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Coordinated development of shale gas benefit exploitation and ecological environmental conservation in China: a mini review

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The large-scale development and utilization of shale gas is significant for achieving the “Carbon Peak and Carbon Neutrality” goals. However, addressing the ecological environmental challenges stemming from extensive hydraulic fracturing is imperative. Drawing from the successful exploration and development of shale gas in the Sichuan Basin, this paper employs a bibliometric approach and utilizes the Web of Science database as its data source to review the impact of shale gas development on the ecological environment. Furthermore, effective strategies for achieving coordinated development of shale gas benefit exploitation and ecological environmental conservation in China are identified. The findings highlight that the ecological impact of shale gas development has been a major focus of research over the past decade, primarily involving concerns such as water resources consumption, groundwater pollution, methane emissions, and waste management. These challenges can be addressed by adopting measures such as responsible water usage, maintaining well integrity, proper storage and disposal of fracturing flowback fluids, and appropriate management of drilling solid waste. The key to achieving green and efficient shale gas development in China lies in constructing a solid theoretical framework for benefit exploitation, refining environmental management standards and regulations, and promoting the development of clean production technologies specific to shale gas. Additionally, establishing a distinct exploration and development theory and fostering technical innovation for deep shale gas (buried depth > 3500m) are pivotal for enhancing and stabilizing production in China. Clarifying the theoretical logic of benefit development and improving the environmental protection law of shale gas development are of great significance for realizing the scale benefit development of shale gas and the harmonious development of ecological environment in China.

KEYWORDS

ecological environment, hydraulic fracturing, fracturing flowback fluid, shale gas, benefit development, cleaner production, coordinated development

1 Introduction

Shale gas is a green, low-carbon, clean, unconventional natural gas resource. Its development meets the demand for energy consumption and optimizes the energy consumption structure (He et al., 2022; Li, 2022; Liu, 2023). By utilizing shale gas, carbon emissions can be reduced, effectively mitigating climate warming (Wang, 2022; Cai, 2023; Hu et al., 2023; Liu and Guo, 2023). China possesses the world's largest reserves of technologically recoverable shale gas, accounting for 15% of the global total (Li et al., 2022a; Zhang K. et al., 2022; Li H. et al., 2023). Currently, China has established four national shale gas demonstration zones, namely Fuling, Changning-Weiyuan, and Zhaotong (Zhu et al., 2023). In 2022, China witnessed a remarkable surge in shale gas production, reaching 230 × 10^8 m^3, indicating a rapid growth trajectory. However, shale formations in China present distinctive characteristics such as an ancient formation age, heterogeneous distribution across stratigraphic layers (primarily including the Cambrian Qiongzhusi Formation, Ordovician Wufeng Formation, and Silurian Longmaxi Formation), considerable burial depth (> 3000 m), active tectonic activity, and intricate surface conditions and thermal evolution history (Li et al., 2019; Fan et al., 2020; Fan et al., 2022; Li et al., 2022b). During shale gas development, leading technologies such as horizontal and cluster wells, and hydraulic fracturing are employed (Jabbari et al., 2017; Dou et al., 2022). Although shale gas belongs to clean energy, and the amount of greenhouse gas emitted by combustion is lower than that of coal and oil, the economic development can only be obtained through fracking and horizontal drilling technology, which has different degrees of impact on the ecological environment (Kargbo et al., 2010; Howarth et al., 2011a; Howarth et al., 2011b; Schnoor, 2012). In recent years, the following studies have been carried out: (1) The impact of the use of fracking fluid and fracturing flowback fluid on local water quality (Jiang et al., 2014; Kondash et al., 2017; Zhang Y. et al., 2022); (2) Evaluate water consumption and greenhouse gas emissions by life cycle assessment methods (Laurenzi and Jersey, 2013; Kondash et al., 2018); (3) Compare the greenhouse gas emissions of shale gas and other energy sources to assess whether it can improve air quality (Qin et al., 2017; Xie et al., 2019). They have provided important ideas for the development of shale gas in the United States, Canada and other countries, and has formed sound environmental protection laws and regulations. However, if we only copy their experience and methods, it is difficult to promote the sustainable high-quality development of shale gas in China, and clarify the ecological environment protection ideas is of guiding significance to realize green development of shale gas.

2 A bibliometric review of the environmental impacts on shale gas development

2.1 Literature analysis

Water usage in shale gas exploration and development is predominantly concentrated in several stages, including pre-drilling preparation, drilling, fracturing, and testing (Figure 1A). The fracturing stage alone accounts for over 95% of water consumption, with potential environmental impacts extending to water resources, surface water, groundwater, the atmospheric environment, noise, and road traffic, among other factors (Shi et al., 2020). The most significant environmental concerns associated with shale gas development revolve around water resource consumption and pollution. Critical sources of water contamination include drilling operations, hydraulic fracturing processes, flowback fluids, and methane gas leakage. These pollution sources are prevalent throughout various stages, encompassing drilling, hydraulic fracturing, flowback, and treatment procedures. Addressing these issues is crucial for sustainable and responsible shale gas operations, ensuring the protection of water resources.

In this paper, we employed bibliometric methods to analyze relevant literature from the Science Citation Index Expanded (SCI-E) database and the Chinese National Knowledge Infrastructure (CNKI). The search query was as follows (on May 28, 2023): Title is "Shale Gas" or "Hydraulic Fracturing" and the subject is "Environment". The findings demonstrate a significant increase in research on shale gas development and its environmental implications since 2010, both domestically and internationally, as depicted in Figure 1B. However, it is evident that domestic research in this field lags behind that of international counterparts. CNKI data show that since Li et al. analyzed the formation conditions of shale gas resources in North America in 2009 (Li et al., 2009), the number of research papers reached the most of 96 in 2016 (Figure 1C). It does not imply a shift in the focus of discussion but rather indicates that domestic scholars have published more papers in SCI-E database source journals, with a rapid increase observed since 2012 (Figure 1D). From 2018 onwards, the number of related papers published by Chinese scholars, both domestically and internationally, has remained consistently high (Figure 1E), and it is also a stage of rapid development of shale gas development in China. Moreover, China contributes to 75% of the research papers, surpassing other countries, with the United States ranking second (Figure 1F). This further confirms the sustained attention of our government and scholars to this research field.

2.2 Overview of the impact of shale gas development on the ecological environment

Shale gas hydraulic fracturing extraction may pose the following potential hazards to the environment, including contamination of groundwater resources, pollution of surface water, gas leaks, geological hazards associated with hydraulic fracturing, and land occupation and landscape destruction (Vengosh et al., 2014). Among these, scholars' research on water resource contamination (surface water and groundwater) and gas leaks has received more attention (Yang et al., 2013; Xu and Gao, 2020). In recent years, many researchers have also started to focus on the possibility of seismic activities induced by hydraulic fracturing (Skoumal et al., 2018).

The United States was the first country to conduct research on the environmental impacts of shale gas development, with a

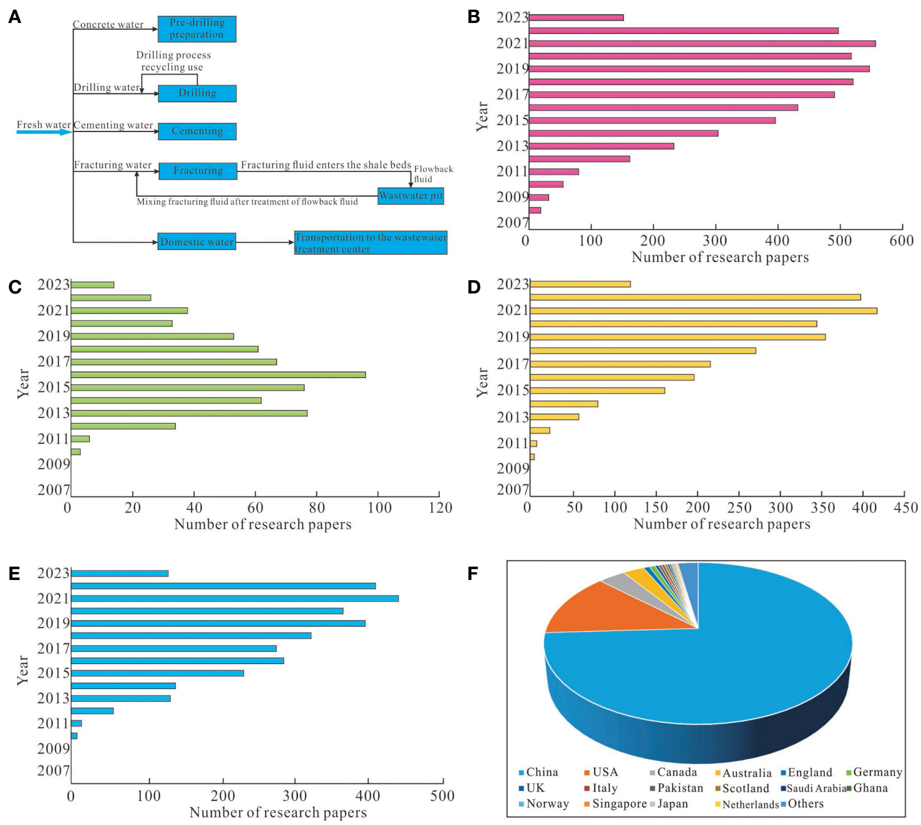

FIGURE 1
Research papers of the environmental impacts on shale gas development at home and abroad (as of May 28, 2023). **(A)** Main links of water consumption in shale gas exploration and development (Shi et al., 2020); **(B)** The number of research papers worldwide; **(C)** The number of papers in domestic CNKI; **(D)** The number of SCI papers published by domestic scholars; **(E)** The number of papers published by Chinese scholars; **(F)** The main areas for the number of global papers.

particular focus on issues such as methane contamination of groundwater, flowback fluids from hydraulic fracturing, drilling solid waste, water resource concerns, and greenhouse gas emissions (Gregory et al., 2011; Osborn et al., 2011). Alongside these research efforts, there have been corresponding technological advancements and innovations. Due to different attitudes towards ecological pollution, hydraulic fracturing or shale gas production has been prohibited in many parts of the United States (such as New York, Maryland, Washington, and California). In addition, France, Bulgaria, Denmark, the Netherlands, Germany, the United Kingdom, and other countries have also banned and restricted shale gas production (Liu et al., 2023a).

Shale gas development in China is later than in the United States and Canada. At first, it mainly refers to foreign exploration and development experience to conduct shale gas resources evaluation and exploration. In China, the impact of shale gas exploitation on the ecological environment has been discussed for many years, and it is clear that shale gas plays a positive role in reducing carbon and improving the ecological environment. However, some environmental problems exist, such as water consumption, groundwater pollution, methane escape, waste disposal, etc. In terms of understanding the impact on water resources, a statistical analysis of the water consumption during hydraulic fracturing in areas such as Changning and Weiyuan reveals relatively low water usage. However, it is crucial to prioritize preventing and controlling water pollution as an important task (Wu et al., 2019). On the premise of ensuring wellbore integrity and proper storage and disposal of waste, shale gas development will not affect groundwater quality. Greenhouse gas emissions from the shale gas industry chain are relatively low relative to the national level (Wang et al., 2017). The disposal method of fracturing backflow fluid with a "large amount of reuse, a small amount of reinjection" and "the new technology, the new method" can effectively reduce groundwater pollution. Shale gas is generally recognized as a low-carbon and clean energy source in line with the "carbon peak and neutralization". Most greenhouse gas emissions occur during hydraulic fracturing and production testing stages. However, the development of shale gas also carries environmental risks. To prevent pollution risks, it is essential to adopt measures such as responsible water extraction, ensuring the integrity of wellbores, and implementing proper storage and disposal methods for flowback fluids and drilling solid waste (Liu et al., 2023a).

3 Progress in the clean production of shale gas

Avner Vengosh and his colleagues studied the risks of hydraulic fracturing on water resources. They identified four main potential risks associated with shale gas development. These risks cover various aspects (Figure 2A). Firstly, hydraulic fracturing may lead to the release of hydrocarbons from shale into shallow aquifers, impacting water quality. Secondly, shale formations may contain toxic and radioactive elements, and during the hydraulic fracturing process, leaks or spills could allow these elements to enter water resources, posing potential hazards to water quality and the environment. Thirdly, proper treatment and handling of the wastewater generated by hydraulic fracturing are necessary to prevent leaks or spills that could result in pollution risks to water quality and the environment. Finally, the significant water demand of hydraulic fracturing may create pressures on local water resources, especially in regions facing drought or water scarcity (Vengosh et al., 2014). In general, scholars focused on three aspects of the impact of shale gas development on the environment, namely, methane will cause pollution of underground water sources, greenhouse gas footprint during shale gas fracking, and the impact of waste disposal (especially fracturing flowback fluid) on the environment (Entrekin et al., 2011; Howarth et al., 2011b; Osborn et al., 2011; Yao and Sui, 2020). Especially they used combined processes such as solid-liquid separation, chemical flocculation, oxidation, and thermal distillation to the treatment of fracturing flowback fluid. Then it is used for preparing water

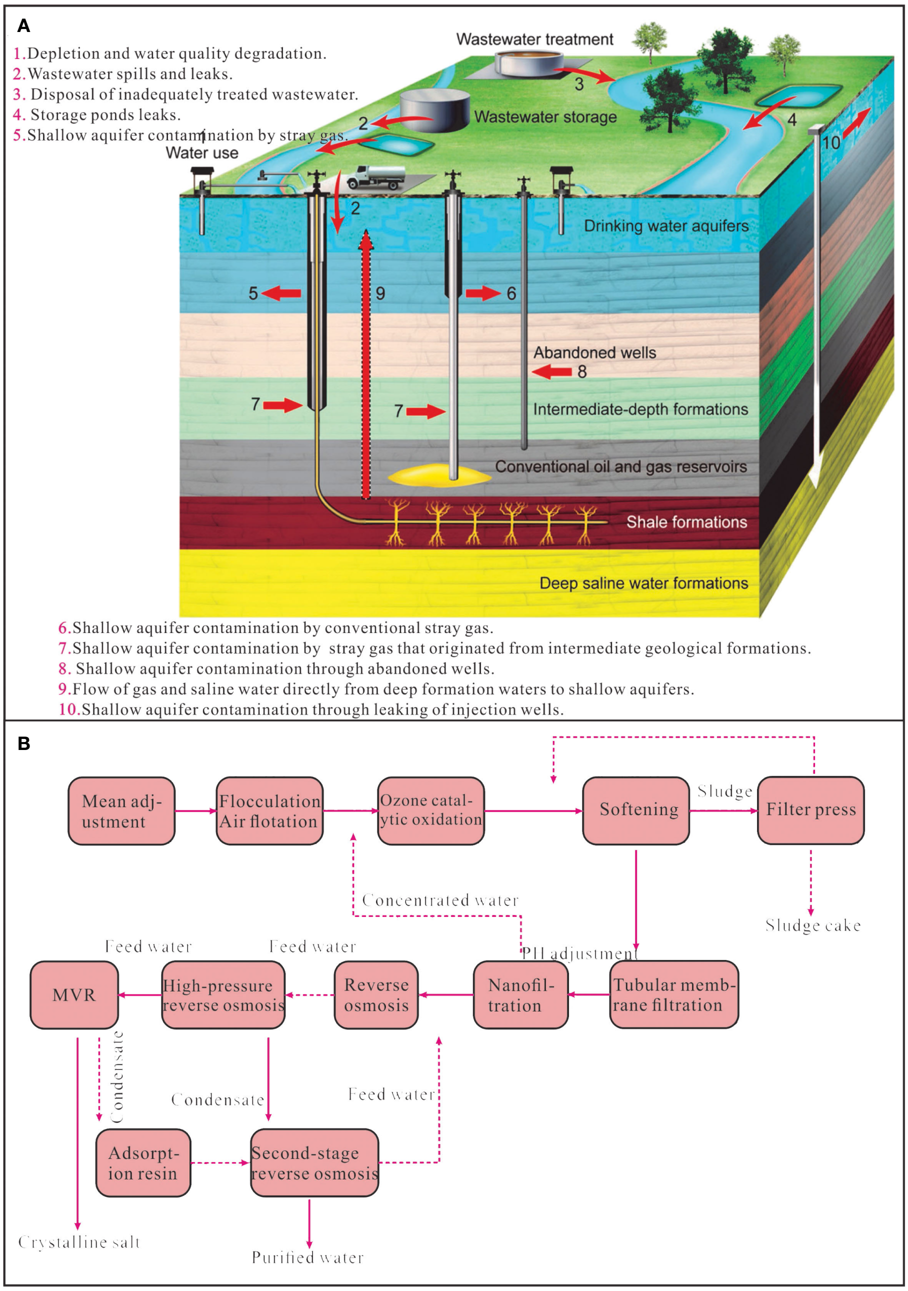

FIGURE 2
Effect of shale gas hydraulic fracturing on water resources **(A)** (Vengosh et al., 2014) and typical fracturing backflow treatment process in China **(B)** (Liu et al., 2023a).

fordrilling mud, water-based fracturing fluid, cementing cement slurry, etc., further improving the reuse efficiency of the fracturing flowback fluid. After intense discussion, it was clear that shale gas development has different impact on the ecological environment. However, it can be effectively solved by formulating a strict environmental protection legal system, an effective monitoring system and a government support system (Liu et al., 2023a; Ye et al., 2023).

In view of the regional geological situation, ecological environment, and water pollution of shale gas in China, we have formulated relevant standards, technical norms, laws, and regulations on environmental protection, wastewater discharge, underground reinjection, waste discharge, solid waste pollution, noise discharge, contaminated site restoration, ecological protection, etc., to protect further and reduce the impact of shale gas exploitation on the environment. The main target pollutants of shale pressure fracturing backflow treatment are chloride, organic matter, ammonia nitrogen, total ammonia, and so on. The treatment efflux process should include solid-liquid separation, softening, organic matter removal, desalination, and other main modules (Figure 2B). A relatively perfect treatment technology for fracturing backflow fluid has been formed in China's main shale gas development areas. Generally, the basic process route of pre-treatment + membrane concentration + evaporation crystallization can be adopted, but the specific treatment process should be tested and verified according to the quality of raw water (Zhang K. et al., 2022). The treatment technology mainly includes physical sewage treatment technology (membrane separation, centrifugation, etc.), chemical sewage treatment technology (neutralization, flocculation, sonochemical oxidation, and pre-chemical treatment of sand settling tank, etc.), biological treatment technology (activated sludge method, biological filter, etc.).

4 Discussions and recommendations

Shale gas is indeed widely acknowledged as a clean energy source. While there are concerns regarding its environmental impact during the development process, it is possible to achieve the benefits of shale gas development while meeting the "dual carbon" goals through appropriate policies, advanced technologies, stringent regulations, and proper guidance. In China, achieving the clean development of low-carbon energy and ensuring strict adherence to the ecological environment's bottom line amidst high-intensity development pose significant technical challenges. Transforming ecological environment constraints into a driving force for green innovation represents a world-class endeavor.

4.1 Establishing the theoretical logic for the efficient development of shale gas and promoting its large-scale benefits

Shale gas development holds great significance in ensuring national energy security, optimizing the energy structure, and promoting economic and social development. It involves multiple stakeholders, including the government, companies, and the general public, who are all invested in the efficient development of shale gas. From a national perspective, the development of shale gas has positive effects on energy structure and supply optimization, contributing to increased energy self-sufficiency and bolstering national energy security. From the companies' perspective, efficient shale gas development becomes the dominant strategy for investment decisions as it aims to increase production and control costs. From the perspective of resource regions, shale gas development plays a significant role in promoting economic and social development (Liu et al., 2023b). Therefore, shale gas development has obvious economic, safety, environmental, and social benefits and is a collection of multiple benefits. Clarifying the theoretical logic of shale gas benefit development is helpful in promoting the benefits development of shale gas in China.

4.2 Establishing refined environmental management standards, regulations, and laws to ensure ecological and environmental safety in high-intensity shale gas development

Shale gas development in the United States and Canada has implemented the whole process fine management and control measures such as the prohibition of wastewater discharge, underground reinjection control, hydraulic fracturing operation risk control, fracturing fluid information disclosure, green completion technology, differential management of on-site waste, diversified utilization, and disposal of oily cuttings (Feng et al., 2020). However, the construction of China's fine environmental management system is still incomplete. It is suggested to establish environmental protection control standards and technical specifications, environmental supervision system, and an environmental risk control system for shale gas development in China to form a series of standards and norms for eco-environmental protection.

4.3 Vigorously developing clean development technologies for shale gas and promoting high-quality development of the shale gas industry

The pollution of shale gas development to the ecological environment mainly manifests in greenhouse gas emissions, fracturing backflow treatment, and hazardous waste disposal. The most direct way to reduce carbon emissions is to introduce diesel engine exhaust treatment technology, but only by electrifying the drilling power system can we fundamentally solve the problem (Liu et al., 2023a). Fracturing flowback fluid is the most significant source of water pollution in shale gas development. Although current flowback fluid treatment technologies are relatively advanced, they still have some shortcomings. Therefore, it is necessary to vigorously develop and promote technologies such as low-water or waterless fracturing, clean fracturing fluid processes, novel microbial treatment techniques, energy-saving treatment technologies for flowback fluid, new energy substitution technologies, and intelligent equipment energy-saving technologies (Dong et al., 2023). These efforts are crucial to ensure the rational development and sustainable growth of shale gas while addressing the concerns associated with flowback fluid management.

4.4 Deepening exploration and development theories and technological innovations to achieve efficient development of deep shale gas in China

The favorable areas of marine shale gas in China are mainly located in the Upper Ordovician Wufeng -Lower Silurian Longmaxi formation in Sichuan Basin. At present, shale gas mainly comes from shallow strata less than 3500m, while deep shale gas (buried depth of 3500 m-4500 m) has more resources, accounting for more than 80%, which is the resource basis for upper and stable production of shale gas (Li J. et al., 2022; Wu et al., 2022; Xie et al., 2022; Li J. et al., 2023). However, deep shale gas has the characteristics of deep buried depth, high temperature, pressure, and crustal stress, and there are difficult construction problems of drillability and compressibility, so the current exploration and development theory and technology cannot meet the needs of deep shale gas development. Therefore, based on summarizing and drawing lessons from both foreign and domestic shallow shale gas exploration theories and development technologies, it is crucial to establish theories of enrichment for deep shale gas, develop classification evaluation criteria, create geological "sweet spot" prediction techniques, optimize horizontal well drilling, environmentally friendly drilling fluids, and complex fracture network technologies suitable for high-stress environments. These efforts can provide support for the efficient development of deep shale gas in terms of scale and benefits.

5 Conclusions

(1) Shale gas is recognized as a green, low-carbon, clean unconventional natural gas resource, but its exploitation often has an impact on the ecological environment. Copying the ecological environment protection methods and technologies of shale gas development in developed countries such as the United States, it is difficult to realize the scale benefit development of shale gas in China.

(2) The harmonious development of shale gas development and ecological environment has been a research hotspot in the past decade, but the ecological environment protection under the high intensity development is still a serious problem facing China at present. Clarifying the economic, safety, environmental and social benefits and connotation characteristics of efficient development of shale gas will help promote the synergy of pollution and carbon reduction, and realize the green upgrading of shale gas development.

Author contributions

HL contributed to the formal analysis, writing, reviewing, editing, and revising of the paper.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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