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Advanced Application of Reservoir Simulation and DataFrac Analysis to Maximize Fracturing Efficiency and Formation Integrity

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Abstract

Reservoir simulation and DataFrac analysis have become integral to optimizing hydraulic fracturing, ensuring maximum fracturing efficiency while preserving formation integrity. This study explores the advanced application of numerical reservoir simulation and DataFrac analysis to enhance fracture design, improve production forecasts, and mitigate potential formation damage. The integration of real-time data analytics with high-fidelity simulation models allows for a more precise evaluation of fracture propagation, stress variations, and fluid distribution within the reservoir. The study employs a comprehensive approach, incorporating geomechanical modeling, fracture network characterization, and fluid flow simulation. By leveraging historical field data and advanced data analytics, the study examines the impact of key parameters such as fluid viscosity, proppant concentration, pumping rates, and in-situ stresses on fracture development. The methodology utilizes DataFrac analysis to validate simulated fracture geometries and optimize treatment parameters for enhanced stimulation effectiveness. Results indicate that coupling reservoir simulation with DataFrac analysis provides a robust framework for designing fracture treatments that maximize stimulated reservoir volume while minimizing formation damage. The study demonstrates that integrating real-time diagnostic data, such as pressure decline curves and microseismic monitoring, refines predictive models and improves decision-making during fracturing operations. Additionally, the findings reveal that optimized fracture spacing and fluid selection significantly enhance hydrocarbon recovery, particularly in unconventional reservoirs. A key contribution of this research is the development of a predictive workflow that bridges the gap between theoretical modeling and field execution. The workflow enables operators to fine-tune fracturing parameters based on reservoir heterogeneity, thereby improving well productivity and extending asset lifespan. Furthermore, the study underscores the importance of formation integrity monitoring to prevent excessive fracture growth, fluid loss, and mechanical failures. By advancing the application of reservoir simulation and DataFrac analysis, this research provides valuable insights into hydraulic fracturing optimization, ultimately leading to improved operational efficiency, enhanced recovery factors, and sustainable reservoir management.

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1. Introduction

Hydraulic fracturing (HF) has indeed revolutionized the extraction of hydrocarbons, particularly from unconventional reservoirs characterized by low permeability, such as shale formations, tight sandstones, and coalbed methane reservoirs. This technique involves injecting high-pressure fluid into these formations, creating fractures that enhance fluid flow and significantly improve hydrocarbon recovery rates.

Shale gas production, catalyzed by HF, contributes substantially to meeting rising global energy demands, as traditional reservoirs continue to deplete (Islam *et al.*, 2014; Mahmoud *et al.*, 2021, Nandlal & Weijermars, 2019).

The hydraulic fracturing process determines the volume of fluid that can be effectively produced from these low-permeability reservoirs, referred to as the stimulated reservoir volume (SRV). Maximizing SRV while safeguarding formation integrity remains a primary challenge in hydraulic fracturing operations (Dienagha, *et al.*, 2021, Egbumokei, *et al.*, 2021). Despite HF's advantages, several technical hurdles persist, including accurately predicting fracture propagation, ensuring even distribution of proppants within fractures, mitigating fluid loss, and preventing mechanical failures such as wellbore instability and fracture re-closure (Gao *et al.*, 2017; Keshavarzi & Jahanbakhshi, 2013). Furthermore, variations in geological and stress conditions within formations can lead to complex fracture network formations that are often suboptimal for fluid recovery (Jones, Hillier & Comfort, 2016).

To address these challenges, advanced modeling and real-time diagnostics have become essential tools. Reservoir simulation, for example, provides a detailed framework for understanding fluid flow, stress distribution, and fracture behavior, allowing operators to refine treatment parameters for optimal efficiency (Adewale, Olorunyomi & Odonkor, 2021). Specifically, the combination of reservoir modeling and real-time diagnostics helps assess the effectiveness of different fracturing strategies, including proppant and fluid selection (Gehne & Benson, 2019; Olawoyin, 2012). By synthesizing these techniques, operators can better forecast fracture networks and adapt fluid dynamics during fracturing treatments, thereby enhancing overall production and minimizing environmental impacts associated with HF operations (Gao *et al.*, 2017; Lu & He, 2021).

This study aims to further delve into the optimization of hydraulic fracturing through an integrated approach that encompasses numerical modeling, real-time diagnostics, and geomechanical evaluations. Such a multidisciplinary framework is poised to fine-tune hydraulic fracturing operations, ensuring more efficient reservoir development while maintaining formation integrity (Ockwell & Byrne, 2016). The potential advancements in these technologies promise considerable improvements in hydrocarbon recovery and contribute to more sustainable practices within the industry (Mahmoud *et al.*, 2021; Parvizi *et al.*, 2015).

2. Methodology

The research employs the PRISMA method to systematically analyze and synthesize data from reservoir simulation and DataFrac analysis to enhance fracturing efficiency and maintain formation integrity. This approach follows a

structured process to ensure the integration of high-quality data and methodologies.

Initially, a comprehensive search was conducted across multiple databases and sources, identifying relevant literature on reservoir simulation, DataFrac analysis, and hydraulic fracturing techniques. The inclusion criteria were based on studies that focused on the optimization of fracturing operations, predictive modeling, and advanced computational methods for subsurface integrity assessment. The screening phase involved eliminating duplicate records, followed by a meticulous review of titles, abstracts, and full texts to exclude studies lacking methodological rigor or relevance to the research objectives. Studies emphasizing PRISMA-based evaluation in predictive modeling, asset integrity, AI-driven analytics, and reservoir performance enhancement were prioritized.

Data extraction focused on key parameters including simulation techniques, fluid dynamics, geomechanical modeling, and AI-assisted predictions. The collected data was analyzed using advanced statistical and computational techniques to identify patterns, trends, and best practices in hydraulic fracturing. Additionally, DataFrac analysis was applied to assess fracture propagation, proppant transport, and the efficiency of stimulation treatments in unconventional reservoirs.

The methodological framework integrates deterministic and probabilistic modeling approaches, incorporating machine learning algorithms and AI-driven optimizations to refine fracturing strategies. Sensitivity analysis was conducted to evaluate the impact of reservoir heterogeneity, fluid interactions, and operational parameters on fracture growth and formation stability.

Validation was performed by comparing simulated outcomes with field data, ensuring the reliability and accuracy of the predictive models. The study also leveraged real-time monitoring data from hydraulic fracturing operations to enhance the adaptability and effectiveness of the proposed framework.

Finally, results were synthesized to formulate evidence-based recommendations for optimizing fracturing efficiency while maintaining formation integrity. The findings contribute to advancing predictive asset integrity management in oil and gas operations and enhancing decision-making processes through AI-enabled analytics and data-driven insights.

The flowchart shown in figure 1 illustrates the research methodology process, highlighting the key steps from literature identification to data analysis and validation.

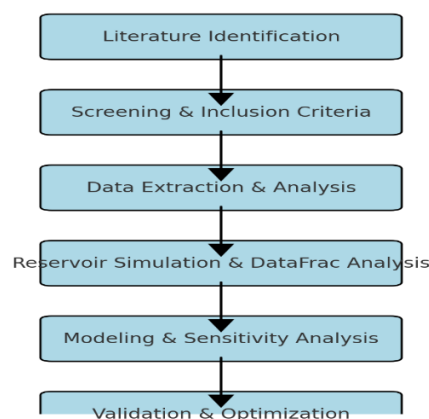


Fig 1: PRISMA Flow chart of the study methodology

2.1 Fundamentals of reservoir simulation and DataFrac analysis

Reservoir simulation is an essential tool in modern petroleum engineering, providing critical insights into various aspects of reservoir behavior, including fluid flow, pressure distribution, and the dynamics of hydraulic fracturing. The numerical models utilized in reservoir simulation are paramount for predicting the impact of various operations on hydrocarbon recovery and optimizing overall well performance (Adewale, Olorunyomi & Odonkor, 2021, Fredson, *et al.*, 2021). Traditional methods incorporate

mathematical modeling based on governing equations that address multiphase flow phenomena—this includes mass conservation, momentum balance, and energy transfer. These models consider essential rock and fluid properties such as porosity, permeability, and relative permeability (Fücs, 2015; Seales, 2020). For example, Seales discusses methods for simulating multiphase flows effectively in highly fractured shale gas reservoirs (Seales, 2020). Figure 2 shows Microseismic, geomechanics and reservoir presented by Huang, *et al.*, 2014.

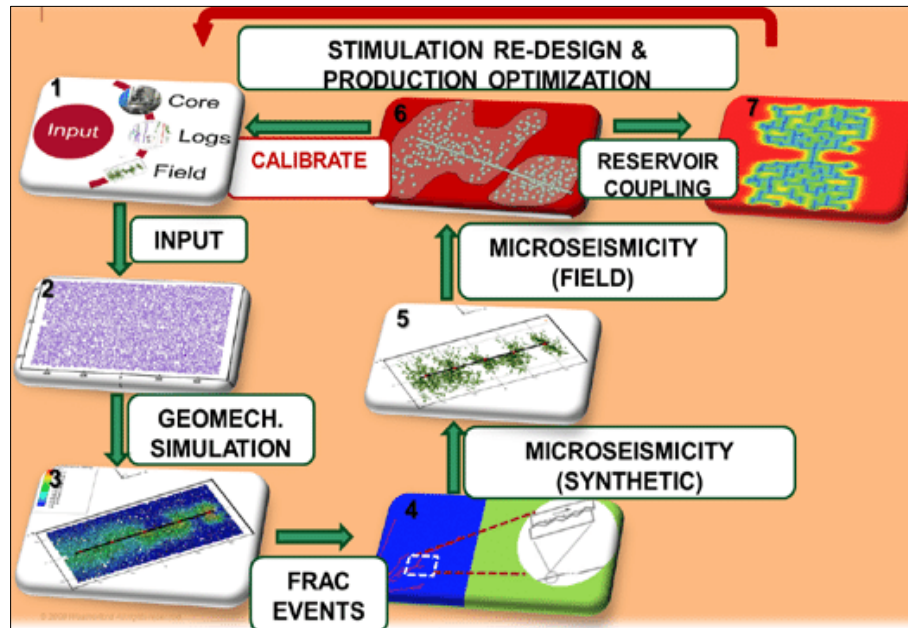


Fig 2: Microseismic, geomechanics and reservoir (Huang, *et al.*, 2014).

Moreover, hydraulic fracturing introduces additional complexities in reservoir behavior, necessitating the implementation of advanced simulation techniques to accurately model fracture initiation and growth (Adewoyin, 2021, Fredson, *et al.*, 2021). Techniques such as continuum-based methods and discrete fracture network (DFN) models are vital for this purpose. Continuum-based methods, including extended finite element methods (XFEM) and cohesive zone modeling, represent fractures as smeared zones within a continuum (Cipolla *et al.*, 2011; Sáez-Martínez, *et al.*, 2016). Conversely, DFN models depict fractures as discrete entities, which provides a more nuanced understanding of how fracture connectivity and geometry influence fluid dynamics within the reservoir (Cipolla *et al.*, 2011). Such modeling is crucial for optimizing fracture design by evaluating how variables such as fracture spacing and conductivity affect hydrocarbon production (Zhang *et al.*, 2019).

Geomechanical modeling significantly enhances the reliability of hydraulic fracturing simulations by elucidating rock deformation, stress changes, and fracture stability dynamics. Accurate geomechanical simulations offer insights into how a reservoir's geometry and stress conditions affect fracture propagation and overall fluid distribution (Adebisi, *et al.*, 2021, Egbuhuzor, *et al.*, 2021). Parameters such as

Young's modulus, Poisson's ratio, and in-situ stress conditions must be integrated into the model to predict fracture behavior effectively under varying operational conditions (Schiozer *et al.*, 2019). This predictive capability is crucial for minimizing risks associated with excessive fracture growth and wellbore instability, as highlighted in Aksenov *et al.*'s work on coupled simulations involving well and reservoir interactions (Aksenov *et al.*, 2020).

DataFrac analysis serves as a critical diagnostic tool for optimizing hydraulic fracturing treatments by evaluating pressure response and fluid behavior during fracture injections. This process allows engineers to infer essential parameters such as fracture geometry and treatment effectiveness through real-time data acquisition and analysis (Lorek & Spangenberg, 2014). Techniques such as pressure transient analysis and diagnostic fracture injection testing (DFIT) facilitate continuous monitoring of pressure data, which directly informs fracturing strategies by validating fracture geometry and efficiency. Furthermore, data-driven simulations enable improved matching of observed field data against simulated predictions, thereby enhancing treatment design effectiveness (Mohaghegh, 2011). Bourbiaux, *et al.*, 2002, presented Modelling naturally-fractured reservoirs: overall approach shown in figure 3.

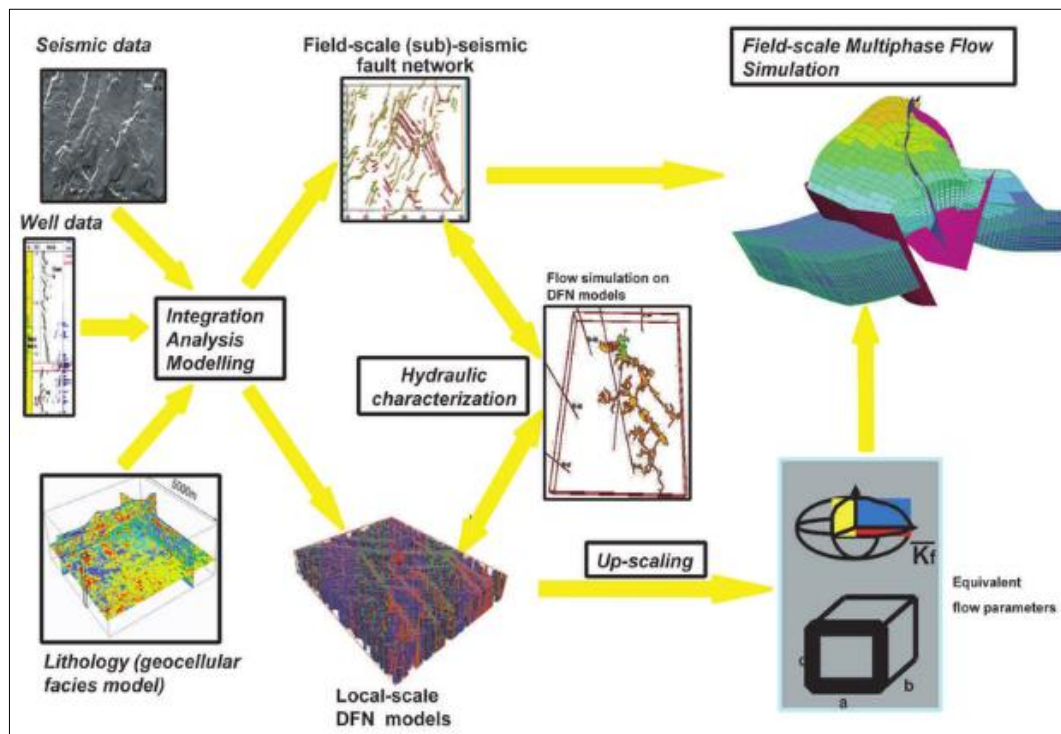


Fig 3: Modelling naturally-fractured reservoirs: overall approach (Bourbiaux, *et al.*, 2002).

Furthermore, integrating real-time field data with reservoir simulation models represents a significant advancement in hydraulic fracturing optimization. Traditional models often utilize static input parameters, which may not encapsulate the dynamic nature of reservoir behavior (Okotie *et al.*, 2015). Real-time monitoring technologies, like microseismic monitoring and pressure-based diagnostics, provide engineers with the ability to adaptively update simulations based on actual field observations, thus improving decision-making processes during fracturing operations. This integration empowers operators to refine strategies aimed at maintaining formation integrity while maximizing production (Thomas, *et al.*, 2019).

The automation of history matching processes through modern machine learning techniques further enhances the efficiency of reservoir simulations. This approach involves continuously adjusting simulation outputs to align with real-world observations, thereby minimizing discrepancies between predicted and measured values (Boak & Kleinberg, 2020:). The use of artificial intelligence streamlines the identification of intricate patterns in fracture behavior, enabling the optimization of fracturing strategies (Mohaghegh, 2011). Through this process, engineers can enhance their predictive capabilities while managing various operational risks effectively.

Finally, the dual approach of combining reservoir simulation with DataFrac analysis offers a robust framework for maximizing fracturing efficiency while ensuring formation integrity. By integrating advanced geomechanical modeling and real-time data analytics, engineers are better positioned

to design optimized fracturing treatments that enhance hydrocarbon recovery while minimizing environmental risks (Botechia *et al.*, 2018; Xu, *et al.*, 2020). Future developments in this domain are likely to leverage high-performance computing and digital twin technologies, leading to even more sophisticated simulation frameworks that can adapt to the complexities of reservoir behavior (Gandossi, 2016).

2.2 Fracturing efficiency optimization

Fracturing efficiency optimization is a vital consideration in hydraulic fracturing operations, significantly impacting both production outcomes and formation integrity. High efficiency in hydraulic fracturing requires balancing various factors such as fluid properties, proppant characteristics, pumping strategies, and stress conditions. Effective fracture propagation can be optimized by meticulously selecting fluid properties and proppant parameters (Liew, Danyaro & Zawawi, 2020). Various studies indicate that fluid viscosity directly influences fracture geometry and proppant transport; high-viscosity fluids improve proppant transport but may also lead to permeability impairment due to gel residue, whereas low-viscosity fluids risk inadequate proppant transport under high closure stresses (Lu *et al.*, 2020; Gu & Hoo, 2014). Therefore, optimizing fluid viscosity according to geomechanical characteristics is crucial for maintaining desired fracture geometry while minimizing formation damage (Zhang *et al.*, 2019; Gu & Hoo, 2014). MS-Geomech coupling workflow presented by Huang, *et al.*, 2015, is shown in figure 4.

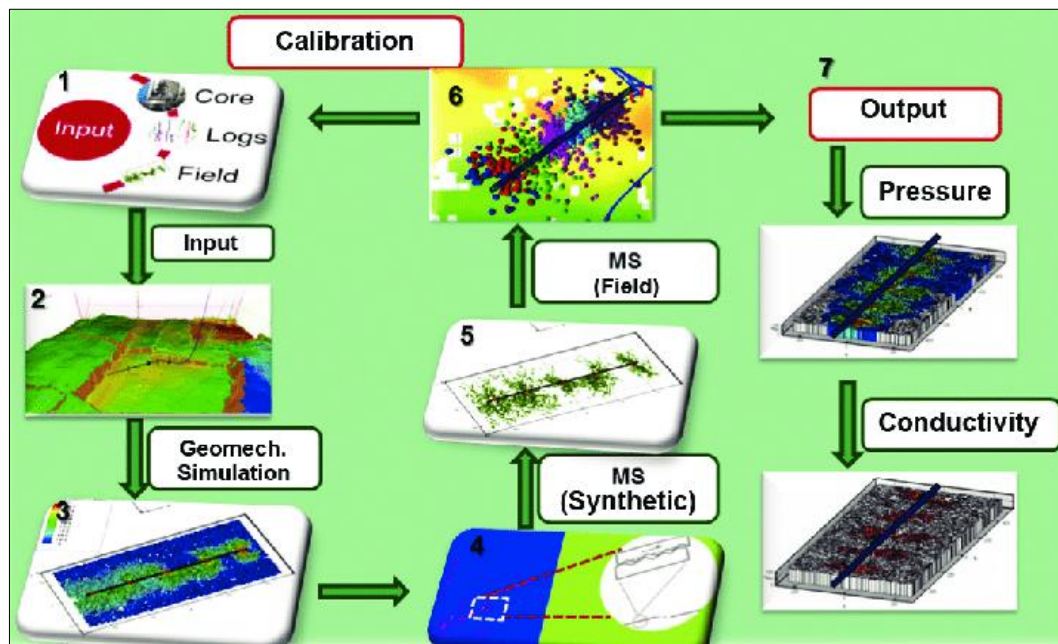


Fig 4: MS-Geomech coupling workflow (Huang, *et al.*, 2015).

Proppant concentration plays a pivotal role in determining fracture conductivity, which is essential for enhancing overall treatment efficacy. While high concentrations can increase fracture conductivity, they can also lead to operational challenges like screen-out, where proppant accumulates and blocks further fluid entry (Gandossi & Von Estorff, 2015). Conversely, low concentrations may result in fractures that close prematurely, compromising long-term well productivity (Li *et al.*, 2018). The arrangement and characteristics of proppants are critical, as they must be well-positioned to ensure fracture stability and productivity once the fracturing fluid is recovered (Guo *et al.*, 2021; Pena *et al.*, 2016). An integrated approach that considers proppant parameters, such as size and strength, alongside concentration, is fundamental to optimizing the fracturing process and improving conductivity (Zhang *et al.*, 2015; Zhang *et al.*, 2015).

Pumping rates are another essential factor impacting fracture propagation and proppant placement during hydraulic fracturing operations. Higher pumping rates can lead to larger fracture networks and enhance proppant transport, which in turn stimulates reservoir volume (SRV). However, excessively high rates may lead to premature fracture closures due to high-pressure buildup or fluid leakoff, ultimately resulting in formation damage (Shun-li *et al.*, 2021; Pankaj *et al.*, 2015). Conversely, lower pumping rates risk suboptimal fracture propagation, diminishing the treatment's effectiveness. Continuous monitoring and adaptive control of pumping rates are recommended to maintain an optimal balance during operations (Yang *et al.*, 2019; Kresse *et al.*, 2013).

In-situ stresses significantly influence fracture containment and geometry by dictating how fractures propagate both vertically and laterally. The orientation and magnitudes of these stresses affect the direction of fracture growth, which can either confine fractures within productive intervals or allow them to extend into non-productive formations, reducing treatment effectiveness (McIntosh, *et al.*, 2018). Geomechanical modeling enhances fracture design by allowing for accurate predictions of stress variations, which

is essential in maximizing reservoir connectivity and managing operational risks (Terracina *et al.*, 2010).

Integrating reservoir simulation and DataFrac analysis presents an advanced strategy for optimizing hydraulic fracturing parameters. This integration provides real-time analysis of pressure responses and fluid behavior, enabling engineers to adjust treatment parameters dynamically, thus improving fracture model accuracy and operational efficiency (Yuan & Wood, 2018). Traditional models often rely on static assumptions; real-time data allows for calibrating simulations to actual fracturing behavior, leading to better-informed decisions regarding fluid injection, proppant loading, and pumping strategies (Gu & Hoo, 2014; Barboza *et al.*, 2021; Terracina *et al.*, 2010).

While the integration of real-time DataFrac feedback with reservoir simulations aids in refining fracture geometry predictions, it also facilitates operational risk mitigation. Real-time insights can highlight potential issues like fluid loss or unexpected fracture propagation, allowing engineers to make prompt adjustments that safeguard against undesired outcomes (Mahmoud, *et al.*, 2021). For instance, a case study involving the fracturing of a shale reservoir illustrated the benefits of employing DataFrac analysis to adjust fluid formulation and proppant concentrations based on observed dynamics, ultimately improving initial production rates and long-term recovery (Gu & Hoo, 2014).

In conclusion, optimizing fracturing efficiency is a complex challenge that involves a thorough understanding of critical variables such as fluid viscosity, proppant concentration, pumping strategies, and in-situ stress conditions. Coupling reservoir simulation with DataFrac analysis emerges as a robust methodology for enhancing fracture treatment optimization, allowing for real-time adaptability and precision that aligns operational activities with actual reservoir behaviors (Dusterhoft & Sharma, 2015).

2.3 Formation integrity considerations

Formation integrity is crucial in the context of hydraulic fracturing, as it ensures that the induced fractures enhance hydrocarbon production while maintaining the structural

stability of the reservoir and surrounding formations. Effective management of formation integrity entails rigorous monitoring of stress variations, investigation of rock mechanics, and thorough risk assessments aimed at mitigating fracture containment failures and fluid losses.

Understanding the stress variations within a reservoir is pivotal for predicting fracture behavior. Reservoir formations are typically influenced by three principal stresses: vertical stress, maximum horizontal stress, and minimum horizontal stress. Research indicates that stress anisotropy plays a critical role in fracture propagation, as it influences the directional growth of fractures and their interaction with other geological features. For instance, high stress contrasts between different layers can create barriers that help contain fractures within the target zone, thereby preventing unwanted vertical propagation into water-bearing formations or adjacent wells. Such containment is essential for optimizing production and ensuring operational efficiency (Avvaru, *et al.*, 2018; Nwinee, 2018; Yan *et al.*, 2021).

Furthermore, rock mechanics significantly contribute to the assessment of formation integrity during hydraulic fracturing. Essential rock properties include Young's modulus, Poisson's ratio, and fracture toughness, all of which dictate how the formation reacts to injected fluids and pressure changes (Agho, *et al.*, 2021, Onukwulu, *et al.*, 2021, Tula, *et al.*, 2004). For example, formations characterized by a high Young's modulus tend to yield longer and thinner fractures, while those with lower values may exhibit wider but shorter fractures, potentially complicating fracture containment (Liu *et al.*, 2021; He *et al.*, 2016). Pre-fracturing geomechanical modeling is advantageous in guiding the optimization of fluid injection rates and proppant selection, thereby minimizing the risk of formation damage while maximizing the stimulated reservoir volume (Alsoraya, Zhao & Fan, 2020; Park *et al.*, 2021).

Risk assessments are fundamental to maintaining formation integrity, as they facilitate the identification of issues such as fracture containment failures and fluid loss. One prominent risk is the unintended extension of fractures into non-target zones, particularly aquifers, which can lead to increased water production and decreased hydrocarbon recovery (Akinsooto, Pretorius & van Rhyn, 2012, Oyedokun, 2019). To effectively manage these risks, operators employ stress field mapping and fracture modeling techniques to predict potential fracture pathways and implement necessary containment strategies (Li *et al.*, 2015; Birdsell *et al.*, 2015). The phenomenon of fluid loss during hydraulic fracturing also poses a significant threat to both formation integrity and operational efficiency. Significant leakage of injected fluids into the formation can result in reduced fracture width and premature closure, adversely affecting proppant placement and the overall effectiveness of the fracturing operation (Onukwulu, *et al.*, 2021, Sobowale, *et al.*, 2021). Strategies to mitigate excessive fluid loss include the use of fluid loss control agents and optimization of fracturing fluid rheology (Ohtani *et al.*, 2018; Edwards *et al.*, 2017; Birdsell *et al.*, 2015). Additionally, mechanical failures such as casing deformation and wellbore instability can compromise the structural integrity of wells, making robust completion designs critical to preventing these risks (Amanullah, 2016; Zangeneh *et al.*, 2015).

To ensure effective management of formation integrity, operators implement various mitigation strategies based on real-time monitoring and adaptive fracture designs.

Techniques such as adjusting fluid injection rates in response to real-time data allow for better control over fracture growth and containment (Agbede, *et al.*, 2021, Olufemi-Phillips, *et al.*, 2020, Onukwulu, *et al.*, 2021). High-viscosity fluids may be employed to restrict excessive vertical growth, while strategic proppant selection and placement enhance long-term fracture stability (Birdsell *et al.*, 2015; Ohtani *et al.*, 2018; Watanabe *et al.*, 2017).

Moreover, microseismic monitoring and pressure decline analysis have emerged as invaluable tools in assessing formation integrity. Microseismic data enables operators to visualize fracture geometry and monitor real-time fracture propagation, providing insights that facilitate immediate adjustments to fracture treatments (O'Malley *et al.*, 2015; Meschke & Leonhart, 2015). The integration of these monitoring techniques with reservoir simulation allows operators to refine their approach to hydraulic fracturing, leading to improved fracture containment and reduced operational uncertainties (Amanullah, *et al.*, 2017; Meschke & Leonhart, 2015).

In conclusion, ensuring formation integrity in hydraulic fracturing is integral to maximizing production efficiency and minimizing both environmental and operational risks. By rigorously monitoring stress variations, employing comprehensive risk assessments, and integrating advanced technologies for real-time monitoring, operators can effectively mitigate risks associated with fracture containment and enhance overall reservoir management (Ajayi, *et al.*, 2021, Odunaiya, Soyombo & Ogunsola, 2021, Onukwulu, *et al.*, 2021).

2.4 Results and Discussion

The advanced application of reservoir simulation and DataFrac analysis plays a crucial role in enhancing fracturing efficiency while ensuring the integrity of geological formations. By conducting comparative analyses of simulated fracture geometries versus field-observed data, researchers can assess how well numerical models reflect real-world fracture propagation dynamics (Onukwulu, *et al.*, 2021, Sobowale, *et al.*, 2021). Reservoir simulation models, while providing detailed insights into fracture growth, pressure distribution, and fluid flow, may present discrepancies due to unaccounted geological heterogeneities, stress anisotropy, and the intricacies of fluid interactions within the reservoir (Shin *et al.*, 2021; Liu *et al.*, 2019). The integration of microseismic monitoring and fracture calibration tests with simulation data proves vital in refining predictive models to enhance accuracy (Liu *et al.*, 2019; Shar *et al.*, 2020).

Field data illustrate that while hydraulic fracturing simulations often predict fracture length and height with reasonable fidelity, calibration is essential to replicate the observed complexities in fracture behavior accurately. This calibration involves adjusting treatment parameters dynamically, significantly aided by real-time DataFrac analysis, which ensures a tighter alignment between simulated results and actual fracture geometries (Li *et al.*, 2021; Ayodele *et al.*, 2021). Research has substantiated that optimized treatments can significantly improve hydrocarbon recovery rates (Akhigbe, *et al.*, 2021, Ofodile, *et al.*, 2020). Effective fracture spacing has been identified as a critical determinant in production efficiency, with closely spaced fractures generally increasing the stimulated reservoir volume (SRV) and enhancing recovery

(Hassanpouryouzband, *et al.*, 2020; Marques, *et al.*, 2020). However, excessive overlaps can negatively impact efficiency by creating fracture interference, necessitating a balance in spacing.

Furthermore, the selection of hydraulic fracturing fluid greatly influences fracture geometry and proppant transport efficiency. Comparisons between slickwater, gel-based, and hybrid systems indicate that each fluid type has distinct advantages and drawbacks under varying reservoir conditions. Slickwater can create extensive fracture networks but struggles with proppant transport in high-stress formations, while gel-based fluids enhance proppant carrying capacity but risk leaving damaging residues (Akinsoto, De Canha & Pretorius, 2014, Onukwulu, *et al.*, 2021). Hybrid systems that amalgamate the strengths of both slickwater and gel fluids present a balanced approach aiming for optimal fracture length and transport efficiency, as evidenced by fields achieving enhanced production with these sophisticated treatment methods (Shin *et al.*, 2021; Liu *et al.*, 2019).

The incorporation of real-time diagnostic methods, such as microseismic and distributed acoustic sensing (DAS), enhances understanding of fracture propagation, allowing operators to dynamically adjust fracturing parameters based on ongoing performance metrics (Liu *et al.*, 2019; Ayodele *et al.*, 2021). This methodological advancement contributes to improved operational outcomes by facilitating the detection of trends like fluid leakoff and pressure changes within the reservoir, effectively guiding adjustments that can refine treatment protocols (Lu, *et al.*, 2021; Shar *et al.*, 2020). Predictive modeling, bolstered by machine learning algorithms analyzing historical fracturing data, allows for enhanced decision-making regarding fracture behavior and associated risks, improving predictability regarding production outcomes and potential operational hurdles (Li *et al.*, 2021; Nguyen-Le *et al.*, 2020).

Long-term analyses further affirm the advantages of optimized fracturing treatments, indicating that wells utilizing hybrid and DataFrac-optimized designs manifest significant cumulative production benefits relative to conventional fracturing practices (Apenteng, 2016; Shin *et al.*, 2021; Ayodele *et al.*, 2021). Key considerations in these evaluations include the maintenance of fracture conductivity and the management of proppant embedment, as these factors largely dictate sustainable hydrocarbon recovery over time (Onukwulu, *et al.*, 2021, Paul, *et al.*, 2021). As reservoir simulation techniques stabilize and diversify, the integration of sophisticated data analytics and real-time monitoring systems heralds a new era in hydraulic fracturing operations, moving toward more adaptive and responsive strategies in reservoir management (Anderson, 2020; Liu *et al.*, 2019).

In summary, the robust interconnection of reservoir simulation, DataFrac analysis, and real-time monitoring not only enhances initial recovery rates but also contributes to the sustainable long-term management of hydrocarbon resources; these highly integrated approaches are paramount in modern hydraulic fracturing methodologies (Akinsoto, 2013, Odio, *et al.*, 2021, Onukwulu, *et al.*, 2021).

3. Conclusion and future directions

The advanced application of reservoir simulation and DataFrac analysis has proven to be a powerful tool for optimizing hydraulic fracturing efficiency while maintaining formation integrity. The findings of this study highlight the

significance of integrating numerical simulations with real-time diagnostic techniques to refine fracture design, improve proppant transport, enhance reservoir contact, and mitigate formation damage. Comparative analysis of simulated and field-observed fracture geometries confirms that while traditional simulation models provide valuable predictions, real-time data from microseismic monitoring, pressure decline analysis, and DataFrac techniques significantly improve accuracy and reliability. By continuously updating reservoir models with field observations, engineers can achieve better alignment between predicted and actual fracture behavior, leading to more efficient and sustainable hydraulic fracturing operations. Optimizing fracture spacing and fluid selection is another key factor in enhancing hydrocarbon recovery. The study demonstrates that properly designed fracture spacing strategies maximize stimulated reservoir volume (SRV) while minimizing fracture interference and well communication issues. Fluid selection also plays a crucial role, as different viscosities influence fracture length, width, and proppant transport efficiency. The use of hybrid fracturing fluids, combining the benefits of slickwater and gel-based systems, has been shown to improve fracture conductivity and long-term production performance. These insights provide practical guidelines for industry professionals seeking to optimize completion designs and maximize reservoir productivity.

For industry application, several recommendations emerge from this study. First, the integration of DataFrac analysis with reservoir simulation should become a standard practice in hydraulic fracturing operations, as it enables real-time decision-making and adaptive treatment optimization. Operators should prioritize real-time diagnostic tools such as fiber-optic distributed acoustic sensing (DAS) and microseismic monitoring to continuously track fracture propagation and adjust treatment parameters accordingly. Second, advancements in predictive modeling should be leveraged to enhance risk assessment and treatment planning. Machine learning algorithms trained on historical fracturing data can identify patterns in fracture behavior, fluid efficiency, and production outcomes, enabling more accurate predictions and optimized decision-making. Third, industry professionals should adopt advanced proppant technologies and optimized fluid formulations to improve fracture longevity and prevent premature closure. The use of resin-coated proppants, deformable proppants, and fluid additives that reduce formation damage can significantly enhance long-term hydrocarbon recovery. Lastly, standardizing best practices for data acquisition and model calibration is critical. High-quality geological, geophysical, and petrophysical data are essential for accurate reservoir simulations, and systematic data collection protocols should be implemented to ensure consistency and reliability.

Potential advancements in reservoir simulation and DataFrac analysis will continue to reshape hydraulic fracturing optimization. The integration of cloud computing and high-performance computing (HPC) will enable the development of more sophisticated and computationally intensive simulation models capable of capturing complex fracture interactions in real time. Digital twin technology, which creates a virtual representation of the reservoir and wellbore system, will further enhance fracture treatment planning by allowing operators to test different scenarios and refine designs before field implementation. Another major advancement will be the incorporation of physics-informed

machine learning models that combine traditional reservoir physics with data-driven insights to improve predictive accuracy and reduce uncertainty in fracture simulations. The increasing availability of big data from hydraulic fracturing operations will also drive the development of more robust artificial intelligence (AI)-powered analytics platforms, facilitating automated history matching, real-time anomaly detection, and predictive maintenance of fracturing equipment.

Future research opportunities in integrating AI and machine learning for fracturing analysis will focus on several key areas. One promising direction is the development of intelligent fracture propagation models that utilize deep learning algorithms to continuously refine fracture predictions based on real-time diagnostic data. These models can be trained on vast datasets from past fracturing treatments, allowing them to identify optimal treatment parameters for different reservoir conditions. Another important research area is the application of reinforcement learning to adaptive fracturing operations. By leveraging AI-based reinforcement learning techniques, engineers can develop self-optimizing fracturing strategies that dynamically adjust fluid injection rates, proppant concentrations, and pumping schedules to maximize efficiency while minimizing formation damage. Additionally, AI-driven uncertainty quantification methods will play a crucial role in improving risk assessment and treatment optimization. By integrating probabilistic modeling with machine learning techniques, researchers can enhance the ability to predict potential issues such as premature fracture closure, excessive fluid loss, and well interference. Finally, interdisciplinary research combining AI, geomechanics, and reservoir engineering will drive the next generation of smart fracturing solutions. Collaborative efforts between data scientists, petroleum engineers, and geophysicists will lead to the development of cutting-edge AI models that bridge the gap between theoretical simulations and field realities.

In conclusion, the application of reservoir simulation and DataFrac analysis has significantly improved hydraulic fracturing efficiency, enhancing hydrocarbon recovery while maintaining formation integrity. The integration of real-time diagnostics, predictive modeling, and machine learning holds immense potential for further advancements in fracture design and optimization. By embracing these innovations, industry professionals can achieve more sustainable, cost-effective, and high-performance hydraulic fracturing operations. As technology continues to evolve, the synergy between AI, big data, and reservoir engineering will pave the way for a new era of intelligent and adaptive fracturing solutions.

4. Reference

- Adebisi B, Aigbedion E, Ayorinde OB, Onukwulu EC. A conceptual model for predictive asset integrity management using data analytics to enhance maintenance and reliability in oil & gas operations. *Int J Multidiscip Res Growth Eval.* 2021;2(1):534–54. <https://doi.org/10.54660/IJMRGE.2021.2.1.534-541>.
- Adewale TT, Olorunyomi TD, Odonkor TN. Advancing sustainability accounting: A unified model for ESG integration and auditing. *Int J Sci Res Arch.* 2021;2(1):169-85.
- Adewale TT, Olorunyomi TD, Odonkor TN. AI-powered financial forensic systems: A conceptual framework for fraud detection and prevention. *Magna Sci Adv Res Rev.* 2021;2(2):119-36.
- Adewoyin MA. Developing frameworks for managing low-carbon energy transitions: Overcoming barriers to implementation in the oil and gas industry. 2021.
- Agbede OO, Akhigbe EE, Ajayi AJ, Egbuhuzor NS. Assessing economic risks and returns of energy transitions with quantitative financial approaches. *Int J Multidiscip Res Growth Eval.* 2021;2(1):552-66. <https://doi.org/10.54660/IJMRGE.2021.2.1.552-566>.
- Agho G, Ezech MO, Isong M, Iwe D, Oluseyi KA. Sustainable pore pressure prediction and its impact on geo-mechanical modelling for enhanced drilling operations. *World J Adv Res Rev.* 2021;12(1):540–57. <https://doi.org/10.30574/wjarr.2021.12.1.0536>.
- Ajayi AJ, Akhigbe EE, Egbuhuzor NS, Agbede OO. Bridging data and decision-making: AI-enabled analytics for project management in oil and gas infrastructure. *Int J Multidiscip Res Growth Eval.* 2021;2(1):567-80. <https://doi.org/10.54660/IJMRGE.2021.2.1.567-580>.
- Akhigbe EE, Egbuhuzor NS, Ajayi AJ, Agbede OO. Financial valuation of green bonds for sustainability-focused energy investment portfolios and projects. *Magna Sci Adv Res Rev.* 2021;2(1):109-28. <https://doi.org/10.30574/msarr.2021.2.1.0033>.
- Akinsooto O. Electrical energy savings calculation in single-phase harmonic distorted systems [dissertation]. South Africa: University of Johannesburg; 2013.
- Akinsooto O, De Canha D, Pretorius JHC. Energy savings reporting and uncertainty in measurement & verification. In: 2014 Australasian Universities Power Engineering Conference (AUPEC). IEEE; 2014. p. 1-5.
- Akinsooto O, Pretorius JHC, van Rhyn P. Energy savings calculation in a system with harmonics. In: Fourth IASTED African Conference on Power and Energy Systems (AfricaPES); 2012.
- Aksenov V, Chertov M, Sinkov K. Application of accelerated fixed-point algorithms to hydrodynamic well-fracture coupling. 2020. <https://doi.org/10.48550/arxiv.2005.01620>.
- Alsoraya M, Zhao M, Fan D. Engineered nanomaterials for sustainable oil separation and recovery. *ChemNanoMat.* 2020;6(11):1539-52.
- Amanullah M. Characteristics, behavior and performance of ARC Plug—a date seed-based sized particulate LCM. In: SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition; 2016. SPE-182840.
- Amanullah M, Al-Arfaj M, Gadalla A, Saleh R, El-Habrouk I, Al-Dhafeeri B, Khayat A. Date seed-based particulate LCM "ARC plug"—its development, laboratory testing and trial test results. In: SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition; 2017. D033S019R002.
- Anderson A. Sustainability across diverse engineering disciplines (geothermal technology, district cooling systems, acid mine drainage, and additive manufacturing) [dissertation]. USA: University of Idaho; 2020.
- Apenteng SO. Patent analysis of shale gas technology to identify the US government's role in its development. 2016.

18. Avvaru B, Venkateswaran N, Uppara P, Iyengar SB, Katti SS. Current knowledge and potential applications of cavitation technologies for the petroleum industry. *Ultrason Sonochem.* 2018;42:493-507.
19. Ayodele O, Chatterjee T, Opuwari M. Static reservoir modeling using stochastic method: A case study of the Cretaceous sequence of Gamtoos Basin, offshore, South Africa. *J Pet Explor Prod Technol.* 2021;11(12):4185-200. <https://doi.org/10.1007/s13202-021-01306-y>.
20. Barboza B, Chen B, Lin M. A review on proppant transport modelling. *J Pet Sci Eng.* 2021;204:108753. <https://doi.org/10.1016/j.petrol.2021.108753>.
21. Birdsell D, Rajaram H, Lackey G. Imbibition of hydraulic fracturing fluids into partially saturated shale. *Water Resour Res.* 2015;51(8):6787-96. <https://doi.org/10.1002/2015wr017621>.
22. Birdsell D, Rajaram H, Dempsey D, Viswanathan H. Hydraulic fracturing fluid migration in the subsurface: A review and expanded modeling results. *Water Resour Res.* 2015;51(9):7159-88. <https://doi.org/10.1002/2015wr017810>.
23. Boak J, Kleinberg R. Shale gas, tight oil, shale oil and hydraulic fracturing. In: *Future Energy.* Elsevier; 2020. p. 67-95.
24. Botechia V, Gaspar A, Avansi G, Davólio A, Schiozer D. Investigation of production forecast biases of simulation models in a benchmark case. *Oil Gas Sci Technol Rev IFP Energies Nouv.* 2018;73:23. <https://doi.org/10.2516/ogst/2018014>.
25. Bourbiaux B, Basquet R, Cacas MC, Daniel JM, Sarda S. An integrated workflow to account for multi-scale fractures in reservoir simulation models: Implementation and benefits. In: *Abu Dhabi International Petroleum Exhibition and Conference; 2002.* SPE-78489.
26. Cipolla C, Fitzpatrick T, Williams M, Ganguly U. Seismic-to-simulation for unconventional reservoir development. 2011. <https://doi.org/10.2118/146876-ms>.
27. Dienagha IN, Onyeke FO, Digiemie WN, Adekunle M. Strategic reviews of greenfield gas projects in Africa: Lessons learned for expanding regional energy infrastructure and security. 2021.
28. Dusterhoft R, Sharma P. Adaptation of modern techniques in economic exploitation of unconventional gas reservoirs in the emerging regions. In: *SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition; 2015.* SPE-178020.
29. Edwards R, Doster F, Celia M, Bandilla K. Numerical modeling of gas and water flow in shale gas formations with a focus on the fate of hydraulic fracturing fluid. *Environ Sci Technol.* 2017;51(23):13779-87. <https://doi.org/10.1021/acs.est.7b03270>.
30. Egbuhuzor NS, Ajayi AJ, Akhigbe EE, Agbede OO, Ewim CP-M, Ajiga DI. Cloud-based CRM systems: Revolutionizing customer engagement in the financial sector with artificial intelligence. *Int J Sci Res Arch.* 2021;3(1):215-34. <https://doi.org/10.30574/ijrsra.2021.3.1.0111>.
31. Egbumokei PI, Dienagha IN, Digiemie WN, Onukwulu EC. Advanced pipeline leak detection technologies for enhancing safety and environmental sustainability in energy operations. *Int J Sci Res Arch.* 2021;4(1):222-8. <https://doi.org/10.30574/ijrsra.2021.4.1.0186>.
32. Fredson G, Adebisi B, Ayorinde OB, Onukwulu EC, Adediwin O, Ihechere AO. Driving organizational transformation: Leadership in ERP implementation and lessons from the oil and gas sector. *Int J Multidiscip Res Growth Eval.* 2021. <https://doi.org/10.54660/IJMRGE.2021.2.1.508-520>.
33. Fredson G, Adebisi B, Ayorinde OB, Onukwulu EC, Adediwin O, Ihechere AO. Revolutionizing procurement management in the oil and gas industry: Innovative strategies and insights from high-value projects. *Int J Multidiscip Res Growth Eval.* 2021. <https://doi.org/10.54660/IJMRGE.2021.2.1.521-533>.
34. Fücks R. *Green growth, smart growth: A new approach to economics, innovation and the environment.* Anthem Press; 2015.
35. Gandossi L. State of the art report on waterless stimulation techniques for shale formations. The Netherlands: Publications Office of the European Union; 2016.
36. Gandossi L, Von Estorff U. An overview of hydraulic fracturing and other formation stimulation technologies for shale gas production. Luxembourg: Publications Office of the European Union; 2015. p. 15-16.
37. Gao Q, Cheng Y, Yan C. A 3D numerical model for investigation of hydraulic fracture configuration in multilayered tight sandstone gas reservoirs. *J Pet Explor Prod Technol.* 2018;8(4):1413-24. <https://doi.org/10.1007/s13202-017-0417-0>.
38. Gehne S, Benson P. Permeability enhancement through hydraulic fracturing: Laboratory measurements combining a 3D printed jacket and pore fluid overpressure. *Sci Rep.* 2019;9(1). <https://doi.org/10.1038/s41598-019-49093-1>.
39. Gu Q, Hoo K. Evaluating the performance of a fracturing treatment design. *Ind Eng Chem Res.* 2014;53(25):10491-503. <https://doi.org/10.1021/ie404134n>.
40. Guo Z, Zhao J, Li Y, Zhao Y, Hu H. Theoretical and experimental determination of proppant-crushing ratio and fracture conductivity with different particle sizes. *Energy Sci Eng.* 2021;10(1):177-93. <https://doi.org/10.1002/ese3.1019>.
41. Hassanpouryouzband A, Joonaki E, Farahani MV, Takeya S, Ruppel C, Yang J, *et al.* Gas hydrates in sustainable chemistry. *Chem Soc Rev.* 2020;49(15):5225-309.
42. He J, Lin C, Li X, Wan X. Experimental investigation of crack extension patterns in hydraulic fracturing with shale, sandstone and granite cores. *Energies.* 2016;9(12):1018. <https://doi.org/10.3390/en9121018>.
43. Huang J, Safari R, Lakshminarayanan S, Mutlu U, McClure M. Impact of discrete fracture network (DFN) reactivation on productive stimulated rock volume: Microseismic, geomechanics and reservoir coupling. In: *ARMA US Rock Mechanics/Geomechanics Symposium; 2014.* ARMA-2014.
44. Huang J, Safari R, Mutlu U, Burns K, Geldmacher I, McClure M, Jackson S. Natural-hydraulic fracture interaction: Microseismic observations and geomechanical predictions. *Interpretation.* 2015;3(3):SU17-31.
45. Islam A, Ziarani A, Cui A, Ehlers S, Schneider B. Experimental and analytical core and geomechanical data analysis of a tight oil carbonate formation. 2014. <https://doi.org/10.2118/170943-ms>.
46. Jones P, Hillier D, Comfort D. Sustainability in the

- hospitality industry: Some personal reflections on corporate challenges and research agendas. *Int J Contemp Hosp Manag.* 2016;28(1):36-67.
47. Keshavarzi R, Jahanbakhshi R. Real-time prediction of complex hydraulic fracture behaviour in unconventional naturally fractured reservoirs. 2013. <https://doi.org/10.2118/163950-ms>.
 48. Kresse O, Weng X, Chuprakov D, Prioul R, Cohe C. Effect of flow rate and viscosity on complex fracture development in UFM model. 2013. <https://doi.org/10.5772/56406>.
 49. Li D, Zhao Z, Bai W, Yang H, Cui W, Ruan J, *et al.* Study on production optimization method of fractured reservoir based on connectivity model. *Front Earth Sci.* 2021;9. <https://doi.org/10.3389/feart.2021.767738>.
 50. Li Q, Xing H, Liu J, Liu X. A review on hydraulic fracturing of unconventional reservoir. *Petroleum.* 2015;1(1):8-15. <https://doi.org/10.1016/j.petlm.2015.03.008>.
 51. Li Y, Meng W, Rui R, Wang J, Jia D, Chen G, *et al.* The calculation of coal rock fracture conductivity with different arrangements of proppants. *Geofluids.* 2018;2018:1-10. <https://doi.org/10.1155/2018/4938294>.
 52. Liew MS, Danyaro KU, Zawawi NAWA. A comprehensive guide to different fracturing technologies: A review. *Energies.* 2020;13(13):3326.
 53. Liu J, Qu L, Song Z, Li J, Liu C, Feng Y, *et al.* Fracability evaluation method and influencing factors of the tight sandstone reservoir. *Geofluids.* 2021;2021:1-15. <https://doi.org/10.1155/2021/7092143>.
 54. Liu Y, Leung J, Chalaturnyk R, Virués C. New insights on mechanisms controlling fracturing-fluid distribution and their effects on well performance in shale-gas reservoirs. *SPE Prod Oper.* 2019;34(3):564-85. <https://doi.org/10.2118/185043-pa>.
 55. Lorek S, Spangenberg JH. Sustainable consumption within a sustainable economy—Beyond green growth and green economies. *J Clean Prod.* 2014;63:33-44.
 56. Lu C, Ma L, Li Z, Huang F, Huang C, Yuan H, *et al.* A novel hydraulic fracturing method based on the coupled CFD-DEM numerical simulation study. *Appl Sci.* 2020;10(9):3027. <https://doi.org/10.3390/app10093027>.
 57. Lu W, He C. Quantitative evaluation indexes of the spatial steering effect of directional perforation hydraulic fractures. *Energy Explor Exploit.* 2021;39(4):1246-61. <https://doi.org/10.1177/01445987211010266>.
 58. Lu Y, Zhu Y, Yang F, Xu Z, Liu Q. Advanced switchable molecules and materials for oil recovery and oily waste cleanup. *Adv Sci.* 2021;8(15):2004082.
 59. Mahmoud A, Gowida A, Aljawad MS, Al-Ramadan M, Ibrahim AF. Advancement of hydraulic fracture diagnostics in unconventional formations. *Geofluids.* 2021;2021(1):4223858.
 60. Mahmoud A, Gowida A, Aljawad M, Ramadan M, Ibrahim A. Advancement of hydraulic fracture diagnostics in unconventional formations. *Geofluids.* 2021;2021:1-17. <https://doi.org/10.1155/2021/4223858>.
 61. Marques AC, Mocanu A, Tomić NZ, Balos S, Stammen E, Lundevall A, *et al.* Review on adhesives and surface treatments for structural applications: Recent developments on sustainability and implementation for metal and composite substrates. *Materials (Basel).* 2020;13(24):5590.
 62. McIntosh JC, Hendry MJ, Ballentine C, Haszeldine RS, Mayer B, Etiope G, *et al.* A critical review of state-of-the-art and emerging approaches to identify fracking-derived gases and associated contaminants in aquifers. *Environ Sci Technol.* 2018;53(3):1063-77.
 63. Meschke G, Leonhart D. A generalized finite element method for hydro-mechanically coupled analysis of hydraulic fracturing problems using space-time variant enrichment functions. *Comput Methods Appl Mech Eng.* 2015;290:438-65. <https://doi.org/10.1016/j.cma.2015.03.005>.
 64. Mohaghegh S. Reservoir simulation and modeling based on pattern recognition. 2011. <https://doi.org/10.2118/143179-ms>.
 65. Nandlal K, Weijermars R. Impact on drained rock volume (DRV) of storativity and enhanced permeability in naturally fractured reservoirs: Upscaled field case from hydraulic fracturing test site (HFTS), Wolfcamp formation, Midland Basin, West Texas. *Energies.* 2019;12(20):3852. <https://doi.org/10.3390/en12203852>.
 66. Nguyen-Le V, Shin H, Little E. Development of shale gas prediction models for long-term production and economics based on early production data in Barnett reservoir. *Energies.* 2020;13(2):424. <https://doi.org/10.3390/en13020424>.
 67. Nwinee SA. Sustainable treatment of oil contaminated waste: Oil-based mud (OBM) drill cuttings and soil [Doctoral dissertation]. 2018.
 68. O'Malley D, Karra S, Currier R, Makedonska N, Hyman J, Viswanathan H. Where does water go during hydraulic fracturing? *Ground Water.* 2015;54(4):488-97. <https://doi.org/10.1111/gwat.12380>.
 69. Ockwell D, Byrne R. Sustainable energy for all: Innovation, technology and pro-poor green transformations. Routledge; 2016.
 70. Odio PE, Kokogho E, Olorunfemi TA, Nwaozomudoh MO, Adeniji IE, Sobowale A. Innovative financial solutions: A conceptual framework for expanding SME portfolios in Nigeria's banking sector. *Int J Multidiscip Res Growth Eval.* 2021;2(1):495-507.
 71. Odunaiya OG, Soyombo OT, Ogunsola OY. Economic incentives for EV adoption: A comparative study between the United States and Nigeria. *J Adv Educ Sci.* 2021;1(2):64-74.
 72. Ofodile OC, Toromade AS, Eyo-Udo NL, Adewale TT. Optimizing FMCG supply chain management with IoT and cloud computing integration. *Int J Manag Entrep Res.* 2020;6(11).
 73. Ohtani H, Mikada H, Takekawa J. DEM-SJM combined 2D-hydraulic fracturing simulation for consideration of the influence of differential stress. 2018. <https://doi.org/10.3997/2352-8265.20140228>.
 74. Okotie S, Stanley B, Ikporo B. Workflow for reservoir study and challenges. 2015. <https://doi.org/10.2118/178290-ms>.
 75. Olawoyin R. Optimal well design for enhanced stimulation fluids recovery and flowback treatment in the Marcellus shale gas development using integrated technologies. *Hydrol Curr Res.* 2012;3(5). <https://doi.org/10.4172/2157-7587.1000141>.
 76. Olufemi-Phillips AQ, Ofodile OC, Toromade AS, Eyo-Udo NL, Adewale TT. Optimizing FMCG supply chain management with IoT and cloud computing integration. *Int J Manag Entrep Res.* 2020;6(11). Fair East Publishers.

77. Onukwulu EC, Agho MO, Eyo-Udo NL. Advances in smart warehousing solutions for optimizing energy sector supply chains. *Open Access Res J Multidiscip Stud.* 2021;2(1):139-57. <https://doi.org/10.53022/oarjms.2021.2.1.0045>.
78. Onukwulu EC, Agho MO, Eyo-Udo NL. Framework for sustainable supply chain practices to reduce carbon footprint in energy. *Open Access Res J Sci Technol.* 2021;1(2):12–34. <https://doi.org/10.53022/oarjst.2021.1.2.0032>.
79. Onukwulu EC, Dienagha IN, Digitemie WN, Egbumokei PI. Predictive analytics for mitigating supply chain disruptions in energy operations. *IRE J.* 2021 Sep 30. <https://www.irejournals.com/index.php/paper-details/1702929>.
80. Onukwulu EC, Dienagha IN, Digitemie WN, Egbumokei PI. AI-driven supply chain optimization for enhanced efficiency in the energy sector. *Magna Sci Adv Res Rev.* 2021;2(1):87–108.
81. Onukwulu EC, Dienagha IN, Digitemie WN, Egbumokei PI. AI-driven supply chain optimization for enhanced efficiency in the energy sector. *Magna Sci Adv Res Rev.* 2021;2(1):87-108.
82. Onukwulu EC, Dienagha IN, Digitemie WN, Egbumokei PI. AI-driven supply chain optimization for enhanced efficiency in the energy sector. *Magna Sci Adv Res Rev.* 2021;2(1):87-108. <https://doi.org/10.30574/msarr.2021.2.1.0060>.
83. Oyedokun OO. Green human resource management practices and its effect on the sustainable competitive edge in the Nigerian manufacturing industry (Dangote) [Doctoral dissertation]. Dublin Business School; 2019.
84. Pankaj P, Geetan S, MacDonald R, Qiu F, Porcu M, Xu J, *et al.* Reservoir modeling for pad optimization in the context of hydraulic fracturing. 2015. <https://doi.org/10.2118/176865-ms>.
85. Park H, Sung W, Wang J. Analysis of hydraulic fracturing efficiency considering the principal stress in Brushy Canyon formation of the Permian Basin. *Appl Sci (Basel).* 2021;11(3):1069. <https://doi.org/10.3390/app11031069>.
86. Parvizi H, Gomari S, Nabhani F, Turner A, Wei F. Hydraulic fracturing performance evaluation in tight sand gas reservoirs with high perm streaks and natural fractures. 2015. <https://doi.org/10.2118/174338-ms>.
87. Paul PO, Abbey ABN, Onukwulu EC, Agho MO, Louis N. Integrating procurement strategies for infectious disease control: Best practices from global programs. *Prevention.* 2021;7:9.
88. Pena P, Zhu D, Hill A. The effect of rock properties on fracture conductivity in the Marcellus shale. 2016. <https://doi.org/10.2118/181867-ms>.
89. Sáez-Martínez FJ, Lefebvre G, Hernández JJ, Clark JH. Drivers of sustainable cleaner production and sustainable energy options. *J Clean Prod.* 2016;138:1-7.
90. Schiozer D, Santos A, Santos S, Filho J. Model-based decision analysis applied to petroleum field development and management. *Oil Gas Sci Technol Rev IFP Energies Nouv.* 2019;74:46. <https://doi.org/10.2516/ogst/2019019>.
91. Seales M. Multiphase flow in highly fractured shale gas reservoirs: Review of fundamental concepts for numerical simulation. *J Energy Resour Technol.* 2020;142(10). <https://doi.org/10.1115/1.4046792>.
92. Shar A, Abro W, Mahesar A, Lee K. Simulation study to evaluate the impact of fracture parameters on shale gas productivity. *Mehran Univ Res J Eng Technol.* 2020;39(2):432-42. <https://doi.org/10.22581/muet1982.2002.19>.
93. Shin H, Nguyen-Le V, Kim M, Shin H, Little E. Development of production-forecasting model based on the characteristics of production decline analysis using the reservoir and hydraulic fracture parameters in Montney shale gas reservoir, Canada. *Geofluids.* 2021;2021:1-12. <https://doi.org/10.1155/2021/6613410>.
94. Shun-li Y, Tian-lin Z, Li-yong Y, Jia Y, Liu X, Liu Y, *et al.* Study on the evaluation method and influencing factors of fracture conductivity of hydraulic fracturing support in shale reservoir. *E3S Web Conf.* 2021;252:03049. <https://doi.org/10.1051/e3sconf/202125203049>.
95. Sobowale A, Nwaozumudoh MO, Odio PE, Kokogho E, Olorunfemi TA, Adeniji IE. Developing a conceptual framework for enhancing interbank currency operation accuracy in Nigeria's banking sector. *Int J Multidiscip Res Growth Eval.* 2021;2(1):481–94.
96. Sobowale A, Odio PE, Kokogho E, Olorunfemi TA, Nwaozumudoh MO, Adeniji IE. Innovative financial solutions: A conceptual framework for expanding SME portfolios in Nigeria's banking sector. *Int J Multidiscip Res Growth Eval.* 2021;2(1):495–507.
97. Terracina J, Turner J, Collins D, Spillars S. Proppant selection and its effect on the results of fracturing treatments performed in shale formations. 2010. <https://doi.org/10.2118/135502-ms>.
98. Thomas L, Tang H, Kalyon DM, Aktas S, Arthur JD, Blotvogel J, *et al.* Toward better hydraulic fracturing fluids and their application in energy production: A review of sustainable technologies and reduction of potential environmental impacts. *J Pet Sci Eng.* 2019;173:793-803.
99. Tula OA, Adekoya OO, Isong D, Daudu CD, Adefemi A, Okoli CE. Corporate advising strategies: A comprehensive review for aligning petroleum engineering with climate goals and CSR commitments in the United States and Africa. *Corp Sustain Manag J.* 2004;2(1):32-38.
100. Watanabe N, Egawa M, Sakaguchi K, Ishibashi T, Tsuchiya N. Hydraulic fracturing and permeability enhancement in granite from subcritical/brittle to supercritical/ductile conditions. *Geophys Res Lett.* 2017;44(11):5468-75. <https://doi.org/10.1002/2017gl073898>.
101. Xu ZX, Li SY, Li BF, Chen DQ, Liu ZY, Li ZM. A review of development methods and EOR technologies for carbonate reservoirs. *Pet Sci.* 2020;17:990-1013.
102. Yan X, Zhang Z, Yu J, Cao Y, Yuan Y. High in situ stress anisotropy leads to formation of complex fracture patterns. *Geofluids.* 2021;2021:1-10. <https://doi.org/10.1155/2021/8823212>.
103. Yang R, Guo J, Zhang T, Zhang X, Ma J, Li Y. Numerical study on proppant transport and placement in complex fractures system of shale formation using Eulerian multiphase model approach. 2019. <https://doi.org/10.2523/iptc-19090-ms>.
104. Yuan B, Wood DA. A comprehensive review of formation damage during enhanced oil recovery. *J Pet Sci Eng.* 2018;167:287-99.

105. Zangeneh N, Eberhardt E, Bustin R. Investigation of the influence of natural fractures and in situ stress on hydraulic fracture propagation using a distinct-element approach. *Can Geotech J.* 2015;52(7):926-46. <https://doi.org/10.1139/cgj-2013-0366>.
106. Zhang J, Kamenov A, Zhu D, Hill A. Development of new testing procedures to measure propped fracture conductivity considering water damage in clay-rich shale reservoirs: an example of the Barnett Shale. *J Pet Sci Eng.* 2015;135:352-9. <https://doi.org/10.1016/j.petrol.2015.09.025>.
107. Zhang J, Ouyang L, Zhu D, Hill A. Experimental and numerical studies of reduced fracture conductivity due to proppant embedment in the shale reservoir. *J Pet Sci Eng.* 2015;130:37-45. <https://doi.org/10.1016/j.petrol.2015.04.004>.
108. Zhang L, Cui C, Ma X, Sun Z, Liu F, Zhang K. A fractal discrete fracture network model for history matching of naturally fractured reservoirs. *Fractals.* 2019;27(1):1940008. <https://doi.org/10.1142/s0218348x19400085>.
109. Zhang Y, Ge H, Liu G, Shen Y, Chen H, Wang J, *et al.* Experimental study of fracturing fluid retention in rough fractures. *Geofluids.* 2019;2019:1-20. <https://doi.org/10.1155/2019/2603296>