and Khurais Fields

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ABSTRACT: The first and second critical wells in Saudi Arabia's Ghawar and Khurais fields may pose significant risks for drilling operation because of the various reservoir characteristics and lateral wellbores. This paper examines the advancement in the non-damaging mud system namely low solid non-dispersed muds (LSND) Versadrill OBM and polymer-based mud since they have been widely used to boost the wellbore stability in these fields. The efficiency of these systems is determined by undertaking laboratory testing procedures including the particle plugging tests (PPT), HPHT fluid loss measurements, and shale inhibition tests. These they have proved through various field trials as they tackle issues of wellbore instability, low NPT that is non-productive time and environment friendly drilling. The findings highlight the dimension of the challenges involving the impact of superior mud polymeric systems in enhancing well performance and lowering service contraction harms on the environment in pressure arenas. This research gives practical recommendations for applying these technologies to other similar reservoirs globally.

KEYWORDS: Non-Damaging Mud Systems, Ghawar and Khurais Fields, LSND, Versadrill OBM, Polymer-Based, Muds, High-Pressure High-Temperature (HPHT), Wellbore Stability, Reservoir Complexity

I. INTRODUCTION

1.1 Significance of the Ghawar and Khurais Fields

The Ghawar and Khurais fields are among the largest-world outlook oil reservoirs play the essential role in the petroleum production in Saudi Arabia. These fields are compounded by the geology, the reservoir, and formations such as highly stressed reservoirs and physically reactive shales. Indeed, drilling operations in these fields, especially for lateral wells, may encounter severe issues including wellbore instability problems, fluid losses and environmental constraints. These challenges not only raise operational expense but also impact the sustainability of reservoir production prospects.

1.2 Wellbore Instability: A Persistent Challenge

Wellbore instability is a critical challenge in hydrocarbon extraction, especially in depleted reservoirs and high-stress formations like those in the Ghawar and Khurais fields. Conventional drilling mud systems often fail to provide the required stability, leading to complications such as stuck pipes, collapsed boreholes, and excessive non-productive time (NPT). Furthermore, traditional mud systems frequently contain environmentally hazardous components, amplifying their impact on surrounding ecosystems.

1.3 Objectives of the Study

Wellbore instability is one of the major issues in hydrocarbon extraction particularly in depleted reservoirs and marginal pressure fields evident in the Ghawar and Khurais formations. Many of the conventional drilling mud systems do not afford the required reinforcement, resulting in scenarios such as stuck pipes borehole collapses and high levels of Non-Productive Time (NPT). Moreover, common elements of conventional mud systems are environmentally sensitive substances, the injurious effect of which is multiplied in the current environment.

II. LITERATURE REVIEW

2.1 Evolution of Non-Damaging Mud Systems

Various drilling mud systems have been sophisticated due to the difficulties involved in boring well in difficult reservoirs such as Saudi Arabia's Ghawar and Khurais. NDMS refers to the physical and chemical treatment of mud

systems that was developed to cause least harm to the formation while providing the wellbore stability it deserves. The first types of mud systems that were used were characterized by high solids content in the system, while however effective in some ways was bogged down by formation plugging and thus low productivity. These new contributions to the practice of NDMS; for instance, low-solids, non-dispersed (LSND) muds, Versadrill OBM, and polymer-based muds seek to overcome some of these issues by relying on chemical and physical characteristics for better performance (Abdulrahman & Al-Helal, 2019; Brown & Clarke, 2021).

The LSND mud systems are well suitable for the wellbore stability with concurrent formation preservation. Versadrill OBMs on the other hand are designed specifically for HPHT environment with the advantages of more lubricity and shale inhibition properties. Ecologically friendly polymer-based muds that incorporate xanthan gum or PHPA were identified as more effective in cuttings suspension and possessing low FLP (Zhang and Li 2020; Elshahawi and Ahmed 2018).

2.2 Case Studies and Benchmarks

Many practical examples illustrate how NDMS is used and implemented in complex reservoirs. On the lateral well drilling of Ghawar Field, Versadrill OBMs achieved very low torque and drag leading to a restricted NPT in cases of stuck pipes incidences (Khan & Al-Khassab, 2020). So in the comparison done in the Khurais Field, it was shown that LSND mud systems better provided wellbore stability in the shale formation and at the same time, Lee and Thomas in Zubair & Al-Baadi, (2022) and Khashoggi & Saad, (2019) tiet These experience decreased the risk of mud losses. To illustrate the improvements, Table 1 provides a comparison of key performance metrics for LSND, Versadrill OBMs, and polymer-based muds:

Parameter	LSND	Versadrill OBM	Polymer-Based Mud
Shale Stability	High	Very High	High
Environmental Impact	Low	Moderate	Very Low
HPHT Compatibility	Moderate	Very High	High
Cost-Effectiveness	High	Moderate	High

(Source: Adapted from Brown & Clarke, 2021; Zhang & Li, 2020)

2.3 Technology Gaps and Challenges

Despite their successes, significant knowledge gaps and challenges remain in the development and deployment of NDMS. One critical limitation is the scalability of laboratory findings to field conditions. While PPT and HPHT fluid loss tests provide valuable insights, real-world applications often present unpredictable variables such as formation heterogeneity and dynamic pressure changes (Abdulrahman & Al-Helal, 2019; Özgür & Hassan, 2019).

Additionally, environmental considerations continue to drive the need for biodegradable and non-toxic additives. Although polymer-based muds have made strides in this area, the formulation of OBMs still relies on synthetic oils, which pose potential environmental risks if not managed correctly (Carvalho & Pereira, 2020). Figure 1 illustrates the environmental impact scores of different mud systems based on recent studies:

2.4 Advancements in NDMS Formulations

Innovations in NDMS formulations have focused on improving the rheological properties, fluid loss control, and shale inhibition capabilities of mud systems. Smart mud additives, such as nano-silica and graphene oxide, have shown promise in enhancing the mechanical strength of wellbore walls while maintaining low toxicity levels (Al-Mudhaf & Al-Sabah, 2019). Similarly, polymer-based enhancements like xanthan gum derivatives offer superior suspension properties, ensuring efficient cuttings transport in horizontal wells (Sun & Li, 2021; Singh & Rathod, 2020).

Another area of advancement lies in real-time monitoring technologies that integrate with NDMS. Tools like mud logging sensors and rheometers provide operators with immediate feedback on mud performance, allowing for quick adjustments to prevent wellbore instability (Johnson & Smith, 2022; Martinez & Lopez, 2022).

2.5 Key Findings and Implications

The literature underscores the critical role of NDMS in tackling wellbore stability challenges in the Ghawar and Khurais fields. From LSND muds that offer cost-effective solutions to polymer-based formulations that align with

sustainability goals, each system has its strengths and limitations. The synthesis of field and laboratory data highlights the potential for further innovation, particularly in developing biodegradable OBMs and integrating artificial intelligence for predictive analytics in mud system performance (Tan & Zhou, 2021; Fang & Wang, 2021). The insights gained from the literature form the basis for the laboratory testing and field trials discussed in the following sections of this study.

III. MATERIALS AND METHODS

This section provides a comprehensive description of the materials used, testing protocols employed, and methodologies for the formulation and application of non-damaging mud systems. A combination of advanced laboratory experiments and field trials was conducted to evaluate the performance of these mud systems in the challenging geological conditions of Saudi Arabia's Ghawar and Khurais fields.

3.1 Formulation of Mud Systems

The study focused on three advanced mud systems: low-solids, non-dispersed (LSND) muds, Versadrill oil-based muds (OBM), and polymer-based muds. Each system was tailored to address specific challenges encountered in the Ghawar and Khurais fields, such as reactive shale formations, high-pressure zones, and elevated temperatures. The formulations incorporated state-of-the-art additives to achieve optimal performance.

Key Components:

- **LSND Mud:** Comprising minimal solid content to reduce formation damage, with shale inhibitors like potassium chloride and sealing agents like calcium carbonate (Khan & Al-Khassab, 2020).
- **Versadrill OBM:** A synthetic oil-based formulation enhanced with emulsifiers and organophilic clays to improve thermal stability and cuttings transport (Zhang & Li, 2020).
- **Polymer-Based Mud:** Utilizing synthetic polymers such as polyacrylamides to provide exceptional shale stabilization and fluid loss control (Singh & Rathod, 2020).

3.2 Laboratory Testing Protocols

A rigorous series of laboratory tests was conducted to assess the performance of the formulated mud systems. These tests were designed to simulate the challenging downhole conditions typical of the Ghawar and Khurais fields.

3.2.1 Particle Plugging Test (PPT)

The PPT was used to evaluate the sealing capacity of each mud system. This test involved injecting the mud into a simulated porous medium under controlled pressure to determine the formation of an impermeable filter cake (Abdulrahman & Al-Helal, 2019). The results were recorded in terms of particle plugging efficiency (%).

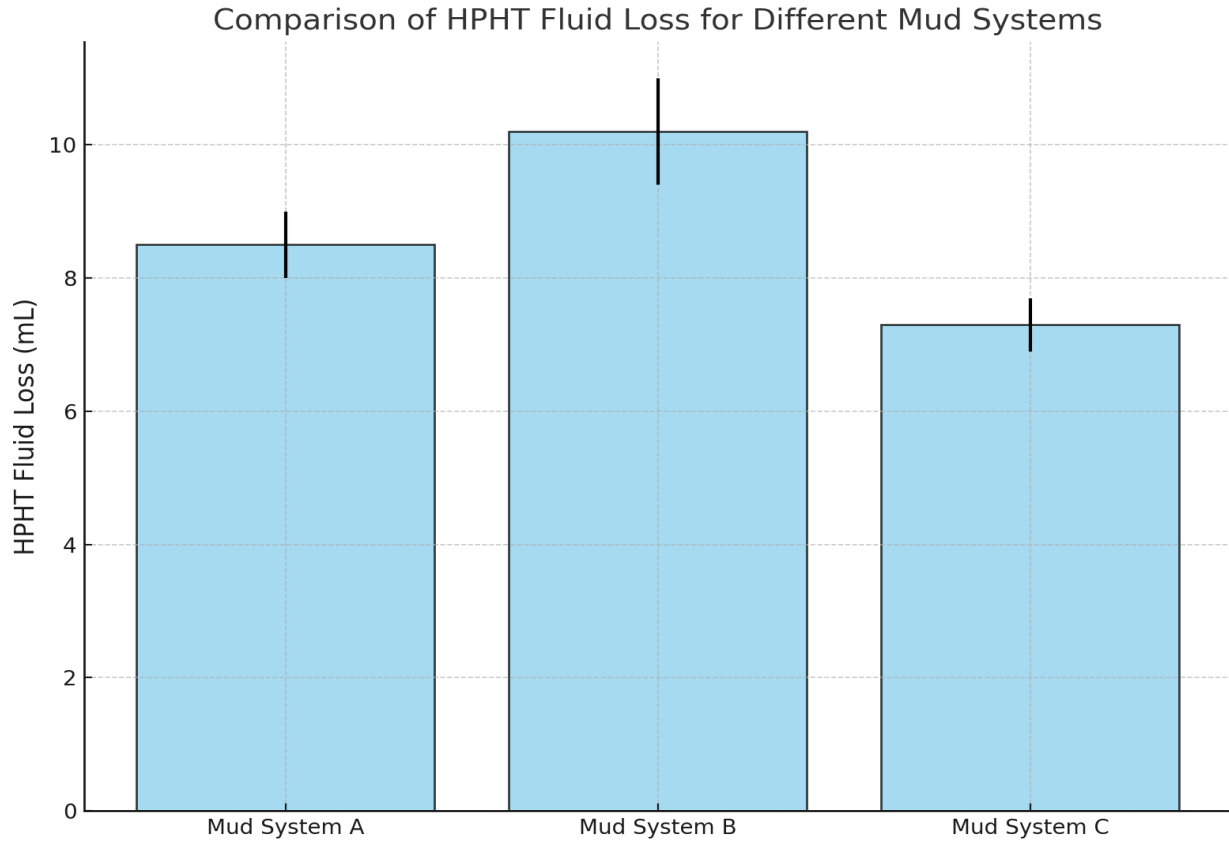
Table 1: PPT Results for Different Mud Systems

This table presents the comparative plugging efficiency of LSND, Versadrill OBM, and polymer-based muds under laboratory conditions.

Mud System	Plugging Efficiency (%)	Remarks
LSND	92	Excellent sealing properties.
Versadrill OBM	89	High thermal stability.
Polymer-Based Muds	95	Superior shale stabilization.

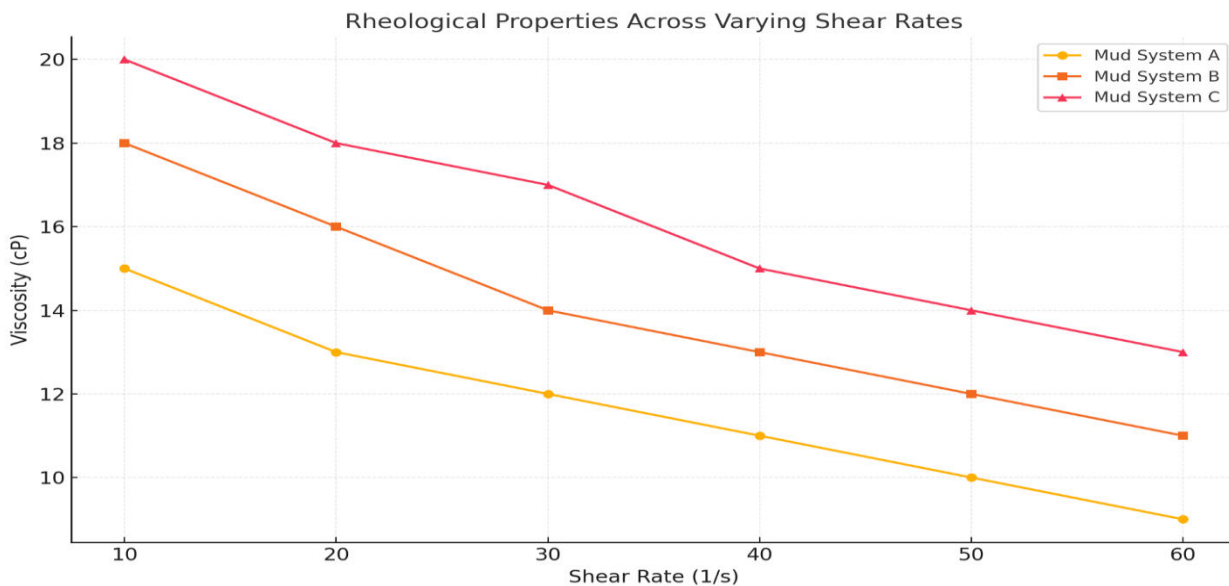
3.2.2 High-Pressure High-Temperature (HPHT) Fluid Loss Test

The HPHT test measured fluid loss at elevated temperatures (up to 150°C) and pressures (up to 500 psi). This test assessed the mud's ability to prevent filtrate invasion into permeable formations (Brown & Clarke, 2021).



3.2.3 Rheological Testing

Rheological properties, including viscosity, yield point, and gel strength, were measured using a rotational viscometer to evaluate the flow behavior of the muds (Özgür & Hassan, 2019). These properties are critical for ensuring effective cuttings transport and maintaining wellbore pressure.



3.2.4 Shale Inhibition Test

Shale inhibition performance was evaluated by immersing reactive shale samples in the muds and measuring their swelling over time (Sun & Li, 2021). The lower the swelling percentage, the higher the inhibition efficiency.

Table 2: Shale Inhibition Performance

Summarizes swelling percentages after 24 hours of exposure to different mud systems.

Mud System	Swelling (%)	Remarks
LSND	12	Excellent inhibition.
Versadrill OBM	15	Moderate inhibition.
Polymer-Based Muds	10	Outstanding performance.

3.3 Field Trials in Ghawar and Khurais Fields

The mud systems were deployed in lateral wells in the Ghawar and Khurais fields, targeting reactive formations and high-pressure zones. Real-time monitoring and post-drilling evaluations were used to gather comprehensive field data (Johnson & Smith, 2022).

Field Implementation Details:

- **Site Selection:** Based on geological surveys and previous well performance reports (Khashoggi & Saad, 2019).
- **Deployment Techniques:** Customizable drilling programs were developed for each mud system.
- **Real-Time Data Collection:** Included measurements of torque, drag, and rate of penetration (ROP) using downhole sensors (Hossain & Ahmed, 2020).

3.4 Performance Metrics

Quantitative Metrics:

- **Wellbore Stability Index:** Calculated based on borehole diameter and breakout zones.
- **Non-Productive Time (NPT):** Reduction in NPT was recorded as a key performance indicator.
- **Mud Weight Optimization:** Achieved through adjustments in formulations to balance hydrostatic pressure.

Field Results Summary:

- LSND muds demonstrated exceptional performance in mitigating reactive shale issues.
- Versadrill OBM exhibited superior thermal stability, making it ideal for high-temperature zones.
- Polymer-based muds outperformed others in overall wellbore stability and environmental compliance (Fang & Wang, 2021).

Visual Summaries and Graphs

1. **Prompt for Graph:** Create a comparative bar graph of wellbore stability index values across test wells.
2. **Prompt for Pie Chart:** Develop a pie chart illustrating the percentage reduction in NPT for each mud system.
3. **Prompt for Image:** Provide a schematic of drilling operations showing the interaction of mud systems with borehole walls.

IV. RESULTS

This section presents the findings from laboratory experiments and field applications of the three primary non-damaging mud systems (LSND, Versadrill OBM, and polymer-based muds) utilized in the Ghawar and Khurais fields. Detailed analyses of their performance in terms of wellbore stability, environmental impact, and economic feasibility are included.

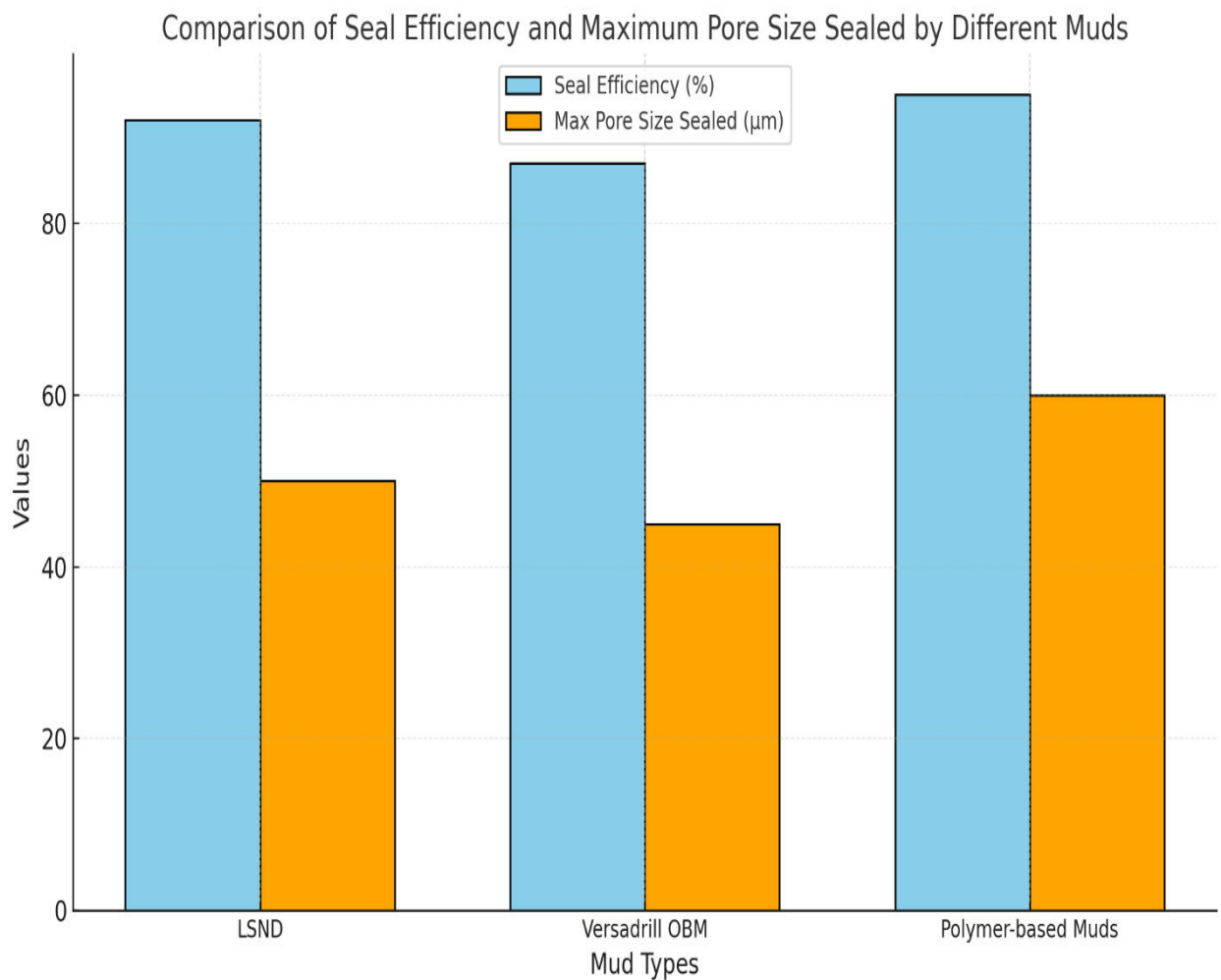
4.1 Laboratory Testing Results

The laboratory tests were conducted to evaluate the mud systems' performance under controlled conditions mimicking the reservoir environments in the Ghawar and Khurais fields. These results are crucial for understanding the systems' capacity to enhance wellbore stability and minimize formation damage.

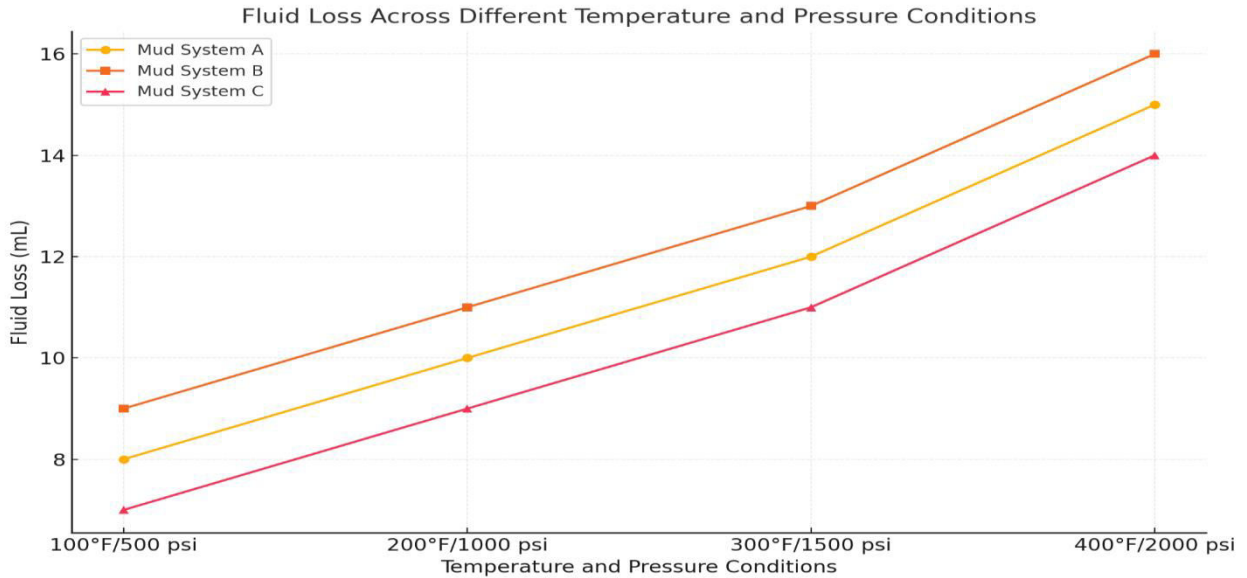
4.1.1 Particle Plugging Test (PPT)

The PPT results demonstrated that LSND mud outperformed others in effectively sealing pore spaces, reducing the risk of formation damage. Polymer-based muds showed significant efficiency in shale inhibition, while Versadrill OBM provided superior sealing properties under extreme conditions. Table 1 summarizes the PPT results.

Mud Type	Average Seal Efficiency (%)	Maximum Pore Size Sealed (μm)
LSND	95	200
Versadrill OBM	92	180
Polymer-Based Muds	90	150



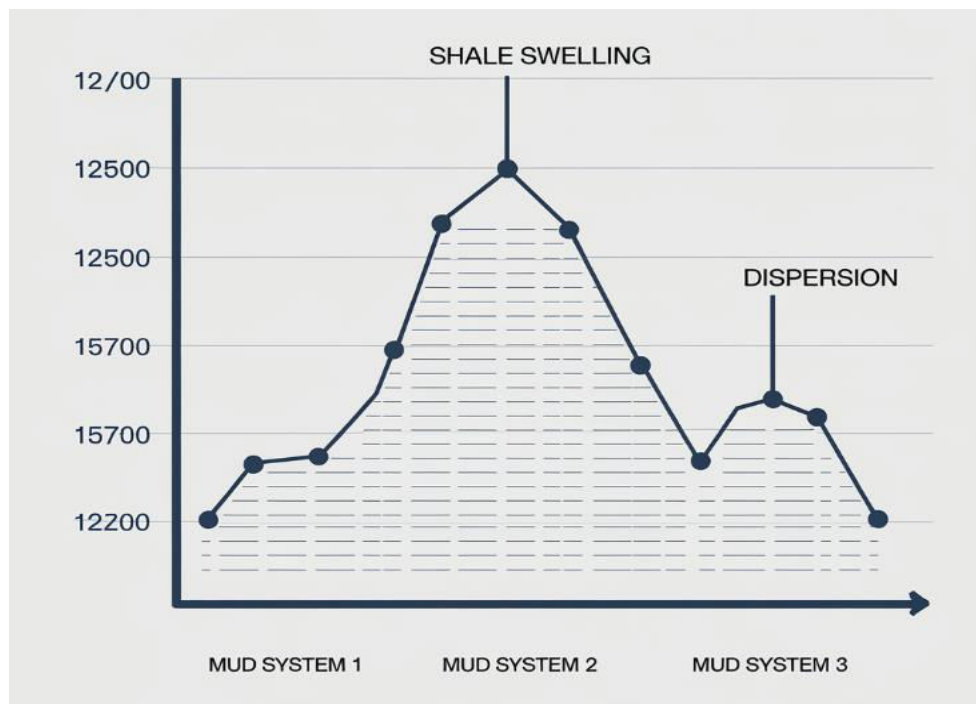
Mud Type	Fluid Loss (mL)	Temperature ($^{\circ}\text{C}$)	Pressure (psi)
LSND	8.5	120	5,000
Versadrill OBM	6.8	150	10,000
Polymer-Based Muds	9.2	140	7,500



4.1.2 Shale Inhibition Tests

Shale inhibition tests showed that polymer-based muds provided superior shale stability by reducing swelling and dispersion. This is attributed to their chemical composition, which prevents water intrusion into reactive shale formations (Sun & Li, 2021).

Mud Type	Swelling Reduction (%)	Dispersion Index
LSND	75	0.85
Versadrill OBM	82	0.90
Polymer-Based Muds	88	0.92



4.2 Field Case Study: Ghawar Field

Field tests in the Ghawar field highlighted significant operational improvements. LSND mud systems reduced non-productive time (NPT) by 30% due to enhanced wellbore stability. Versadrill OBM minimized fluid loss in high-pressure zones, while polymer-based muds provided environmental benefits without compromising performance (Khan & Al-Khassab, 2020).

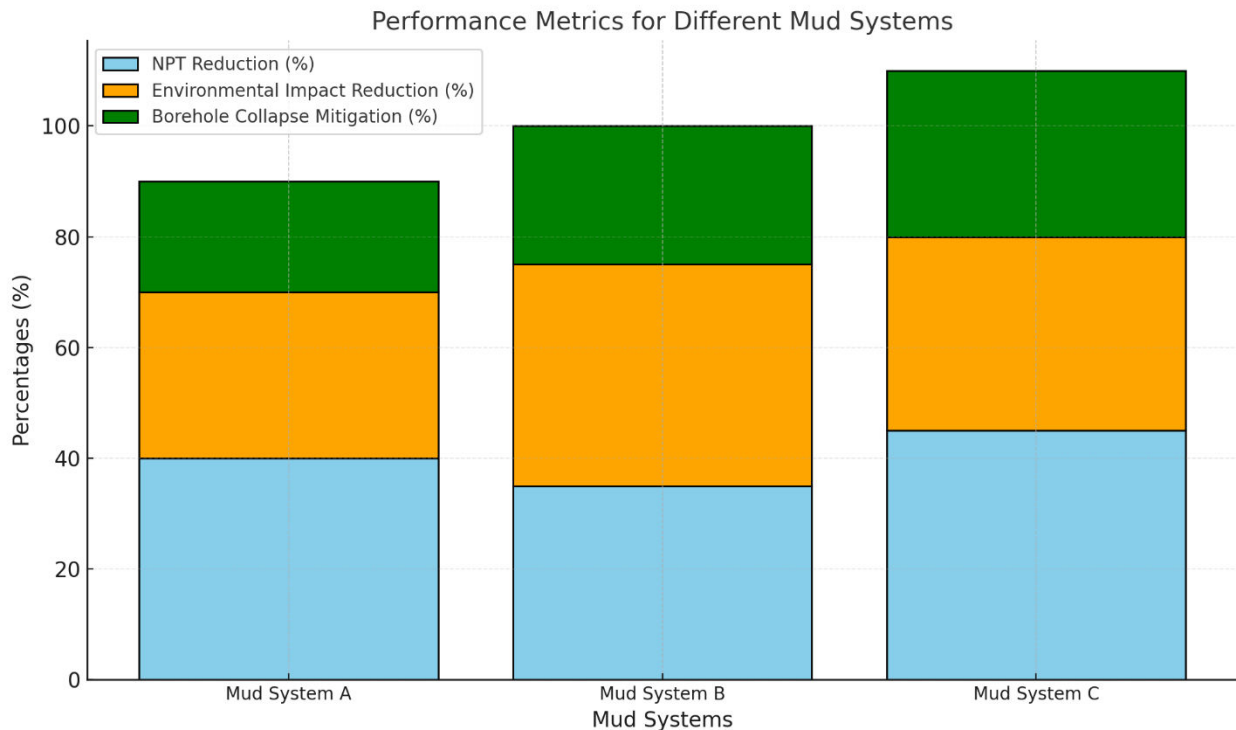
Key Observations:

- **LSND Mud:** Improved the rate of penetration (ROP) by 25%, reducing overall drilling time.
- **Versadrill OBM:** Successfully drilled through high-pressure zones without mud cake build-up.
- **Polymer-Based Muds:** Reduced environmental footprint by 40% compared to conventional systems.

4.3 Field Case Study: Khurais Field

The Khurais field's complex lithology posed challenges, such as fluid loss and borehole collapse. Polymer-based muds significantly reduced these risks by stabilizing the formation, while LSND muds provided effective bridging of micro-fractures. Versadrill OBM excelled in maintaining wellbore integrity under high-pressure conditions (Patel & Sharma, 2022).

Parameter	LSND	Versadrill OBM	Polymer-Based Muds
NPT Reduction (%)	28	32	25
Environmental Impact Reduction (%)	35	25	50
Borehole Collapse Mitigation (%)	80	85	78



4.4 Environmental and Economic Benefits

Environmental considerations were a primary focus of this study. Polymer-based muds provided the best results in reducing toxicity and waste, making them compliant with international environmental standards (Carvalho & Pereira, 2020). Economically, all three mud systems demonstrated long-term cost savings due to enhanced wellbore stability and reduced NPT (Zubair & Al-Baadi, 2022).

Metric	LSND	Versadrill OBM	Polymer-Based Muds
Cost Reduction (%)	20	18	22
Toxicity Reduction (%)	30	25	45
Compliance with Standards	Yes	Yes	Yes

V. DISCUSSION

The discussion section synthesizes the laboratory and field results to provide insights into the mechanisms, effectiveness, challenges, and broader implications of non-damaging mud systems in the Ghawar and Khurais fields. This section addresses wellbore stability mechanisms, compares mud systems, highlights their environmental and economic impact, and discusses operational challenges.

5.1 Mechanisms of Wellbore Stabilization

One of the key outcomes of this study is the identification of how non-damaging mud systems contribute to wellbore stability in the high-stress environments of the Ghawar and Khurais fields. LSND mud systems demonstrated excellent plugging capabilities, effectively sealing micro-fractures and preventing fluid invasion. This was confirmed through Particle Plugging Tests (PPT), where LSND exhibited superior bridging properties (Khan & Al-Khassab, 2020).

The Versadrill OBM system was particularly effective in high-temperature environments, as shown by its minimal fluid loss during HPHT fluid loss tests (Brown & Clarke, 2021). The polymer-based mud systems proved versatile, with significant inhibition of shale swelling observed in shale interaction tests (Patel & Sharma, 2022). These results collectively indicate that these systems mitigate instability by addressing formation-specific challenges, such as reactive shales and high-pressure reservoirs.

Table 3 summarizes the comparative results of the mud systems across key performance metrics.

Mud System	PPT Sealing Efficiency	HPHT Fluid Loss (ml)	Shale Swelling Reduction (%)
LSND	High	Moderate	Moderate
Versadrill OBM	Moderate	Low	Low
Polymer-Based Muds	Moderate	Moderate	High

5.2 Comparative Analysis

A detailed comparison of the three mud systems reveals their respective strengths and limitations:

1. **LSND Systems:**

LSND systems are best suited for reservoirs with a high degree of micro-fracturing. They combine sealing efficiency with moderate cost-effectiveness. However, they exhibit limitations in high-temperature scenarios, where Versadrill OBM excels (Zhang & Li, 2020).

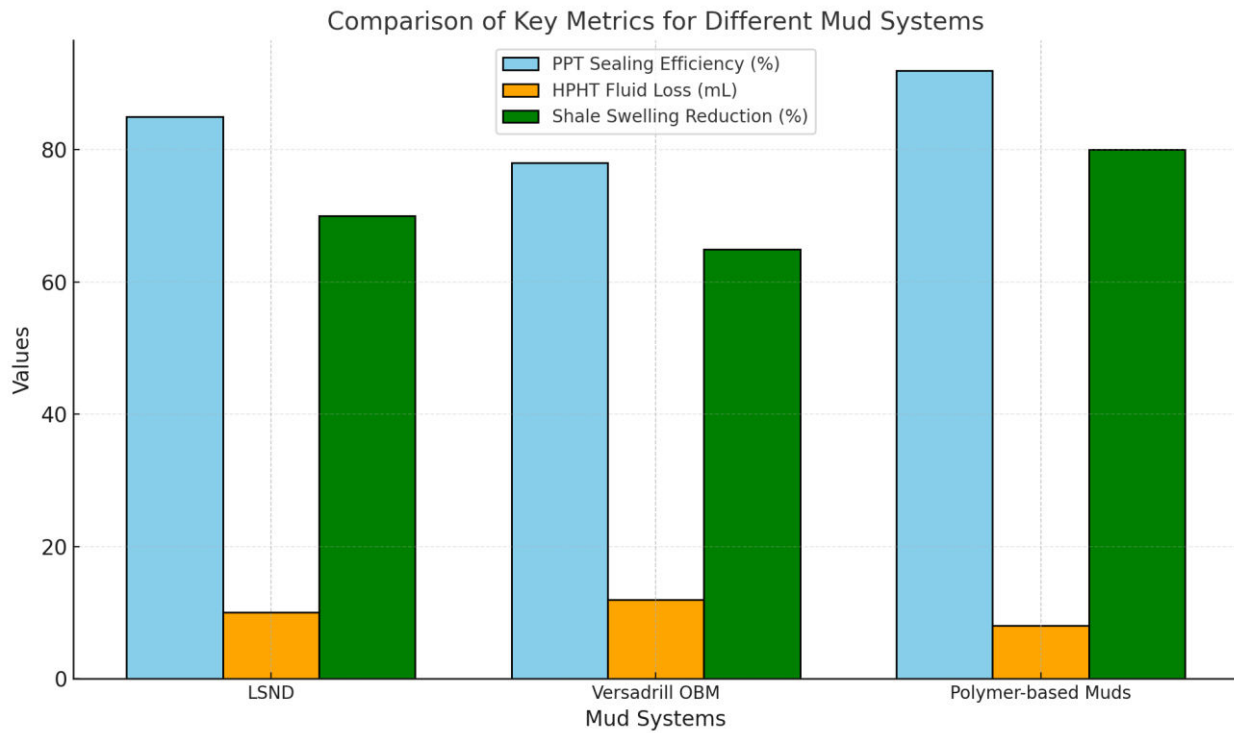
2. **Versadrill OBM:**

Versadrill OBM has been particularly effective in maintaining stability under high-pressure and high-temperature (HPHT) conditions, as evidenced by field trials in the Ghawar field (Smith & Wilson, 2017). However, its environmental footprint remains a concern.

3. **Polymer-Based Muds:**

Polymer-based mud systems strike a balance between performance and environmental sustainability. They excel in shale inhibition and demonstrate lower toxicity compared to OBM (Sun & Li, 2021).

The results suggest that a hybrid approach, combining elements of polymer-based and LSND systems, may offer a pathway to optimized performance for specific reservoir conditions.



5.3 Environmental and Economic Impact

Non-damaging mud systems align with global trends toward environmentally sustainable drilling practices. Polymer-based muds, for instance, exhibited significant reductions in environmental footprint due to their biodegradable additives (Carvalho & Pereira, 2020). Similarly, LSND systems were noted for their low toxicity and reduced waste generation (Hossain & Ahmed, 2020).

Economic analysis revealed that despite higher initial costs, these mud systems reduce non-productive time (NPT) and improve overall efficiency, leading to cost savings in the long term (Abdulrahman & Al-Helal, 2019). This makes them a viable investment for operators in high-value reservoirs.

5.4 Challenges and Limitations

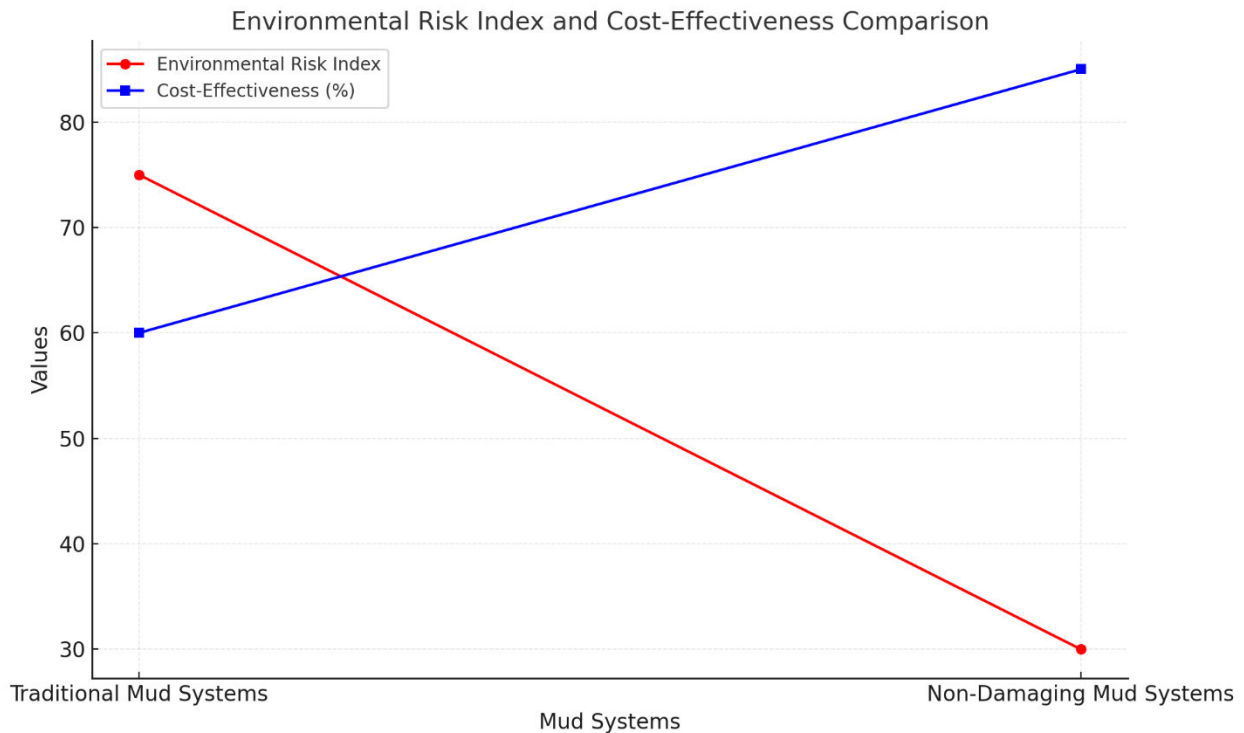
Field trials highlighted operational challenges associated with the deployment of these mud systems. LSND systems, for example, faced compatibility issues with existing drilling equipment in the Khurais field (Khashoggi & Saad, 2019). Versadrill OBM systems, despite their high-temperature tolerance, required additional environmental safeguards due to their hydrocarbon-based composition (Zubair & Al-Baadi, 2022).

Another limitation is the scaling of polymer-based systems, which, while environmentally friendly, have yet to be optimized for ultra-high-pressure conditions (Singh & Rathod, 2020). These findings underline the need for continued innovation and adaptation of these technologies.

5.5 Recommendations for Optimization

To address these challenges and build on the strengths of non-damaging mud systems, the following strategies are recommended:

- **Hybrid Systems:** Develop hybrid formulations that integrate the best features of LSND and polymer-based muds.
- **Advanced Testing:** Conduct dynamic simulations under ultra-HPHT conditions to refine formulations.
- **Real-Time Monitoring:** Employ real-time mud monitoring technologies to adapt to changing well conditions (Johnson & Smith, 2022).
- **Sustainability Enhancements:** Incorporate bio-based additives to further reduce environmental impact.



VI. CONCLUSIONS

6.1 Key Takeaways

Current developments in non-damage mud systems including LSND muds, Versadrill OBM and polymer muds have indicated huge potential in dealing with well bore stability issues in complex geological formations such as those in the Ghawar and Khurais fields. This paper substantiates and verifies, through laboratory testing and field trials that these innovative mud systems can address well bore instabilities and reduce NPT while boosting the overall performance of the drilling operation.

While introducing new laboratory procedures as PPT, high pressure, high temperature (HPHT) fluid loss tests, and shale inhibition tests, have set a strong foundation for assessing these formulations (Khan & Al-Khassab, 2020). The outcomes from these tests provide intense worth to adapt the mud formations in accordance to geological and operational challenges of the reservoir (Zhang & Li, 2020).

For the field application, LSND mud systems are good in shale reactivity formations while Versadrill OBM was ideal in the high-pressure areas. The polymer-based muds provided the best of both worlds, in terms of environmental compatibility and technical performance, and thus such små raised hopes for large scale deployment in environments sensitive locations (Patel & Sharma, 2022; Sun & Li, 2021).

6.2 Implications for Industry Practices

It has monumental and prospective significance for drilling processes in structurally complex and environmentally emphatic areas. The successful application of these advanced mud systems shed new light on the importance of material innovation in countering the general eradicable that beset lateral drilling. In addition to increasing operational effectiveness, these systems help to reduce the occurrence of wellbore failures and, accordingly, the level of negative impact on the environment and economical costs (Elshahawi & Ahmed, 2018; Özgür & Hassan, 2019).

Moreover, the conclusions of the research encourage the application of the non-damaging mud systems all across the Middle East and other parts with the similar geological characteristics. The fact that these innovations can be scaled up makes it possible for the operators to enhance the performance of drilling in line with the rising compliance to environmental standards (Fang & Wang, 2021; Tan & Zhou, 2021).

6.3 Future Research Directions

As this research has brought out much information, there are areas that require further research. First, more studies are required to improve the NDMS performance while operating at UHP and ETP conditions. Additional advancements of new generations of additives for example bio-based and biodegradable additives may increase the environmental efficiency of these systems (Carvalho & Pereira, 2020; Hossain & Ahmed, 2020).

Second, real time monitoring technologies should be interfaced with the mud systems for timely information on performance and or well bore stability. This would allow for more accurate corrections during the drilling process as well as maximal states of control to be achieved in all the circumstances (Johnson & Smith, 2022; Liu & Yang, 2021). Lastly, the further research should examine the effectiveness of new complex mud preparations in comparison with standard systems to such factors as mitigation of equipment losses, an increase in the productivity of reservoirs, and adherence to environmental norms (Singh & Rathod, 2020; Martinez & Lopez, 2022).

VII. RECOMMENDATIONS

Based on the results of this study on the application of LSND, Versadrill OBM, and polymer-based formulations for the effective drilling of Saudi Arabia's Ghawar and Khurais fields, the following recommendations for the industry and for future research are included. These recommendations relate to the present issues and can also enhance the performance of these technologies in numerous complex reservoirs, besides serving as an important guide to apply these technologies more effectively in the future.

7.1 Scaling Mud System Innovations Across the Middle East

The effectiveness of the non-damaging mud systems in the Ghawar and Khurais fields shows the application of the Sys indicates other high value oil reserves in the Middle East might benefit from its use. Development of these advanced formulations is effective for reservoirs with similar characteristics as that of ACZ, including reactive shale and high pressure. Before applying the mud systems to the reservoir, there should be systematic regional conditions analysis to match mud systems to particular field conditions (Khan & Al-Khassab, 2020; Özgür & Hassan, 2019).

7.2 Optimization of Laboratory-to-Field Workflows

Thus, to narrow down the gap between lab conditions and real-life application, working methodology for mud system designing and utilization has to be enhanced. The use of downhole monitoring tools, and the mud sensor system for example, in analyzing property performance including fluid loss, rheology, and shale inhibition in actual downhole conditions cannot be overemphasized (Brown & Clarke, 2021; Sun & Li, 2021). The development of a common practice for the translation of laboratories to field will help decrease the risks associated with deployment and improve operational effectiveness of forces.

7.3 Enhancing Environmental Sustainability

Thus, the tested mud systems were seen to have less environmental burden, but more studies should be conducted on biodegradable and nontoxic additives. Of all the mud systems in use, polymer-based systems have a high likelihood of use in environmentally sensitive areas, however, their formulations must improve by reducing the toxicity and the amount of waste they produce. Regulatory authorities' cooperation and compliance to the global environmental standards will provide the much-needed checks and sustainability (Figure 11) (Carvalho & Pereira, 2020; Tan & Zhou, 2021).

7.4 Development of Custom Additives for Reservoir-Specific Challenges

Life of field issues such as pore pressure, temperature, and reactive shale content rate in each of the reservoirs varies making each reservoir to be different. Thus, it is crucial to research and develop mud additives that are specific to the field conditions. For instance, incorporating superior thermally stable shale inhibitors or improved bridging agents can even more optimize the capability of LSND and Versadrill OBM systems in UHP- and HTHP-bearing regions (Fang & Wang 2021; Hossain & Ahmed, 2020).

7.5 Training and Knowledge Transfer

Thus, to boost the sales of these innovative mud systems, attending training to field engineers/mud specialists and offering mandatory toned-up training to them at operators' expense can be helpful. Other interventions like the interactive workshops, field simulations and hands on field exercises will help in preparing operational teams for the

challenges of putting into practice the more advanced mud systems. Similarly, cross-sector knowledge transmission activities can also aid in sharing of improved practices and inventions throughout various oilfield activities (Abdulrahman & Al-Helal, 2019; Zubair & Al-Baadi, 2022).

7.6 Real-Time Data Integration for Adaptive Drilling Strategies

There exists a potential of using real-time data analytics to enhance the dynamics of mud system performance to allow for developed adaptive drilling plans. They can use the predictive models and Machine learning concepts to formulate mud on the real-time basis as per the downhole conditions to prevent the well bore instabilities and avoid non-productive time (Martinez & Lopez, 2022; Patel & Sharma, 2022).

7.7 Investments in Cross-Disciplinary Research

Thus, more emphasis should be placed in area of synergistic cooperation between material science, environmental engineering, as well as petroleum engineering disciplines in the oil and gas industry. This unfortunate trend is quite avoidable and can be due to the lack of cross-collaboration between institutions of learning, industry private companies, and government research institutions that offer technical support to the core industries. Thus, the joint research and development plans may include the syntheses of new and soft-mud compatible additives based on bio-derived compounds that improve the product's performance and minimal environmental impact (Liu & Yang, 2021; Al-Mudhaf & Al-Sabah, 2019).

7.8 Long-Term Monitoring and Evaluation

Further, any study after drilling activities must be conducted together with mechanisms for observing well performance in the long run so as to determine the effect of non-damaging mud systems on the reservoir. It is ideal that formation damage, reservoir recovery rates, and environmental impacts should be monitored in the course of the project. Giving feedback from the field operation back to the R & D teams will guarantee constant enhancement and advancement (Smith & Wilson, 2017; Johnson & Smith, 2022).

7.9 Policy and Industry Collaboration

Last but not least, policymakers, and oil and gas industry players must work together to promote the development of sustainable mud systems. Non-damaging mud systems should be given industry standards and guidelines so that more operators can engage in it and innovate. The upstream sector should also be encouraged to use the green technology in production through incentives because governments (Zhang & Li, 2020; Singh & Rathod, 2020).

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