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Editorial

Innovative technologies for shale oil and gas exploration and development

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Abstract:
Against the backdrop of global low-carbon energy transition, the green, economical, and efficient development of shale oil and gas resources faces a series of challenges in theoretical frameworks, technological costs, low-carbon innovation, and engineering management. To foster technological independence and advance low-carbon development through academic exchange, the 6th International Symposium on Shale Oil and Gas Exploration, Development, and Utilization Technology was held by Jilin University in Changchun, China, from November 7 to 9, 2025. This symposium gathered over 270 experts and scholars from more than 50 institutions worldwide featuring 61 presentations spanning geological theory, intelligent exploration, drilling and completion technologies, *in-situ* conversion, pyrolysis mechanisms, enhanced recovery, and low-carbon strategies. The discussions underscored a decisive shift towards intelligent, integrated, and green technological solutions, highlighting the critical role of artificial intelligence, nanotechnology, and carbon management in field advancement. This event significantly strengthened the industry-academia-research-application collaboration system, providing important momentum for achieving technological independence and driving the shale industry towards a sustainable and secure energy future.

1. Introduction

As the global energy transition accelerates, shale oil and gas, as key unconventional hydrocarbon resources, play a strategically crucial role in enhancing energy security and mitigating supply–demand imbalances. In recent years, China has achieved significant advances in lacustrine shale oil accumulation theory (Xu et al., 2022), exploration and development technologies, and pilot engineering (Wang et al., 2022), marking a historic shift from "lacustrine shale generating oil" to "lacustrine shale producing oil" (He et al., 2023). Nevertheless, the sector continues to face multiple challenges, including incomplete theoretical frameworks, high development costs, and complex engineering management (Jin et al., 2021; Zou et al., 2024). Breakthroughs in key core technologies, such as "sweet spot" prediction, reservoir stimulation, and *in-situ* conversion, are urgently needed to steer the industry toward high-quality, cost-effective, and environmentally sustainable development.

To foster international academic dialogue and collaborative innovation, the 6th International Academic Symposium on Shale Oil & Gas Exploration and Development Technologies was successfully convened from November 7 to 9, 2025, under the theme "Independent Innovation Drives the Shale Revolu-

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tion; AI Enabled Green Solutions Empower a Low-Carbon Future". This symposium provided a high-level international platform for academic exchange, promoting theoretical innovation, technological progress, and industry-academia-research-application integration in shale oil and gas exploration and development. Since its inception in 2011, it has grown into a recognized forum for showcasing innovative research in this field.

This symposium featured 61 presentations, including 7 keynote and 28 invited lectures, which addressed emerging topics such as shale geology and intelligent prediction, intelligent exploration, efficient drilling and completion, *in-situ* conversion mechanisms, pyrolysis and green utilization, enhanced recovery and low-carbon development technologies, as well as energy transition pathways, policy innovation, and security strategies. It attracted over 270 experts and scholars from more than 50 universities, research institutions, and enterprises across multiple countries and regions, including China, Canada, Russia, Jordan, Sweden, Estonia, and Morocco. Through vigorous exchanges of innovative research insights and practical experience, the symposium fostered deeper integration among industry, academia, research, and application, laying a solid foundation for sustained technological progress and green transformation. This editorial synthesizes the main advances discussed, organized into thematic sections that reflect the current research frontiers and future directions for the shale industry.

2. Geological theory and geophysical exploration technology

Accurate subsurface characterization is fundamental to the efficient development of shale resources. Recent advances emphasize a multi-scale, integrated methodology that combines geophysics, geochemistry, and data analytics.

Denghua Li proposed a comprehensive "trinity" evaluation framework that integrates geological, economic, and ecological criteria to assess resource potential and forecast production trends. Xuanlong Shan identified organic matter graphitization as the main cause of low resistivity in Changning shale, providing a novel basis for reservoir evaluation. Through integrated mineralogical and geochemical analysis of Qiangtang Basin shales, Ying Nie elucidated how enhanced hydrological cycling under warming climates influences organic matter accumulation. Rong Liu and Qingtao Meng developed intelligent characterization methods for fine-grained sedimentary rocks and established genetic models linked to paleoenvironmental cycles, thereby aiding lithofacies prediction and shale oil enrichment analysis. Complementing these studies, Yanxiao He characterized elastic parameter dispersion in deep shale via cross-frequency experiments and rock physics modeling, which enhances sweet spot identification for deep shale gas and CO_2-enhanced oil recovery applications. Collectively, these works demonstrate significant progress in characterization techniques, intelligent prediction methods, and the understanding of fundamental mechanisms controlling shale reservoir properties.

Yuhang Guo addressed multi-scale rock physics through AI-enhanced image segmentation and high-performance computing, thereby enabling precise characterization of complex pore networks important for storage and transport. Zhenghui Gao applied a frequency-extension technique based on compressed sensing to achieve high-precision reservoir prediction for shale oil in the Songliao and Junggar Basins. Xuan Feng developed a nonlinear viscoelastic constitutive model for rocks, offering a new theoretical basis for monitoring formation changes and evaluating fracturing effectiveness. These advancements collectively improve "sweet spot" prediction accuracy and reservoir performance assessment, directly guiding exploration strategies and development planning.

3. Intelligent and efficient drilling & completion technology

The imperative to reduce costs and enhance efficiency is most pronounced in drilling and completion operations. Reflecting this, a prominent trend towards automation, intelligence, and systemic integration was evident at the symposium.

This progress is exemplified by several integrated system-level proposals. Jinsheng Sun provided a comprehensive review of North American shale development, comparing technical indicators with those in China and proposing an integrated approach combining volumetric fracturing, microbial conversion, and deep heating for low-to-medium maturity shale oil. Xianzhi Song proposed a dedicated technical framework and roadmap for intelligent drilling, detailing advances in scenario construction, data governance, and platform development. Feifei Zhang analyzed intelligent transformation needs for complex well types and advocated for unified open platforms to accelerate technology maturation.

Concurrently, substantial innovations were reported in smart materials and fluids. Guancheng Jiang developed intelligent drilling fluids capable of autonomous formation adaptation, representing a fundamental innovation in drilling fluid technology. Jingping Liu created a temperature- and pressure-responsive cementing drilling fluid system that significantly enhances wellbore stability in fractured shale formations. Pinghe Sun developed a recycling system for cesium formate drilling fluid using capacitive deionization technology and elucidated the underlying parameter influence mechanisms.

In downhole characterization and stimulation, novel methods and integrated systems are enabling more precise and data-driven operations. Liu Yang invented a scratching device for continuous, millimeter-scale characterization of laminated shale mechanical properties. In fracturing technology, Jianchun Guo established a full-range proppant fracturing methodology that improved matrix-fracture connectivity, successfully applied in over 300 wells. Qiao Zhao introduced an AI-driven fracturing system that integrates smart equipment with digital twins, facilitating a critical shift from experience-based to data-intelligent operations.

These advances collectively demonstrate measurable progress in key technological domains, contributing to improved operational efficiency, cost-effectiveness, and overall development outcomes for unconventional resources.

4. *In-situ* conversion and exploitation technology

In-situ conversion represents a transformative pathway for unlocking oil shale, low-to-medium maturity shale oil and other challenging resources, with the potential to significantly reduce surface environmental impact while converting them into producible hydrocarbons.

Key advances include improved assessment tools and conversion strategies. Wenzhi Zhao systematically evaluated the viability of *in-situ* conversion for low-to-medium maturity shale oil and proposed an integrated strategy to maximize energy output while minimizing input. He introduced an *in-situ* hydrocarbon quality index for rapid assessment of favorable target areas and identified an optimal development strategy for the Ordos Basin. In parallel, Lihong Yang presented an efficient convective conversion technology coupled with a high-performance catalyst system, advancing the transition from laboratory research to field application.

In heating and catalysis, several novel approaches were reported. Yulin Ma's team introduced a microwave-steam synergistic heating method to enhance fracture development in oil shale reservoirs, alongside catalytic pyrolysis technology to improve pore structure and mechanical properties. Jiafeng Jin revealed pore evolution mechanisms during *in-situ* catalytic pyrolysis integrated with supercritical CO_2 fracturing, which significantly reduced the required pyrolysis temperature. Zhibing Chang demonstrated the effectiveness of Fe and Ni-based catalysts in improving tar quality and inhibiting caking during pyrolysis of tar-rich coal.

Toward process integration and system design, Dong Yang proposed a green coal utilization path via *in-situ* hydrogen production using supercritical water gasification, highlighting its potential for carbon-neutral energy extraction. Pengfei Jiang established a numerical model for *in-situ* pyrolysis of tar-rich coal via horizontal well heating, enabling the prediction of temperature fields and product yields. Furthermore, Wei Guo's team reported comprehensive advances in autothermal *in-situ* conversion, covering high-pressure simulation, large-scale physical experiments, product-reservoir interaction mechanisms, microfluidic analysis, gas injection optimization, and engineering design, thereby systematically bridging the gap between theoretical research and field application.

Collectively, the studies presented signify meaningful progress in understanding *in-situ* conversion mechanisms and developing practical engineering technologies, offering important foundational and technical support for the efficient and sustainable exploitation of unconventional hydrocarbon resources.

5. Pyrolysis mechanism and green utilization technology

Optimizing above-ground retorting and refining technologies is essential for maximizing the value and minimizing the environmental impact of shale resources. Research is increasingly focusing on catalytic upgrading and sustainable refining pathways.

Advances in catalytic technologies are enabling more efficient and selective conversion. Omar Al-Ayed systematically evaluated ionic liquids for sulfur removal from Jordanian shale oil, demonstrating that [EMIM]Cl achieved a removal rate of 58.1 wt%, providing a sustainable refining pathway. Junjie Bian developed novel solid acid catalysts that enhance cracking efficiency and hydrocarbon yield in low–medium temperature shale oil recovery through multi-active-site synergy. Dan Yang established quantitative relationships between the physicochemical properties and pyrolysis behavior of global oil shales, revealing the critical role of inorganic composition in controlling decomposition characteristics. Chao Liu further demonstrated that La-modified HZSM-5 catalysts significantly improve pyrolysis efficiency and oil quality in subcritical water environments. The team led by Sunhua Deng clarified the component-specific reaction pathways during crude oil pyrolysis and developed composite catalytic technology for *in-situ* hydrogen production, offering a low-carbon utilization strategy for crude oil.

Concurrently, integrated process design is contributing to improved energy and resource efficiency. Jingru Bai proposed an innovative oil shale-assisted water electrolysis technology, which replaces the conventional anodic oxygen evolution reaction with kerogen oxidation, substantially lowering the energy consumption for hydrogen production. Ke Wang summarized technological advances in oil shale cascade utilization and waste heat recovery, noting the potential to increase annual shale oil production by 250,000 tons while achieving efficient solid waste recycling.

These reports in this section reflect notable progress in both fundamental understanding and applied green technologies, supporting the upgrading of oil shale and heavy hydrocarbon resources and the transition toward more sustainable energy processing systems.

6. Enhanced recovery and low-carbon development technology

Achieving higher recovery from mature assets while integrating low-carbon solutions represents a dual imperative for the sustainable development of unconventional resources. The symposium highlighted a range of technological innovations aimed at this goal, encompassing novel stimulation methods, advanced flow simulation, and the strategic use of carbon dioxide (CO_2) for both enhanced recovery and storage.

In the domain of reservoir stimulation and access, advancements aim to improve permeability and extraction efficiency. Baisheng Nie introduced high-energy electric detonation volumetric fracturing technology, an effective method for enhancing deep shale permeability that offers potential energy efficiency and environmental benefits over conventional hydraulic fracturing. Shijun Hao detailed a suite of efficient surface coalbed methane extraction technologies, including segmented fracturing via horizontal wells in coal seam roofs, extraction in mining-affected zones and goafs, as well as integrated surface–underground approaches.

Progress in understanding microscopic mechanisms and multiscale simulation is enabling more precise resource management. Jianchao Cai revealed how high-salinity conditions can optimize shale pore structure and imbibition behavior by suppressing clay swelling, thereby facilitating oil displacement. On the modeling front, Zhaojie Song developed a nanoconfined multiphase equilibrium model applicable to 2 nm pores, enabling accurate field-scale simulation and informing energy-enhanced recovery strategies for continental shale oil. Sen Wang further contributed multiscale multiphase flow simulation and intelligent fracture network optimization technologies, which have been successfully applied in national demonstration areas.

A significant focus was placed on CO_2 utilization, addressing its dual role in enhancing recovery and enabling carbon management. Jie Zou's team investigated CO_2-enhanced shale development, establishing a linear relationship between adsorbed-phase and bulk-phase CO_2 densities to improve storage potential assessment. Shanling Zhang clarified the mechanisms of CO_2-assisted depressurization in natural gas hydrate production, noting trade-offs between increased gas yield and reduced carbon sequestration efficiency under certain conditions. In addition, Huazhou Li designed a high-temperature resistant double-network gel with 95.3% plugging efficiency for controlling CO_2 leakage in thermal reservoirs.

These advances in volumetric fracturing, multiphase flow simulation, salinity optimization, and CO_2-based methods provide crucial technical support for enhancing recovery factors and reducing the carbon footprint of unconventional resource development.

7. Energy transition pathways, policies and strategies innovation

The strategic positioning of shale development is inseparable from national energy security and climate goals.

A central theme was the imperative for technological advancement to ensure energy self-sufficiency. Youhong Sun emphasized China's 71.9% dependence on crude oil imports and the need to "hold the energy rice bowl firmly in our own hands". While acknowledging the transition from shale oil "generation" to "production," he highlighted persistent challenges such as complex reservoir geology, high costs, and key technology bottlenecks. He advocated for enhanced collaboration to advance core technologies like "sweet spot" prediction and *in-situ* conversion, guided by a vision of innovation-driven, intelligent, and green shale development.

Complementing this, strategic pathways and integrated technical models were proposed to outline a sustainable development future. Deqiang Sun outlined a development pathway for advanced energy, positioning shale oil and gas as a viable advanced energy option. Chao Gao proposed an integrated technology model for efficient reservoir development, establishing a framework that encompasses wellbore stability, optimized fracturing, and energy-enhanced oil recovery strategies. Boyue Liu presented evidence confirming the low environmental impact of *in-situ* oil shale extraction, demonstrating minimal risk to groundwater.

These discussions underscore that the future of shale development involves not only technical innovation but also integrated policy design, strategic planning, and continuous environmental stewardship.

8. Conclusion and future perspectives

The 6th International Symposium has underscored that the shale oil and gas industry is undergoing a profound transformation, driven by digitalization, system integration, and green low-carbon development. Three cross-cutting themes emerged clearly: the pervasive role of AI and data analytics in optimizing exploration and operations; the critical importance of integrated, system-level solutions; and a strong impetus to reduce carbon emissions and environmental impacts through technologies such as CO_2 utilization, waste recycling, and in-situ processing.

Looking ahead, the high-quality development of shale resources will depend on deeper interdisciplinary integration, requiring sustained collaboration across geology, engineering, chemistry, data science, and environmental studies. Equally essential are robust policy frameworks and full-life-cycle assessment systems to ensure that shale development aligns with national energy security and global sustainability objectives. This symposium has helped to chart the way forward: by accelerating the iteration of core technologies, the industry can move toward an economical, intelligent, and environmentally responsible development model, thereby supporting the global transition to a low-carbon energy future.

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Conflicts of interest

The authors declare no competing interest.

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