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Sustainable drilling practices through advanced pore pressure prediction: Reducing environmental impact in hydrocarbon exploration

Ovie Vincent Erhueh [1,*], Andrew Emuobosa Esiri [2], Ebimobowei Kevin Wodu [3] and Friday Emmanuel Adikwu [4]

[1] *Independent Researcher, Nigeria.*
[2] *Independent Researcher, Houston Texas, USA.*
[3] *Shell Petroleum Development Company Nigeria.*
[4] *Waltersmith Refining and Petrochemical Company Ltd, Lagos.*

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Abstract

This paper explores the role of advanced pore pressure prediction in promoting sustainable practices within hydrocarbon exploration, with a focus on reducing environmental impacts associated with drilling operations. Conventional drilling methods present significant ecological risks, including blowouts, subsurface contamination, and carbon emissions, which undermine efforts to operate sustainably. Advanced pore pressure prediction methods—encompassing machine learning, real-time monitoring, and data analytics—offer a proactive solution to these challenges by enhancing wellbore stability and minimizing unplanned incidents. Through a comprehensive examination of the latest predictive technologies, this study highlights the benefits of integrating pore pressure prediction into drilling operations to reduce ecological disruption, optimize energy use, and enhance overall safety. Additionally, the paper presents recommendations for industry-wide adoption of these sustainable technologies, emphasizing training, data management, technological partnerships, and regulatory support. The hydrocarbon industry can achieve a more sustainable balance between energy production and environmental preservation by implementing advanced predictive practices.

Keywords: Sustainable drilling; Pore pressure prediction; Environmental impact; Hydrocarbon exploration; Real-time monitoring

1. Introduction

Hydrocarbon exploration remains a critical component of the global energy sector, providing the oil and gas that fuel industries, transportation, and households (American Association of Petroleum Geologists, 2019). However, this exploration process poses notable environmental challenges, particularly through its various stages, including seismic surveys, drilling, extraction, and transportation (Alemzero et al., 2021). Traditional drilling practices are often associated with significant environmental risks, such as land degradation, air pollution, and water contamination. The impact of these operations on surrounding ecosystems is considerable, as drilling can lead to habitat loss, biodiversity reduction, and exposure to harmful substances that affect both wildlife and human health (Saha & Bauddh, 2021). In recent years, the global emphasis on sustainability has brought increased scrutiny to the energy sector, urging companies to adopt practices that minimize ecological impact and align with environmental protection regulations. Thus, finding ways to make hydrocarbon exploration more sustainable has become a priority for both industry stakeholders and regulatory bodies (Rukhaya, Yadav, Rose, Grover, & Bisht, 2021).

* Corresponding author: Ovie Vincent Erhueh

The importance of sustainable practices in the drilling process cannot be overstated. By adopting environmentally-friendly drilling techniques, companies can reduce their ecological footprint, conserve resources, and promote the health and safety of both natural habitats and local communities. Sustainable practices also enable companies to comply with regulatory requirements and enhance their corporate reputation, as the public and investors increasingly favor businesses that demonstrate environmental responsibility. Traditional drilling operations often rely on exhaustive resource extraction methods that inadvertently release greenhouse gases and other pollutants into the atmosphere (Mac Kinnon, Brouwer, & Samuelsen, 2018). In contrast, sustainable drilling practices focus on reducing emissions, minimizing waste, and using energy-efficient equipment, collectively contributing to a lower environmental impact. This shift toward sustainability in drilling operations reflects a growing awareness of the need to balance energy demands with ecological stewardship (Nwaila et al., 2022).

In recent years, advanced pore pressure prediction has emerged as a key innovation to support sustainable drilling practices. Pore pressure refers to the pressure of fluids within the pores of a subsurface rock formation and is a critical factor in drilling operations (Eyinla, Oladunjoye, Olayinka, & Bate, 2021). Accurate prediction of pore pressure is essential to prevent blowouts, a hazardous situation in which uncontrolled release of oil or gas from the well can occur. Blowouts pose serious risks to the safety of personnel and equipment and lead to severe environmental pollution, as seen in catastrophic events like the Deepwater Horizon spill in 2010 (Abdali, Mohamadian, Ghorbani, & Wood, 2021). Traditional pore pressure prediction methods relied on conservative estimates, which often resulted in either overly cautious drilling (leading to resource inefficiencies) or underestimation (leading to blowouts and other hazards). Advanced pore pressure prediction technologies, however, utilize real-time data analytics, machine learning, and subsurface imaging to enhance the accuracy of pressure estimates, thereby reducing the likelihood of environmental incidents and making the drilling process more sustainable (Huang et al., 2022).

The role of pore pressure prediction in reducing ecological risks is twofold. Firstly, accurate prediction reduces the chances of unintentional leaks or spills that can harm the surrounding environment. By preventing blowouts and other well-control issues, companies can protect marine life, prevent soil and water contamination, and reduce emissions of greenhouse gases. Secondly, advanced pore pressure prediction can improve operational efficiency by allowing drillers to optimize their approach based on accurate subsurface data (Wood, 2022). This leads to lower resource wastage and enables drillers to reach reservoirs more safely and efficiently, contributing to a reduced environmental footprint. Advanced pore pressure prediction methods incorporate sophisticated algorithms and data from various sources, such as seismic surveys and logging tools, which help to predict pressure changes more reliably and make real-time adjustments possible. These technological advancements represent a promising solution for mitigating environmental impacts in hydrocarbon exploration (Schimmel, Liu, & Worrell, 2019).

The objective of this paper is to explore the potential of advanced pore pressure prediction as a means of enhancing sustainability in drilling practices. The paper examines the environmental impacts of conventional drilling methods and compares them with sustainable drilling practices that leverage pore pressure prediction technologies. It also discusses the technological advancements in this field, such as real-time monitoring and machine learning applications, which are enabling companies to achieve more accurate predictions and thereby reduce environmental risks. Additionally, this paper seeks to provide insights into the practical implementation of advanced pore pressure prediction in hydrocarbon exploration, identifying both the benefits and challenges of this approach. By focusing on advanced pore pressure prediction, the paper aims to contribute to the broader discussion on sustainable energy practices, highlighting how technological innovation can play a pivotal role in reducing the ecological footprint of oil and gas exploration.

2. Theoretical Background of Pore Pressure Prediction in Drilling

2.1. Pore Pressure and Its Significance in Drilling Operations

Pore pressure is a fundamental concept in geology and drilling, representing the pressure exerted by fluids within the pore spaces of subsurface rock formations. Accurate knowledge of pore pressure is crucial for safe and efficient drilling operations, particularly in hydrocarbon exploration. It plays a significant role in well planning, as the failure to correctly predict pore pressure can lead to costly delays, drilling hazards, or catastrophic blowouts (Morais et al., 2020). Understanding pore pressure dynamics allows engineers to make informed decisions regarding drilling mud weight, well casing designs, and other operational parameters essential to maintaining well stability and controlling fluid influx. Hence, the ability to predict pore pressure with precision has become a focal point in advancing sustainable drilling practices (Li et al., 2022).

During drilling, pore pressure impacts a wellbore's stability and the surrounding rock formations. Suppose the pore pressure is higher than expected. In that case, it can cause "kicks," or unintended formation fluids influx into the wellbore. If uncontrolled, these kicks may escalate into blowouts, which endanger personnel and equipment and pose severe environmental risks due to the potential for oil or gas spills (Gamperl, 2017). Conversely, drilling with excessively high mud weights to counter pore pressure can fracture surrounding formations, leading to fluid losses and increased drilling costs. Thus, accurately predicting pore pressure helps strike a balance, ensuring that drilling operations can proceed safely without risking significant environmental or economic damage (Raabe & Jortner, 2021).

Historically, several methods and models have been used for pore pressure prediction, each offering unique advantages and limitations. The primary methods for pore pressure prediction include empirical models, seismic methods, and petrophysical analysis. Empirical models like the Eaton method are based on historical data and empirical relationships between depth and formation pressure. The Eaton method, for example, uses sonic log data to estimate pore pressure gradients, which can indicate changes in formation pressure with depth. While empirical models are relatively simple and cost-effective, they rely heavily on assumptions, which may limit their accuracy in certain geological settings (Allawi, Al-Jawad, & Alfarge, 2022).

Seismic methods have become increasingly popular in pore pressure prediction because they provide insights into subsurface structures and pressure variations. This approach uses seismic velocity data, where variations in wave velocities correlate with changes in pore pressure (Heidari, Nikolinakou, & Flemings, 2018). Geophysicists can estimate pore pressure across large regions by analyzing seismic data, allowing for comprehensive pre-drill planning. One of the common seismic methods is the velocity-to-pore pressure transform, which utilizes seismic travel times to infer pressure gradients within formations. Although seismic methods are useful for regional pore pressure assessment, their resolution may not be sufficient for fine-scale variations, making them more appropriate for broad exploratory purposes rather than detailed drilling guidance (Buckley & Cottee, 2017).

Petrophysical methods offer another means of pore pressure prediction, relying on well log data, such as resistivity, density, and sonic logs, to assess pressure changes. This approach allows for a direct evaluation of formation properties and has proven particularly valuable in high-stakes, high-pressure environments. By analyzing variations in these logs, geoscientists can infer changes in pore pressure and adapt drilling practices accordingly. Petrophysical methods can be effective for real-time monitoring during drilling, as they offer near-continuous data that reflect changes in pressure and formation behavior. However, petrophysical approaches may be limited in complex geological formations where rock properties vary widely (Zhang et al., 2022).

2.2. Advances In Predictive Techniques and Their Impact on Drilling Efficiency and Safety

In recent years, advances in predictive techniques have transformed pore pressure prediction, enhancing both drilling efficiency and safety. Technologies such as real-time data monitoring, machine learning, and artificial intelligence have introduced new levels of precision in pressure estimation. Real-time data monitoring systems, for instance, utilize a combination of well log and drilling parameters to provide continuous updates on pore pressure. These systems enable operators to adjust mud weight or casing design instantly, reducing the likelihood of incidents and minimizing downtime. By leveraging real-time data, companies can make more accurate and dynamic decisions, increasing the overall safety of drilling operations (Cai et al., 2020).

Machine learning and artificial intelligence have also significantly impacted pore pressure prediction, offering the ability to analyze vast datasets quickly and accurately. Machine learning algorithms can process historical drilling data, seismic information, and geological features to identify patterns and predict pore pressure with greater precision (Tahmasebi, Kamrava, Bai, & Sahimi, 2020). For example, supervised learning models can be trained on historical well data to recognize the conditions under which pore pressure variations occur. Once trained, these models can apply this knowledge to new drilling locations, providing more reliable pressure predictions even in unfamiliar formations. Artificial intelligence can also support predictive modeling through deep learning networks that can adapt and improve over time, leading to increasingly accurate pressure forecasts as more data is collected (Chen, Challita, Saad, Yin, & Debbah, 2019).

These advances in predictive techniques have considerably impacted drilling efficiency and safety. Accurate pore pressure prediction enables operators to optimize drilling speeds, reducing the time and resources needed for exploration and production. Additionally, these technologies help reduce non-productive time (NPT), which refers to delays or stoppages during drilling operations. By accurately anticipating pressure changes, drilling teams can avoid many of the issues that lead to NPT, such as formation damage or fluid losses. From a safety perspective, enhanced pore pressure prediction minimizes the risks of uncontrolled blowouts, ensuring the safety of personnel and protecting nearby ecosystems from contamination (Cox et al., 2020).

In summary, pore pressure prediction is a critical aspect of drilling that supports both operational efficiency and environmental safety. The evolution of predictive techniques, from traditional empirical models to advanced machine learning algorithms, reflects the industry's ongoing commitment to safer and more sustainable practices. As hydrocarbon exploration continues, these advances in pore pressure prediction are expected to play a vital role in promoting sustainable drilling operations by reducing environmental risks, improving resource management, and enhancing the reliability of exploration efforts. Integrating new technologies in pore pressure prediction bolsters operational outcomes and aligns with the broader goal of minimizing the ecological impact of hydrocarbon extraction.

3. Environmental Impact of Conventional Drilling vs. Sustainable Practices

3.1. Analysis Of Environmental Challenges in Traditional Drilling Methods

The environmental impact of conventional drilling methods in hydrocarbon exploration has long been a subject of scrutiny, particularly as concerns over climate change, pollution, and biodiversity loss have intensified. Traditional drilling practices have been associated with a range of ecological challenges, from habitat destruction and soil degradation to air and water pollution. The extraction and processing of oil and gas produce substantial emissions, including carbon dioxide (CO_2), methane, and other greenhouse gases that contribute to global warming (Balcombe, Anderson, Speirs, Brandon, & Hawkes, 2017). Furthermore, conventional drilling often involves invasive techniques that disturb local ecosystems, cause deforestation, and, in offshore operations, threaten marine habitats. With the demand for energy continuing to rise, the challenge lies in finding methods that allow for resource extraction without compromising the environment. In this context, sustainable drilling practices have emerged as a vital approach to reduce the ecological impact of hydrocarbon exploration (Yoro & Daramola, 2020).

One of the primary environmental challenges of traditional drilling is its carbon footprint. Conventional drilling methods are energy-intensive, with the use of heavy machinery, transportation, and processing equipment that rely on fossil fuels, producing large amounts of CO_2. Methane emissions, a potent greenhouse gas, are also a significant concern, as they occur through venting and leaks during drilling (Islam & Hossain, 2020). Methane has a global warming potential over 25 times greater than CO_2 over a 100-year period, making its control critical to climate efforts (Dean et al., 2018). In addition to emissions, conventional drilling methods often disrupt surrounding ecosystems through land clearing, reducing natural habitats for wildlife and removing carbon-storing vegetation. In offshore environments, drilling can lead to oil spills that cause extensive damage to marine biodiversity, contaminating water sources and harming species such as fish, seabirds, and marine mammals (Thakur & Koul, 2022).

Water contamination is another significant environmental issue linked to traditional drilling practices. During drilling, a process known as hydraulic fracturing (or “fracking”) is often used to extract hydrocarbons from deep rock formations. This process involves injecting large volumes of water mixed with chemicals into the ground to fracture rocks and release oil or gas (Pereira, Sad, Castro, Filgueiras, & Lacerda Jr, 2022). The chemicals used in fracking fluid can contaminate groundwater, potentially affecting drinking water supplies and agricultural land. Additionally, the disposal of wastewater, which contains high levels of toxic substances and heavy metals, poses a risk to nearby water bodies if not managed properly. Conventional drilling has also been linked to increased seismic activity in certain regions, as wastewater injection can alter subsurface pressures and trigger minor earthquakes. Collectively, these environmental challenges highlight the need for a shift toward more sustainable drilling practices (Porter, Striolo, Mahgerefteh, & Faure Walker, 2019).

In response to these environmental challenges, sustainable drilling practices have been developed to minimize ecological disruption and reduce the carbon footprint of hydrocarbon exploration. Sustainable practices involve adopting less invasive drilling methods, using cleaner technologies, and implementing more efficient resource management strategies. One approach is to switch to energy sources that emit fewer greenhouse gases, such as natural gas or renewable energy, to power drilling equipment. Many companies are also investing in carbon capture and storage (CCS) technologies that capture CO_2 emissions from drilling operations and store them underground, preventing them from entering the atmosphere. By reducing emissions at the source, these practices help mitigate the impact of hydrocarbon exploration on global warming (Filippov & Zhdaneev, 2022).

Another sustainable practice is the use of environmentally-friendly drilling fluids, or “mud,” which are essential in stabilizing the wellbore, cooling the drill bit, and removing cuttings. Traditional drilling fluids often contain harmful chemicals that can leach into the environment, posing a soil and water quality risk. Environmentally-friendly alternatives use biodegradable or low-toxicity substances that perform the same functions without the harmful side effects. Additionally, by employing closed-loop systems, companies can recycle drilling fluids, reducing waste and minimizing the potential for contamination. This shift toward eco-friendly materials and systems helps preserve local ecosystems and protect water quality (Islam & Hossain, 2020).

3.2. Role Of Advanced Pore Pressure Prediction in Mitigating Environmental Risks

Advanced technologies such as real-time monitoring and predictive analytics are also contributing to more sustainable drilling operations. For example, advanced drilling equipment can adjust parameters in real time to optimize energy use and reduce emissions, while sensors can detect leaks or spills immediately, allowing for rapid containment and minimizing environmental impact. Predictive analytics, including advanced pore pressure prediction, is crucial in reducing the environmental risks associated with drilling (Desai, Pandian, & Vij, 2021). By accurately forecasting subsurface pressure, drilling teams can avoid blowouts and other hazardous events that would lead to spills and contamination. This proactive approach not only improves operational safety but also aligns with the goals of sustainable resource management (Gooneratne et al., 2020).

Advanced pore pressure prediction is instrumental in minimizing environmental risks in hydrocarbon exploration. This technology uses a combination of historical data, real-time monitoring, and machine learning algorithms to estimate the pressure within rock formations, ensuring that drilling operations proceed safely (Huang et al., 2022). Advanced pore pressure prediction enables drillers to adjust mud weights and wellbore integrity measures that prevent unintentional leaks and blowouts by accurately predicting pressure changes. Blowouts are particularly devastating for the environment, as they release large volumes of hydrocarbons and other harmful substances into the ecosystem, causing extensive soil and water contamination. Preventing blowouts reduces the risk to local wildlife and human populations and avoids the long-term ecological damage that can result from oil spills (Little, Sheppard, & Hulme, 2021).

In addition to preventing environmental disasters, advanced pore pressure prediction also enhances drilling efficiency, which contributes to sustainability by reducing the time, energy, and resources required for exploration. When drilling teams clearly understand subsurface conditions, they can optimize their operations, minimizing the amount of drilling fluid and other resources used. This results in a lower overall environmental impact, as fewer resources are consumed, and less waste is generated. Additionally, efficient operations reduce the likelihood of non-productive time (NPT), which refers to delays that can result from unexpected events or poor planning. By minimizing NPT, companies can reduce their resource consumption and associated environmental footprint (Gooneratne et al., 2020).

4. Technological Innovations in Pore Pressure Prediction for Sustainability

4.1. Latest Technologies in Pore Pressure Prediction

Recent advancements in pore pressure prediction are driven largely by the integration of machine learning and artificial intelligence (AI) in drilling operations. Machine learning algorithms analyze vast amounts of historical and real-time drilling data to predict pore pressure in subsurface formations accurately (Abdelaal, Elkatatny, & Abdulraheem, 2021). Traditional methods relied on manual data interpretation and relatively simplistic models, which limited the precision and speed of pore pressure predictions. Machine learning, however, can detect patterns within complex datasets that may not be evident through conventional analysis. By utilizing these insights, drilling teams can make more informed decisions on mud weight, casing design, and drilling trajectory to mitigate risks such as blowouts or wellbore instability (Jafarizadeh et al., 2022).

Real-time monitoring is another major technological innovation in pore pressure prediction. Through the use of downhole sensors, engineers can track changes in subsurface pressure as they happen, adjusting drilling parameters immediately to prevent potential issues. Sensors placed within the wellbore measure parameters such as mud weight, fluid density, and formation pressure, allowing for a continuous stream of data that is analyzed in real time. This immediate feedback is crucial for maintaining the stability of the wellbore and avoiding unexpected surges or losses. Real-time monitoring improves operational safety and minimizes environmental impacts by preventing uncontrolled fluid releases or blowouts that could lead to soil and water contamination (Barzegar, Blanks, Sainsbury, & Timms, 2022).

Moreover, the adoption of data analytics platforms enables companies to streamline the pore pressure prediction process. Engineers gain a holistic view of subsurface conditions by centralizing data from multiple sources—including seismic data, well logs, and historical drilling information. Advanced software can visualize pore pressure gradients across different layers, giving geologists and engineers a clearer picture of subsurface risks and allowing for precise pressure prediction across complex geological formations. This comprehensive approach improves decision-making and allows for more sustainable, low-impact drilling operations that prioritize ecological preservation (Gooneratne et al., 2020).

4.2. Case Studies of Successful Implementation

A notable example of successful implementation of advanced pore pressure prediction techniques can be observed in deepwater drilling projects in the Gulf of Mexico. Drilling in deepwater environments poses unique challenges due to extreme depths and high-pressure conditions that can lead to increased risk of blowouts. Several energy companies have employed machine learning algorithms to improve pore pressure predictions, leveraging extensive datasets from previous regional drilling operations. By integrating real-time monitoring and machine learning insights, these companies have significantly reduced the frequency of drilling-related incidents, enhancing both safety and environmental protection (Gooneratne et al., 2020).

In another case, offshore drilling operations in the North Sea have utilized real-time monitoring and machine learning for precise pore pressure predictions. Given the region's regulatory requirements for environmental preservation, operators must prevent accidental hydrocarbon releases at all costs. Companies have effectively maintained wellbore stability by implementing downhole sensors and predictive models, even in complex geological formations. This proactive approach mitigates environmental risks and contributes to cost efficiency by preventing non-productive time (NPT) associated with unanticipated incidents (Lothe, Cerasi, & Aghito, 2020).

A final example is the application of predictive pore pressure models in onshore unconventional shale gas projects in the United States. Hydraulic fracturing, or fracking, in shale formations often involves challenging pressure conditions that can lead to groundwater contamination if not managed correctly. By employing AI-driven models that predict pore pressure across various strata, operators can optimize drilling fluid density and adjust injection pressures to avoid unintentional fracturing in nearby aquifers. The success of these models has demonstrated that sustainable drilling practices, supported by advanced prediction tools, can limit the environmental footprint of shale gas extraction (Soeder, 2018).

4.3. Potential Challenges and Limitations

While these technological innovations hold promise, several challenges and limitations remain. One major issue is the need for high-quality data, which is essential for machine learning models to provide accurate predictions. For AI algorithms to learn effectively, they require large and well-curated datasets. In some cases, companies may have limited access to historical data, particularly in unexplored or newly opened drilling regions. Without robust data, the accuracy of machine learning predictions diminishes, making it difficult to rely on these tools for critical drilling decisions.

Another challenge involves the cost and complexity of implementing real-time monitoring systems. The installation of downhole sensors, real-time data transmission infrastructure, and data analytics platforms requires substantial investment, which may be prohibitive for smaller companies or projects in marginal fields. Additionally, while real-time monitoring improves safety and sustainability, it also increases operational costs, as maintenance and calibration of these sophisticated systems are necessary to ensure reliability and accuracy. For companies focused on cost-efficiency, these additional expenses could be a deterrent, slowing the adoption of real-time monitoring on a broader scale.

The third challenge is the complexity of geological formations in certain areas, which may hinder the effectiveness of predictive models. While machine learning and data analytics have advanced significantly, they may still struggle to account for unexpected variations in subsurface conditions, such as sudden pressure anomalies in highly faulted or heterogeneous formations. Traditional expertise and manual interpretation may still be required alongside technological tools to ensure drilling safety. This hybrid approach, however, can be time-intensive and may require specialized personnel, adding another layer of complexity to the operation.

Finally, regulatory challenges can also affect the deployment of these technologies. In some regions, stringent regulations may delay the introduction of innovative tools, particularly if regulatory bodies require extensive validation or testing of new technologies before approving their use in drilling operations. This can limit the adoption of advanced pore pressure prediction technologies in areas where they are most needed to reduce environmental impact.

5. Conclusion

Advanced pore pressure prediction brings numerous benefits to sustainable hydrocarbon exploration. First, these predictive technologies allow for greater precision in managing wellbore pressure, reducing the likelihood of sudden releases of hydrocarbons or other hazardous substances into the surrounding environment. By preventing blowouts and other pressure-related accidents, companies can protect nearby ecosystems, decrease contamination risks to soil and groundwater, and reduce the environmental footprint of each operation. This focus on prediction and prevention aligns with the goals of sustainability, where avoiding ecological harm is paramount.

Another significant benefit of advanced pore pressure prediction is its role in reducing the carbon footprint of drilling operations. Unplanned events, such as blowouts or pressure kicks, often lead to prolonged drilling times and increased energy consumption, resulting in higher emissions. By leveraging predictive tools, companies can optimize their drilling processes, avoiding non-productive time (NPT) and enhancing efficiency. This reduces the carbon output of each well and lowers operational costs, making sustainable practices more economically feasible and appealing to companies.

The real-time data insights generated by these advanced technologies also enhance safety for personnel and equipment. Real-time monitoring provides continuous feedback on subsurface pressure changes, enabling immediate adjustments to drilling parameters. This proactive approach improves decision-making on the rig, minimizes downtime, and helps safeguard workers. With a safer, more predictable drilling environment, companies are better equipped to protect both human and environmental resources, enhancing their reputation and regulatory compliance as well.

Recommendations

The energy industry should prioritize several key strategies to fully harness the potential of advanced pore pressure prediction technologies. First, companies should invest in workforce training and education on the benefits and implementation of these technologies. Skilled personnel are essential for operating predictive tools and interpreting data effectively, so training programs are needed to equip drilling teams with the expertise to utilize machine learning models, data analytics platforms, and real-time monitoring systems. Moreover, educating the workforce on the environmental benefits of these tools can foster a culture of sustainability within the industry, aligning operational goals with environmental values.

Investment in high-quality data collection and management infrastructure is another essential recommendation. Machine learning and real-time prediction models rely on accurate, comprehensive datasets to produce reliable insights. Thus, companies should focus on data acquisition, maintenance, and security to support these technologies. Implementing data-sharing agreements across the industry could also enhance predictive models by expanding the available datasets, especially in regions where historical drilling data is scarce. Collaboration between companies, research institutions, and regulatory bodies could help establish standardized data protocols, improving the quality of predictions across the industry.

Furthermore, collaboration with technology providers is crucial for developing and adapting predictive tools tailored to specific operational needs. Given the unique geological and regulatory challenges in different regions, customized solutions may be required to maximize the efficacy of advanced pore pressure prediction technologies. Partnerships with technology firms specializing in AI, sensor technology, and big data analytics could accelerate innovation in pore pressure prediction, driving down costs and making these tools more accessible for widespread adoption. Smaller energy companies, in particular, may benefit from collaborative frameworks that reduce the financial burden of adopting new technology.

Finally, regulatory support is essential to encourage sustainable practices within the hydrocarbon sector. Governments and environmental agencies could offer incentives, such as tax credits or grants, to companies that adopt advanced pore pressure prediction technologies. In addition, regulatory bodies should establish clear guidelines on the use of these technologies to ensure safety and environmental compliance while encouraging innovation. Creating regulatory frameworks that emphasize environmental stewardship will provide companies with a compelling reason to integrate predictive tools into their operations, facilitating a larger shift toward sustainability within the industry.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Abdali, M. R., Mohamadian, N., Ghorbani, H., & Wood, D. A. (2021). Petroleum well blowouts as a threat to drilling operation and wellbore sustainability: causes, prevention, safety and emergency response. Journal of Construction Materials| Special Issue on Sustainable Petroleum Engineering ISSN, 2652, 3752.

[2] Abdelaal, A., Elkatatny, S., & Abdulraheem, A. (2021). Data-driven modeling approach for pore pressure gradient prediction while drilling from drilling parameters. ACS omega, 6(21), 13807-13816.

[3] Alemzero, D. A., Iqbal, N., Iqbal, S., Mohsin, M., Chukwuma, N. J., & Shah, B. A. (2021). Assessing the perceived impact of exploration and production of hydrocarbons on households perspective of environmental regulation in Ghana. Environmental Science and Pollution Research, 28, 5359-5371.

[4] Allawi, R. H., Al-Jawad, M. S., & Alfarge, D. (2022). New empirical equation to predict the pore pressure in oil reservoirs. Arabian Journal of Geosciences, 15(8), 701.

[5] American Association of Petroleum Geologists, E. M. D. f. h. a. c. (2019). Unconventional energy resources: 2017 review. Natural Resources Research, 28(4), 1661-1751.

[6] Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2017). The natural gas supply chain: the importance of methane and carbon dioxide emissions. ACS Sustainable Chemistry & Engineering, 5(1), 3-20.

[7] Barzegar, M., Blanks, S., Sainsbury, B.-A., & Timms, W. (2022). MEMS technology and applications in geotechnical monitoring: a review. Measurement Science and Technology, 33(5), 052001.

[8] Buckley, F. A., & Cottee, L. (2017). A petrophysical approach to the investigation of shallow marine geology. Near Surface Geophysics, 15(4), 367-385.

[9] Cai, W., Wang, J., Jiang, P., Cao, L., Mi, G., & Zhou, Q. (2020). Application of sensing techniques and artificial intelligence-based methods to laser welding real-time monitoring: A critical review of recent literature. Journal of Manufacturing systems, 57, 1-18.

[10] Chen, M., Challita, U., Saad, W., Yin, C., & Debbah, M. (2019). Artificial neural networks-based machine learning for wireless networks: A tutorial. IEEE Communications Surveys & Tutorials, 21(4), 3039-3071.

[11] Cox, D. R., Knutz, P. C., Campbell, D. C., Hopper, J. R., Newton, A. M., Huuse, M., & Gohl, K. (2020). Geohazard detection using 3D seismic data to enhance offshore scientific drilling site selection. Scientific Drilling, 28, 1-27.

[12] Dean, J. F., Middelburg, J. J., Röckmann, T., Aerts, R., Blauw, L. G., Egger, M., . . . Rasigraf, O. (2018). Methane feedbacks to the global climate system in a warmer world. Reviews of Geophysics, 56(1), 207-250.

[13] Desai, J. N., Pandian, S., & Vij, R. K. (2021). Big data analytics in upstream oil and gas industries for sustainable exploration and development: A review. Environmental Technology & Innovation, 21, 101186.

[14] Eyinla, D. S., Oladunjoye, M. A., Olayinka, A. I., & Bate, B. B. (2021). Rock physics and geomechanical application in the interpretation of rock property trends for overpressure detection. Journal of Petroleum Exploration and Production, 11, 75-95.

[15] Filippov, S., & Zhdaneev, O. (2022). Opportunities for the application of carbon dioxide capture and storage technologies in case of global economy decarbonization. Thermal Engineering, 69(9), 637-652.

[16] Gamperl, F. (2017). Analysis of the Impact of Wellbore Quality.

[17] Gooneratne, C. P., Magana-Mora, A., Otalvora, W. C., Affleck, M., Singh, P., Zhan, G. D., & Moellendick, T. E. (2020). Drilling in the fourth industrial revolution—Vision and challenges. IEEE Engineering Management Review, 48(4), 144-159.

[18] Heidari, M., Nikolinakou, M. A., & Flemings, P. B. (2018). Coupling geomechanical modeling with seismic pressure prediction. Geophysics, 83(5), B253-B267.

[19] Huang, H., Li, J., Yang, H., Wang, B., Gao, R., Luo, M., . . . Liu, L. (2022). Research on prediction methods of formation pore pressure based on machine learning. Energy Science & Engineering, 10(6), 1886-1901.

[20] Islam, M. R., & Hossain, M. E. (2020). Drilling Engineering: Towards achieving total sustainability: Gulf Professional Publishing.

[21] Jafarizadeh, F., Rajabi, M., Tabasi, S., Seyedkamali, R., Davoodi, S., Ghorbani, H., . . . Csaba, M. (2022). Data driven models to predict pore pressure using drilling and petrophysical data. Energy Reports, 8, 6551-6562.

[22] Li, C., Luo, X., Zhang, L., Fan, C., Xu, C., Liu, A., . . . Lei, Y. (2022). New understanding of overpressure responses and pore pressure prediction: Insights from the effect of clay mineral transformations on mudstone compaction. Engineering Geology, 297, 106493.

[23] Little, D. I., Sheppard, S. R., & Hulme, D. (2021). A perspective on oil spills: What we should have learned about global warming. Ocean & Coastal Management, 202, 105509.

[24] Lothe, A. E., Cerasi, P., & Aghito, M. (2020). Digitized uncertainty handling of pore pressure and mud-weight window ahead of bit: North Sea Example. SPE Journal, 25(02), 529-540.

[25] Mac Kinnon, M. A., Brouwer, J., & Samuelsen, S. (2018). The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. Progress in Energy and Combustion science, 64, 62-92.

[26] Morais, S., Cario, A., Liu, N., Bernard, D., Lecoutre, C., Garrabos, Y., . . . Hartman, R. L. (2020). Studying key processes related to CO 2 underground storage at the pore scale using high pressure micromodels. Reaction Chemistry & Engineering, 5(7), 1156-1185.

[27] Nwaila, G. T., Frimmel, H. E., Zhang, S. E., Bourdeau, J. E., Tolmay, L. C., Durrheim, R. J., & Ghorbani, Y. (2022). The minerals industry in the era of digital transition: An energy-efficient and environmentally conscious approach. Resources Policy, 78, 102851.

[28] Pereira, L. B., Sad, C. M., Castro, E. V., Filgueiras, P. R., & Lacerda Jr, V. (2022). Environmental impacts related to drilling fluid waste and treatment methods: A critical review. Fuel, 310, 122301.

[29] Porter, R. T., Striolo, A., Mahgerefteh, H., & Faure Walker, J. (2019). Addressing the risks of induced seismicity in subsurface energy operations. Wiley Interdisciplinary Reviews: Energy and Environment, 8(2), e324.

[30] Raabe, G., & Jortner, C. S. (2021). Universal Well Control: Gulf Professional Publishing.

[31] Rukhaya, S., Yadav, S., Rose, N. M., Grover, A., & Bisht, D. (2021). Sustainable approach to counter the environmental impact of fast fashion. The Pharma Innovation Journal, 10(8), 517-523.

[32] Saha, L., & Bauddh, K. (2021). Characteristics of mining spoiled and oil drilling sites and adverse impacts of these activities on the environment and human health. In Phytorestoration of abandoned mining and oil drilling sites (pp. 87-101): Elsevier.

[33] Schimmel, M., Liu, W., & Worrell, E. (2019). Facilitating sustainable geo-resources exploitation: A review of environmental and geological risks of fluid injection into hydrocarbon reservoirs. Earth-Science Reviews, 194, 455-471.

[34] Soeder, D. J. (2018). Groundwater quality and hydraulic fracturing: Current understanding and science needs. Groundwater, 56(6), 852-858.

[35] Tahmasebi, P., Kamrava, S., Bai, T., & Sahimi, M. (2020). Machine learning in geo-and environmental sciences: From small to large scale. Advances in Water Resources, 142, 103619.

[36] Thakur, A., & Koul, B. (2022). Impact of oil exploration and spillage on marine environments. In Advances in Oil-Water Separation (pp. 115-135): Elsevier.

[37] Wood, D. A. (2022). Sustainability challenges for the upstream sectors of the natural gas industry. In Sustainable Natural Gas Reservoir and Production Engineering (pp. 349-378): Elsevier.

[38] Yoro, K. O., & Daramola, M. O. (2020). CO2 emission sources, greenhouse gases, and the global warming effect. In Advances in carbon capture (pp. 3-28): Elsevier.

[39] Zhang, G., Davoodi, S., Band, S. S., Ghorbani, H., Mosavi, A., & Moslehpour, M. (2022). A robust approach to pore pressure prediction applying petrophysical log data aided by machine learning techniques. Energy Reports, 8, 2233-2247.