*International Journal of Earth Sciences Knowledge and Applications (2025) 7 (1) 122–127*

International Journal of Earth Sciences Knowledge and Applications
journal homepage: http://www.ijeska.com/index.php/ijeska
**e-ISSN: 2687-5993**

**Review Article** **https://doi.org/10.5281/zenodo.15342893**

# Optimization Strategies for Hydraulic Fracturing in Unconventional Reservoirs: A Review

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**Article history**
Received 30 March 2025
Accepted 28 April 2025
Published 30 April 2025

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**How cite**
Wang, L., 2025. Optimization Strategies for Hydraulic Fracturing in Unconventional Reservoirs: A Review. International Journal of Earth Sciences Knowledge and Applications 7 (1), 122-127. https://doi.org/10.5281/zenodo.15342893.

**Abstract**
The development of unconventional reservoirs has transformed the global energy landscape, primarily driven by advancements in hydraulic fracturing technologies. However, achieving optimal production performance in these complex, ultra-low-permeability formations requires more than conventional stimulation—it demands an integrated approach encompassing candidate selection, fracture treatment design, execution efficiency, and advanced production forecasting. This review synthesizes recent developments in hydraulic fracturing optimization, drawing on field case studies, numerical simulations, and emerging technological innovations. The paper examines best practices for candidate well selection using productivity index (PI) and skin factor analysis, the evolution of fracture design from geometric to geo-engineered completions, and the influence of material selection—such as high-drag proppants and energized fluid systems—on fracture conductivity and proppant transport efficiency. Execution challenges, including limited cluster contribution and non-uniform proppant placement, are addressed through technologies such as under-displacement plugs, diversion agents, and real-time adaptive fracturing strategies. Furthermore, advancements in production forecasting are discussed, with a particular focus on machine learning models, including Auto Regressive Integrated Moving Average (ARIMA) and Long Short-Term Memory (LSTM) networks, which demonstrate superior predictive performance compared to traditional decline curve analysis. Finally, the review highlights innovations such as Fishbone Drilling to enhance reservoir stimulation and contact area in tight formations. Overall, this study emphasizes the integration of engineered materials, adaptive execution technologies, and data-driven forecasting models as the foundation for intelligent and efficient hydraulic fracturing optimization in unconventional reservoirs.

**Keywords**
Hydraulic fracturing, unconventional reservoirs, fracture design, completion efficiency, proppants, forecasting

## 1. Introduction

The exploitation of unconventional reservoirs has become a cornerstone in global energy development, particularly in North America. These formations–including shale gas, tight oil, and coalbed methane–present significant challenges due to their ultra-low permeability and complex geological characteristics. As a result, hydraulic fracturing has emerged as the most effective technique to stimulate these reservoirs and enhance hydrocarbon recovery (Temizel et al., 2022).

Hydraulic fracturing, especially when combined with horizontal drilling, transforms marginal plays into economically viable developments. The introduction of multistage fracturing along horizontal laterals enables access to extensive rock volumes, facilitating the production of hydrocarbons from nanodarcy-range formations like the Bakken, Eagle Ford, and Wolfcamp (Palisch et al., 2012). However, achieving optimal recovery from such reservoirs requires more than just mechanical stimulation–it demands a systematic, data-driven, and integrated approach to candidate selection, treatment design, execution, and post-fracturing evaluation (Martin and Economides, 2010; Omer and Fragachan, 2020).

Despite significant advancements, the hydraulic fracturing industry faces persistent challenges: inefficient cluster contribution, poor proppant placement, and a frequent disconnect between fracture design and actual reservoir response (Fonseca et al., 2015). Moreover, the increasing complexity of formations calls for innovative completion strategies, new materials, and smarter execution technologies. Recent developments in geo-engineered completions, novel proppants, and fluid systems have opened new avenues for enhancing fracture conductivity and treatment effectiveness (Kolawole et al., 2019; Fulks et al., 2016).

Beyond design and execution, forecasting production performance in unconventional wells is critical to field development and economic planning. Traditional decline curve analysis methods often fall short in capturing the transient, non-linear flow behavior typical of these reservoirs. This has prompted a shift toward data-driven and machine learning-based forecasting models such as ARIMA and LSTM, which offer improved accuracy and adaptability (Laalam et al., 2024).

In this review, we synthesize key advancements in hydraulic across design, execution, and forecasting domains. Drawing from field case studies, simulation analyses, and cutting-edge research, this paper aims to provide a comprehensive perspective on the current state, ongoing challenges, and future directions of hydraulic fracturing in unconventional reservoirs.

## 2. Candidate Selection and Design Principles

Selecting the right candidate wells for hydraulic fracturing is the first and arguably most critical step toward optimizing reservoir stimulation. While unconventional formations often require stimulation across most wells, not all wells respond equally. Effective candidate selection aims to maximize return on investment by prioritizing wells with the highest potential for sustainable productivity improvement (Martin and Economides, 2010).

Historically, selection was often based on offset performance or underperformance ("this well needs a frac"), rather than scientific criteria. However, the best practices now emphasize a more quantitative approach involving skin factor analysis, productivity index (PI), and reservoir quality indicators. Martin and Economides (2010) outlined methods to estimate post-treatment performance using steady-state flow equations with assumed negative skin values, helping engineers approximate potential gains and economic feasibility.

Once a well is selected, the next step involves designing the hydraulic fracturing treatment. The overarching goal is to maximize reservoir contact and conductivity, while minimizing operational risks and costs. Design parameters include fracture length, width, height containment, fluid type, and proppant characteristics. In ultra-low permeability reservoirs, fracture conductivity becomes the most important design driver, directly influencing well productivity (Palisch et al., 2012). Fig. 1 illustrates how different proppant types impact fracture width, which is critical to maximizing conductivity and post-frac productivity.

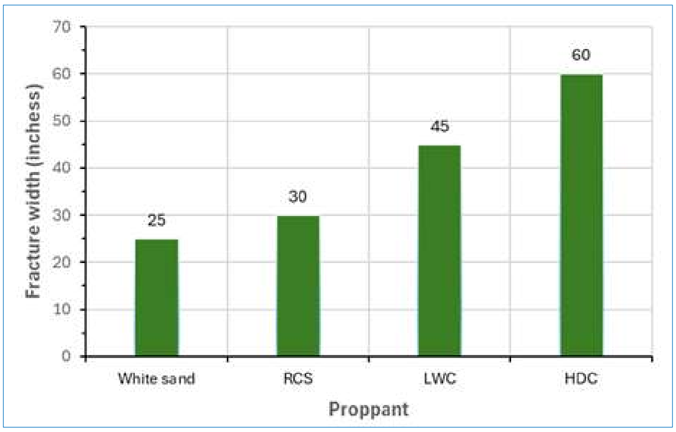

Fig. 1. Fracture width comparison for various proppant types. Higher strength proppants such as HDC (High Density Ceramic), RCS (Resin Coated Sand ) and LWC (Light Weight Ceramic) maintain greater fracture widths under stress, improving flow capacity. Data adapted from Palisch et al. (2012), SPE-160206-MS

Fracture geometry—particularly the stimulated reservoir volume (SRV)—is largely influenced by cluster spacing, perforation strategy, and fluid/proppant interactions. Recent advancements in geo-engineered completions allow for better matching of fracture stages with local rock properties, resulting in more uniform stimulation and improved recovery (Fulks et al., 2016). This contrasts with traditional geometric designs, which apply uniform stage spacing regardless of reservoir heterogeneity.

Additionally, candidate selection and design must account for formation-specific challenges such as stress anisotropy, natural fracture networks, and the risk of water production. In formations like the Eagle Ford or Bakken, these considerations become crucial to achieving successful stimulation (Kolawole et al., 2019; Dehdouh et al., 2024).

The integration of drilling, completion, and geomechanical models has further improved design efficiency. For instance, Omer and Fragachan (2020) proposed an integrated workflow that links wellbore stability modeling with stimulation design, minimizing risks such as stuck pipe and improving the efficiency of fluid diversion across clusters.

Ultimately, the shift from rule-of-thumb approaches to data-driven, integrated design philosophies marks a significant leap in hydraulic fracturing practices. It lays the groundwork for the emerging generation of optimized, low-cost, high-efficiency completions tailored to each reservoir's unique geology and stress regime.

## 3. Fracturing Materials and Execution Technologies

The effectiveness of any hydraulic fracturing operation depends not only on proper candidate selection and treatment design but also on the materials used and how efficiently the treatment is executed in the field. Despite sophisticated modeling and simulation tools, field results often reveal gaps between expected and actual performances due to execution inefficiencies or limitations in fracturing materials (Fonseca et al., 2015).

### *3.1. Fracturing Fluids*

Fracturing fluids play a vital role in transporting proppants, creating fractures, and minimizing formation damage. In unconventional reservoirs, slickwater fluids have become increasingly popular due to their cost-effectiveness, low viscosity, and minimal residue (Temizel et al., 2022). However, their lower viscosity can result in poor proppant suspension and reduced propped height.

To address this, hybrid fluid systems and energized fluids using $CO_2$ or $N_2$ are gaining attention. Energized fluids enhance cleanup, reduce water usage, and improve proppant placement in tight formations. Their application in plays like Montney has shown productivity improvements ranging from 1.6 to 2.1 times over non-energized fluids (Temizel et al., 2022).

### *3.2. Proppants and Transport Challenges*

Proppant selection directly affects fracture conductivity. In unconventional formations, the use of lightweight ceramic proppants, resin-coated sands, and high-drag proppants has improved conductivity under high closure stress (Palisch et al., 2012; Fonseca et al., 2015).

Polymer-coated proppants, in particular, reduce settling rates and maintain fracture width, enabling greater propped area and improved hydrocarbon flow, as illustrated in Fig. 2, which compares the fracture conductivity performance of various proppant types.

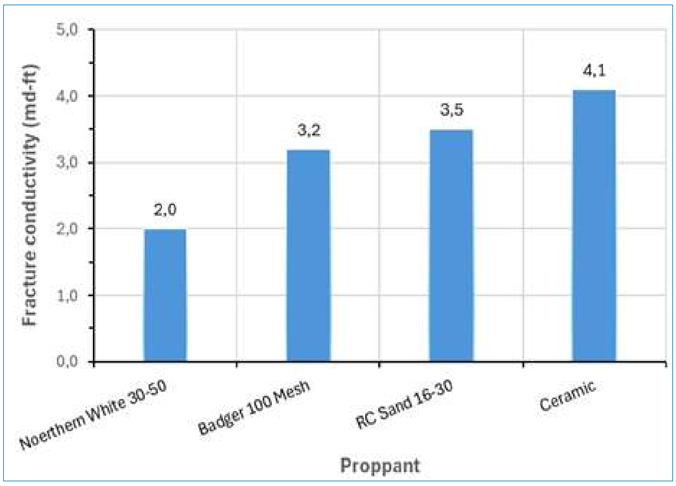

Fig. 2. Fracture conductivity comparison for various proppant types under downhole conditions. Polymer-coated and ceramic proppants exhibit higher conductivity, especially under high stress. Adapted from Kolawole et al. (2019), SPE-198031-MS

Emerging proppant designs also tackle the challenges of embedment, spalling, and fines migration, which compromise conductivity over time. Field studies have demonstrated that ceramic and high-drag proppants offer improved performance under downhole conditions, especially in deeper formations like the Haynesville and Bakken (Fonseca et al., 2015).

### *3.3. Execution Efficiency and Cluster Effectiveness*

Execution technologies have advanced significantly, yet inefficiencies persist. Internal estimates show that only 40–75% of fracture clusters in a stage actually contribute to production, with many clusters under-stimulated or completely bypassed due to over-displacement of fluids (Fonseca et al., 2015). As shown in Fig. 3, execution technologies significantly improve cluster contribution, resulting in more balanced and productive fracture stimulation.

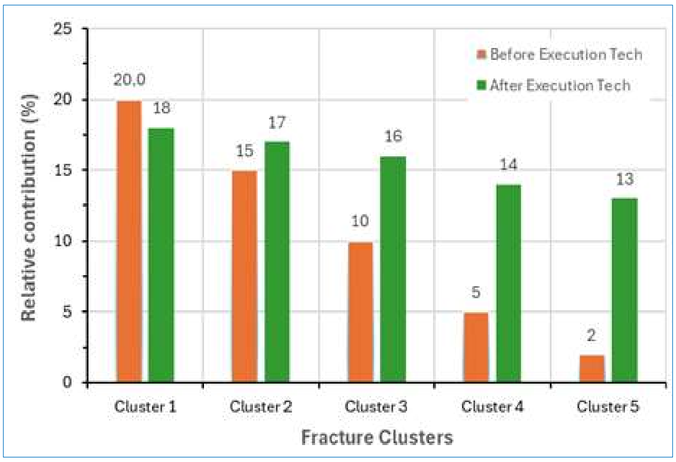

Fig. 3. Cluster-level contribution to production before and after applying execution-enhancing technologies. Under-displacement plugs and diverters help redistribute treatment fluid, improving stimulation efficiency. Data trend inspired by Fonseca et al. (2015), SPE-174822-MS

To improve fracture uniformity, technologies such as under-displacement plugs have been introduced. These plugs reduce the risk of fluid overrun into dominant clusters and help stimulate lesser-accessed zones without increasing costs. Similarly, real-time monitoring and diverter systems are being deployed to adaptively manage fracture growth, improve fluid coverage, and enhance stage-level efficiency (Omer and Fragachan, 2020).

In advanced completions, diverters and particulate materials are injected during the job to temporarily block dominant fractures, forcing fluids into under-stimulated areas. This technique increases stimulated reservoir volume (SRV) and helps achieve more balanced proppant distribution (Kolawole et al., 2019).

## 4. Forecasting and Performance Prediction

Accurately forecasting production in unconventional reservoirs is a critical component of field development, investment decision-making, and reservoir management. However, the complex geology, variable fracture networks, and multiphase flow behavior in tight formations make conventional forecasting techniques less effective. As a result, the industry is increasingly adopting hybrid approaches that integrate empirical models with modern data-driven methods (Laalam et al., 2024).

### *4.1. Traditional Forecasting Techniques*

Historically, decline curve analysis (DCA) has been the most widely used method for forecasting well performance. Methods like Arps' hyperbolic decline model remain a staple due to their simplicity and ease of implementation. However, these models assume idealized flow behavior and often fail to capture the early transient production phases and boundary-dominated flow common in unconventional wells (Temizel et al., 2022; Kolawole et al., 2019).

Alternative models such as the Duong, logistic growth, and stretched exponential decline have been introduced to better represent the complex flow regimes in shale and tight formations. Yet, each model performs variably depending on reservoir heterogeneity, well spacing, and fracture interference effects (Laalam et al., 2024).

### *4.2. Time Series and Machine Learning Models*

To overcome these limitations, recent studies have applied statistical and machine learning techniques to improve forecast accuracy. In a study focused on 11 wells in the Wolfcamp A formation, Laalam et al. (2024) compared traditional DCA with time series models like ARIMA and deep learning approaches such as LSTM and GRU (Gated Recurrent Units).

The results showed that ARIMA provided the highest accuracy among all models tested, achieving an R²-score of 93.5%, significantly outperforming empirical decline models in both early and late production periods. Fig. 4 illustrates this comparison, where ARIMA closely tracks actual production, while DCA begins to deviate over time. Deep learning models such as LSTM and GRU were also effective, particularly in capturing complex nonlinear trends and seasonality in production data.

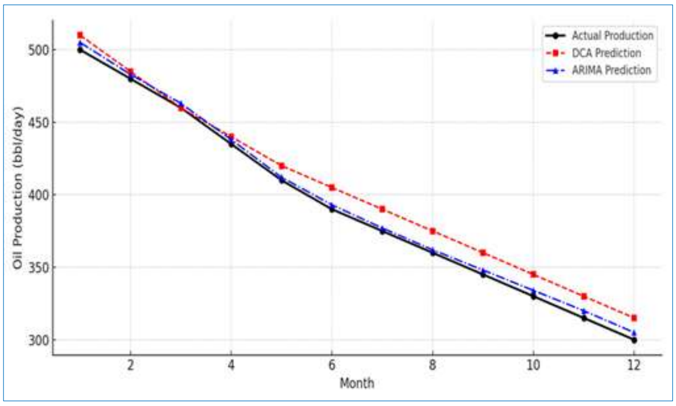

Fig. 4. Comparison of forecasting models against actual production data over a 12-month period. ARIMA demonstrates higher prediction accuracy than traditional Decline Curve Analysis (DCA), particularly in the later months. Data modeled based on Laalam et al. (2024), URTeC-4043738-MS

These models are particularly valuable when production data is noisy or limited in duration—common challenges in early-stage development of unconventional plays. Moreover, their adaptability makes them suitable for continuous learning and improvement as new data becomes available. As shown in Fig. 5, ARIMA and LSTM models achieve higher accuracy in predicting unconventional performance than traditional DCA.

### *4.3. Implications for Field Optimization*

The move toward data-driven forecasting not only enhances accuracy but also supports better decision-making in completion design, refracturing strategies, and economic evaluations. For instance, production forecasts can be used in real-time to adjust treatment size, proppant concentration, or stage spacing in future wells within the same formation (Omer and Fragachan, 2020).

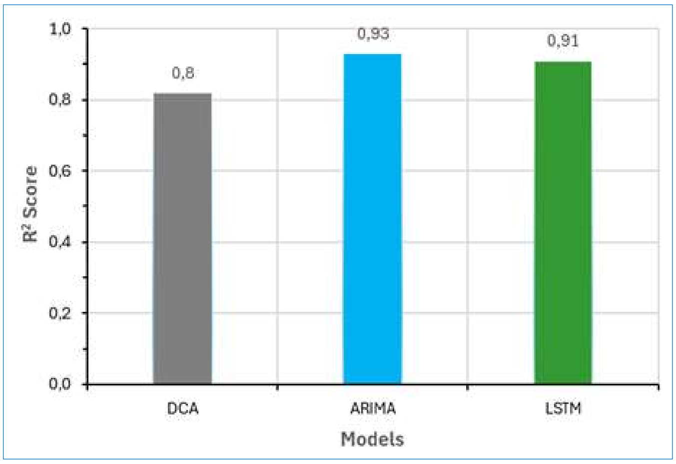

Fig. 5. R² score comparison for traditional and machine learning forecasting models. ARIMA and LSTM demonstrate improved predictive performance for unconventional well production. Performance trends based on Laalam et al. (2024), URTeC-4043738-MS

However, a key limitation of these models is their dependency on high-quality, continuous data streams, which are not always available in every asset or region. Integration of machine learning with physics-based models may offer a balanced approach, leveraging both physical understanding and data adaptability.

## 5. Innovations in Drilling and Enhanced Oil Recovery

While horizontal drilling combined with multistage hydraulic fracturing has revolutionized hydrocarbon recovery from unconventional reservoirs, these methods still face limitations in recovery efficiency. Most unconventional wells recover less than 10% of the original oil in place (OOIP) during their primary production phase (Laalam et al., 2024; Temizel et al., 2022). As a result, the industry is turning to novel drilling and stimulation technologies to increase reservoir contact and boost production. One such promising technique is Fishbone Drilling (FbD).

### *5.1. Concept of Fishbone Drilling (FbD)*

Fishbone Drilling is an advanced drilling configuration that involves creating multiple small-diameter lateral branches, known as “micro laterals,” extending from a main wellbore. These laterals resemble the structure of a fish skeleton, which gives the technique its name. The goal of FbD is to increase the reservoir contact area and better intersect natural fracture networks, especially in low-permeability zones where hydraulic fractures may be limited in height or reach (Dehdouh et al., 2024).

This technique is particularly beneficial in formations like the Bakken, where heterogeneity, natural fracture complexity, and pressure depletion limit the efficiency of conventional fracturing. By extending multiple micro laterals from a central borehole, FbD enhances stimulation coverage and improves the likelihood of connecting to existing natural fracture corridors.

### *5.2. Performance and Field Application*

In the Bakken formation, Dehdouh et al. (2024) evaluated the performance of FbD using numerical simulations and field case analyses. The study revealed that FbD wells achieved a significant increase in effective drainage area, with improved hydrocarbon flow pathways and more uniform reservoir depletion. Despite the higher initial drilling cost compared to standard horizontal wells, the increased recovery factor and extended productive life of the well made the approach economically viable over time.

The study also emphasized key design parameters for FbD: the number of branches, branch length, spacing, and sidetrack angle. Optimal configurations involved 6–12 branches per segment, with each branch ranging from 100 to 300 meters in length and angles between 20° to 30° from the main borehole. These parameters were found to significantly affect production efficiency and should be tailored to the formation's stress regime and fracture orientation.

### *5.3. Integration with Stimulation and Monitoring*

The success of FbD depends not only on drilling execution but also on proper integration with stimulation strategies. In many cases, coiled tubing or underbalanced drilling is used to place the micro laterals effectively. When combined with particulate diverters and real-time monitoring, FbD can be strategically adapted during execution to maximize coverage and manage risks like wellbore instability or fracture interference (Omer and Fragachan, 2020).

Furthermore, integrating FbD with reservoir modeling and pressure transient analysis allows for better post-fracturing evaluation and refracturing decision-making. These tools can be used to estimate effective stimulated volume, compare production against forecasted decline curves, and assess the long-term economics of FbD vs. traditional completions.

## 6. Discussion and Future Directions

The evolution of hydraulic fracturing in unconventional reservoirs has been marked by continuous innovation — from early vertical stimulations to today’s multistage horizontal completions with geo-engineered designs. Yet, despite significant technical advances, challenges remain in maximizing well productivity, minimizing cost, and improving long-term recovery efficiency.

### *6.1. Integration is Key*

One of the strongest themes emerging from this review is the importance of integration—across disciplines (geology, geomechanics, petrophysics), across workflows (drilling, completion, forecasting), and across technologies (materials, execution tools, and models). The combination of smart candidate selection, advanced materials, and real-time execution management is proving to be more effective than treating each step in isolation (Martin and Economides, 2010; Omer and Fragachan, 2020).

Integrated workflows, such as those incorporating rock mechanics into fracture planning or real-time monitoring into execution, have shown quantifiable improvements in performance metrics like cluster contribution, effective proppant placement, and stimulated reservoir volume (Kolawole et al., 2019; Fulks et al., 2016).

### *6.2. Materials and Execution Gaps*

Despite sophisticated design tools, execution remains a bottleneck. As Fonseca et al. (2015) noted, a significant percentage of fracture clusters contribute little to no production, often due to over-displacement or ineffective fluid/proppant transport. This disconnects between design and execution underlines the need for smarter materials – such as high-drag or polymer-coated proppants – and real-time adaptive technologies to dynamically adjust treatment during pumping.

Under-displacement plugs, diverters, and pressure monitoring technologies are promising developments that can improve treatment effectiveness, but widespread field deployment and cost-effectiveness still need validation at scale.

### *6.3. Forecasting and Data-Driven Decisions*

Forecasting remains a critical area, not only for predicting production but also for guiding design improvements and investment strategies. As shown by Laalam et al. (2024), machine learning models like ARIMA and LSTM offer substantial improvements over empirical decline methods, particularly in the early life of wells and in complex formations. However, these models depend heavily on high-resolution, consistent data, which may not be universally available – especially in international plays.

Looking ahead, hybrid models that integrate physics-based simulations with machine learning may offer a robust solution that balances interpretability with adaptability.

### *6.4. Future Technologies and Field Readiness*

Technologies like Fishbone Drilling (Dehdouh et al., 2024) highlight the industry’s move toward more complex but potentially higher-reward well architectures. These systems show promise in formations where traditional fracturing has reached performance limits. However, successful deployment depends on balancing the increased upfront cost with long-term recovery benefits, and ensuring that operational risks (e.g., wellbore instability, fluid isolation) are manageable.

Other forward-looking areas include:

- Energized fracturing fluids using $CO_2/N_2$ for better cleanup and gas recovery
- Digital twins and real-time modeling to simulate fracture growth and adjust parameters live
- Re-fracturing strategies that use production diagnostics to identify bypassed zones

In summary, the future of hydraulic fracturing in unconventional reservoirs is trending toward greater customization, integration, and intelligence. The industry's next breakthroughs are likely to come not from any single innovation, but from bringing together the best elements of design, execution, and data-driven decision-making in a seamless, adaptive workflow.

## 7. Conclusion

Hydraulic fracturing remains the cornerstone of unconventional reservoir development, enabling the economic recovery of hydrocarbons from ultra-low permeability formations. As this review has demonstrated, the effectiveness of fracturing operations depends on a series of interrelated decisions – from selecting the right candidate wells to designing the treatment, choosing suitable materials, executing the job efficiently, and forecasting production with accuracy. Recent advances in integrated workflows, proppant and fluid systems, execution technologies, and data-driven forecasting have significantly improved the performance and reliability of hydraulic fracturing operations. Best practices in candidate selection and treatment design have evolved from empirical rules to data-informed methodologies that incorporate geomechanics, petrophysics, and historical performance (Martin and Economides, 2010; Palisch et al., 2012). Execution technologies such as under-displacement plugs and advanced proppants help bridge the gap between design and field reality (Fonseca et al., 2015), while modern forecasting tools like ARIMA and LSTM improve production prediction and guide long-term asset management (Laalam et al., 2024). Additionally, innovative drilling strategies like Fishbone Drilling are opening new frontiers in enhanced oil recovery by expanding reservoir contact and better leveraging natural fracture networks (Dehdouh et al., 2024). Looking ahead, the convergence of engineering expertise, field data, machine learning, and adaptive execution systems will define the next generation of hydraulic fracturing optimization. Success will depend not on isolated technologies but on fully integrated systems capable of learning, adjusting, and improving across the entire lifecycle of a well. This review underscores the need for continued innovation, cross-disciplinary integration, and real-world validation as the industry works toward more efficient, economical, and sustainable exploitation of unconventional resources.

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