

Advances in Coalbed Methane Bioengineering: Mechanisms, Key Technologies, and Engineering Challenges

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ABSTRACT

Coalbed methane (CBM) bioengineering has emerged as a promising approach for enhancing methane recovery from low-permeability and marginal coal reservoirs. This study systematically reviews the mechanisms of biogenic methane generation, recent advances in key bioengineering technologies, and the associated engineering challenges. Biogenic methane production in coal seams is driven by a multi-stage anaerobic metabolic network involving hydrolytic, fermentative, and methanogenic microorganisms, in which syntrophic interactions play a critical role in maintaining system stability and efficiency. Recent technological developments have focused on microbial stimulation and bioaugmentation strategies, aiming to enhance methane generation through nutrient regulation and functional microbial consortia. In addition, coupling biological processes with reservoir stimulation techniques, such as hydraulic fracturing and gas injection, has been explored to improve treatment efficiency and expand the effective reaction zone. Advances in monitoring and numerical simulation have further contributed to the understanding and optimization of subsurface biogeochemical processes. Despite these progress, field-scale application remains constrained by reservoir heterogeneity, slow microbial kinetics, and limited process controllability. Moreover, challenges related to microbial stability, substrate conversion efficiency, and environmental risks continue to hinder large-scale deployment. Overall, future research should focus on improving mechanistic understanding, enhancing process control, and integrating multidisciplinary approaches to advance CBM bioengineering toward practical and sustainable applications.

KEYWORDS

Coalbed methane; Biogenic methane; Bioengineering; Microbial stimulation; Bioaugmentation; Geomicrobiology; Unconventional natural gas.

1. INTRODUCTION

Coalbed methane (CBM) is an unconventional natural gas resource predominantly composed of methane and hosted within coal seams and their adjacent strata. Its role has evolved from being considered a hazardous byproduct in coal mine safety management to a valuable source of clean energy[1]. Currently, CBM development primarily relies on physical extraction techniques based on pressure depletion and gas desorption, such as hydraulic fracturing and well-pattern drainage. However, in China, where coal seams are widely characterized by low permeability, low reservoir pressure, and pronounced heterogeneity, these conventional approaches often suffer from low single-well productivity, rapid production decline, and limited ultimate recovery, thereby constraining efficient resource exploitation. Meanwhile, substantial quantities of methane released during coal mining are directly emitted into the atmosphere, resulting not only in resource wastage but also in significant environmental impacts, given methane's considerably higher global warming potential relative to carbon dioxide.

Against this backdrop, microbially enhanced coalbed methane technologies have emerged as a promising alternative. These approaches aim to convert complex organic matter in coal into methane through the regulation of in situ microbial community structure and metabolic activity, thereby enabling a transition from conventional “resource extraction” to “resource regeneration”[2]. The underlying mechanism involves the injection of exogenous nutrients or functional microbial consortia to stimulate or reconstruct indigenous microbial systems, facilitating syntrophic interactions among fermentative bacteria, hydrogen-producing microorganisms, and methanogenic archaea, ultimately enhancing methane generation efficiency. In addition, metabolites such as organic acids and biosurfactants produced during microbial processes may alter coal matrix properties, improving pore connectivity and permeability to a certain extent, and thereby contributing to reservoir modification.

Compared with traditional physical extraction methods, microbially enhanced approaches offer several potential advantages. First, they exhibit greater adaptability to low-permeability and marginal reservoirs, thus expanding the range of economically recoverable CBM resources. Second, these processes generally occur under relatively mild physicochemical conditions, resulting in reduced environmental disturbance and lower ecological risk. Third, by facilitating the bioconversion of coal-bound carbon into methane, this approach enhances resource utilization efficiency and may provide ancillary environmental benefits in the context of low-carbon energy development.

Despite these advantages, the field-scale implementation of CBM bioengineering remains challenging. Key limitations include insufficient stability of microbial communities under reservoir conditions, restricted rates of substrate conversion, and an incomplete understanding of synergistic interactions among microbial consortia derived from different sources. Therefore, a systematic elucidation of the metabolic pathways, microbial interactions, and regulatory mechanisms governing biogenic methane production in coal seams is essential for advancing both the theoretical framework and practical application of this technology.

2. MECHANISMS OF BIOGENIC GAS GENERATION AND ADVANCES IN MICROBIAL ECOLOGICAL UNDERSTANDING

The development of coalbed methane (CBM) bioengineering relies fundamentally on a systematic understanding of the mechanisms governing biogenic gas formation, particularly secondary biogenic methane. In recent years, advances in high-throughput sequencing, metagenomics, and stable isotope tracing have significantly improved our understanding of subsurface biogeochemical processes. Research has evolved from descriptive analyses toward functional characterization of microbial communities and quantitative elucidation of metabolic pathways[3, 4]. These studies indicate that biogenic methane production in coal seams is essentially a complex anaerobic metabolic network driven by the synergistic interactions of diverse microbial groups.

2.1. Anaerobic Food Chain and Microbial Syntrophy

The bioconversion of coal to methane is not mediated by a single microbial species but rather depends on a multi-stage anaerobic food chain composed of bacteria and archaea. This process generally involves three sequential stages:

(1) Hydrolysis and primary fermentation: Hydrolytic and fermentative bacteria secrete extracellular enzymes that degrade complex macromolecular organic matter in coal, such as aromatic structures and their side chains, into soluble low-molecular-weight compounds, including fatty acids, alcohols, and simple aromatic hydrocarbons[5-7].

(2) Hydrogen and acetate production: The fermentation products are further converted by hydrogen-producing and acetogenic microorganisms into key intermediates such as acetate, hydrogen (H₂), and carbon dioxide (CO₂) [8, 9].

(3) Methanogenesis: Methanogenic archaea utilize these intermediates to produce methane via two primary pathways: the acetoclastic pathway ($\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2$) and the hydrogenotrophic pathway ($\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$) [10-12]. In most coal seam environments, the hydrogenotrophic pathway is dominant, and its efficiency is strongly dependent on the dynamic regulation of hydrogen partial pressure.

Overall, this process represents a typical division-of-labor metabolic system, which underpins sustained biogenic methane production in coal reservoirs.

2.2. Syntrophic Metabolism and Key Functional Mechanisms

Within this multi-step anaerobic system, syntrophic interactions among microorganisms play a decisive role in maintaining metabolic stability. In particular, interspecies hydrogen transfer (IHT) between hydrogen-producing bacteria and methanogenic archaea is widely recognized as a key mechanism for ensuring thermodynamic feasibility. Methanogens continuously consume hydrogen, maintaining low hydrogen partial pressure conditions that drive upstream reactions forward.

In addition to hydrogen transfer, interspecies formate transfer has also been identified as an important pathway in certain systems. Recent studies employing metagenomic and functional gene analyses—such as those targeting hydrogenase-encoding genes—have begun to quantitatively characterize these processes, providing deeper insights into the metabolic coupling within microbial consortia.

2.3. Biodegradation Pathways of Coal Organic Matter

The microbial degradation of complex aromatic structures in coal remains a central research focus. Existing studies suggest that certain microorganisms can initiate coal degradation via non-specific oxidative enzyme systems analogous to lignin degradation, or through anaerobic activation pathways of aromatic hydrocarbons.

Metagenomic analyses have identified functional genes associated with polycyclic aromatic hydrocarbon (PAH) degradation and aromatic ring cleavage in coal-associated formation waters, indicating that coal biodegradation pathways are diverse and highly complex. However, the key rate-limiting steps in these processes remain insufficiently understood and require further investigation.

2.4. Environmental Controls on Microbial Processes

Biogenic methane production in coal seams is governed by multiple environmental factors, including temperature, pH, salinity, redox potential, and nutrient availability [13-15]. Among these, macronutrients such as nitrogen and phosphorus, as well as trace elements including iron, nickel, and cobalt, play critical roles in microbial metabolism.

These trace elements serve as essential cofactors for key enzymes, such as methyl-coenzyme M reductase, and their deficiency can significantly limit methanogenic activity. Current research is shifting from single-factor analyses toward the development of multi-factor coupled regulatory models to better understand and predict system behavior.

2.5. Characteristics of Indigenous Microbial Communities

Extensive studies on microbial communities in coal seams with varying coal ranks and depositional environments have generated substantial datasets [16]. These studies reveal that coal reservoirs commonly host functional microbial groups dominated by fermentative bacteria (e.g., Clostridia, Bacteroidetes) and methanogenic archaea (e.g., Methanobacterium, Methanoregula) [17-19].

The structure and composition of these microbial communities are closely linked to geological conditions, formation water chemistry, and gas composition. Such relationships provide an essential

foundation for the targeted design and implementation of microbial enhancement strategies in CBM bioengineering.

3. ADVANCES IN KEY TECHNOLOGIES FOR COALBED METHANE BIOENGINEERING

With the deepening understanding of biogenic methane generation mechanisms in coal seams, CBM bioengineering technologies have evolved from early exploratory studies into a multi-pathway application framework. Current research primarily focuses on two core aspects: microbial community regulation and reservoir environment optimization, with technological development increasingly characterized by greater precision and controllability.

3.1. Microbial Stimulation

Microbial stimulation, which involves the injection of nutrients into coal seams to enhance the metabolic activity of indigenous microbial communities, is currently one of the most widely applied approaches.

In terms of nutrient systems, research has progressed from the supplementation of single nutrients to the development of complex, functional nutrient formulations. In addition to conventional macronutrients such as nitrogen and phosphorus, additives such as humic substances and biosurfactants have been introduced to improve the bioavailability of organic matter and modify coal wettability. Furthermore, the development of slow-release or controlled-release nutrient delivery systems has been shown to sustain nutrient availability and mitigate the negative effects of concentration fluctuations on microbial activity. Tailoring nutrient formulations to specific formation water chemistries has also emerged as a critical strategy for enhancing field adaptability.

With regard to injection strategies, approaches have gradually shifted from single, static injection to dynamic regulation. Periodic or pulsed injection schemes have been suggested to better maintain microbial activity and community stability. In addition, emerging studies have explored bioelectrochemical methods, in which externally applied electric fields may facilitate interspecies electron transfer, thereby enhancing overall metabolic efficiency.

3.2. Microbial Augmentation

In coal reservoirs where indigenous microbial activity is insufficient or key metabolic functions are lacking, bioaugmentation introduces exogenous functional microbial consortia to enhance methane production capacity.

In terms of microbial preparation, research has focused on the isolation of robust strains from extreme environments and the construction of functionally specialized consortia. More recently, synthetic biology approaches have been explored to engineer microbial strains with enhanced capabilities for coal degradation or tolerance to adverse reservoir conditions. However, the field-scale application of genetically modified microorganisms remains constrained by biosafety concerns and regulatory frameworks.

At the engineering level, the survival and successful colonization of introduced microorganisms represent critical bottlenecks. To address this issue, strategies such as biofilm pre-cultivation, carrier-based immobilization, and co-injection with slow-release nutrient systems have been proposed to improve microbial adhesion, resistance to environmental stress, and long-term stability within coal matrices.

3.3. Coupling of Biological Processes with Reservoir Stimulation

The effectiveness of standalone biological processes is often limited by reservoir physical properties. Consequently, the integration of bioengineering with reservoir stimulation techniques has become an important research direction.

On the one hand, incorporating nutrients or functional microorganisms into hydraulic fracturing systems enables biological processes to directly act on newly created fracture networks, thereby expanding the effective treatment area. On the other hand, the coupling of gas injection technologies (e.g., CO₂ or N₂) with microbial processes has attracted increasing attention. In particular, CO₂ can both enhance methane desorption and serve as a carbon source for microbial metabolism, potentially enabling methane regeneration under favorable conditions.

The key challenge of such coupled systems lies in understanding the interactions among multiphase flow, mass transfer, and microbial reactions.

3.4. Process Monitoring and Numerical Simulation

Due to the inherent complexity and subsurface nature of CBM bioengineering processes, the development of effective monitoring and modeling approaches is essential.

For monitoring, integrated analyses combining gas and water sampling with molecular biological techniques (e.g., high-throughput sequencing) and stable isotope methods (e.g., $\delta^{13}\text{C-CH}_4$ and $\delta\text{D-CH}_4$) enable comprehensive characterization of microbial community structure, metabolic pathways, and gas origins[20].

For modeling, the development of numerical models that couple multiphase flow, geochemical reactions, and microbial kinetics remains a major challenge. Such models can simulate nutrient transport, microbial succession, and methane generation processes, providing critical support for field-scale optimization and performance prediction.

4. ENGINEERING CHALLENGES AND DEVELOPMENT DIRECTIONS

Despite the promising potential of coalbed methane (CBM) bioengineering, its large-scale implementation remains constrained by multiple challenges, including complex reservoir conditions, inherently slow microbial processes, and limited controllability in field operations. Addressing these issues requires coordinated advances across multiple disciplines.

4.1. Reservoir Heterogeneity and Flow Control Challenge

Coal reservoirs are characterized by complex pore structures and strong heterogeneity, which often result in preferential flow of injected fluids along high-permeability pathways. This leads to uneven distribution of nutrients and microorganisms, thereby reducing treatment efficiency.

To mitigate this issue, detailed reservoir characterization combined with optimized injection strategies is essential to improve fluid distribution. In addition, the use of temporary plugging agents or flow diversion materials can effectively modify flow pathways, enhancing the utilization of low-permeability zones.

4.2. Slow Bioprocesses and Economic Constraints

The relatively low metabolic rates of microorganisms lead to prolonged methane generation cycles, which pose a significant challenge to economic feasibility at the field scale.

Current research focuses on improving gas production efficiency through the selection of high-potential target zones and the optimization of operational parameters. Furthermore, integrating bioengineering approaches into the full lifecycle of coal mining—such as pre-mining stimulation, production enhancement during operation, or post-mining resource recovery—may help improve overall economic performance and resource utilization.

4.3. Formation Impacts and Environmental Risks

The injection of exogenous nutrients and microorganisms may alter in situ geochemical conditions, potentially affecting pore structure and the stability of indigenous microbial ecosystems. Such changes could lead to unintended formation damage or ecological disturbances.

Therefore, compatibility assessments between injected materials and formation conditions should be conducted prior to field implementation. Environmentally benign materials should be prioritized whenever possible. In addition, long-term monitoring systems should be established to evaluate potential impacts on subsurface environments, including groundwater quality and microbial community dynamics.

4.4. Technical Standardization and Industrial Development

As an emerging field, CBM bioengineering still lacks well-established technical standards, performance evaluation criteria, and scalable industrial models. These limitations hinder its broader adoption and commercialization.

Future efforts should focus on developing standardized methodologies for resource assessment, process design, and performance evaluation. At the same time, the integration of supportive policies and market mechanisms will be essential to promote the standardization, industrialization, and large-scale deployment of this technology.

5. CONCLUSION

Coalbed methane (CBM) bioengineering, as an emerging interdisciplinary technology, provides a promising approach for the development of low-permeability coal reservoirs and other difficult-to-recover resources. This study systematically reviewed the mechanisms of biogenic methane production, recent advances in key technologies, and the enhancement mechanisms of mixed microbial consortia derived from different sources. The main conclusions are summarized as follows:

- (1) Biogenic methane production from coal is a complex anaerobic process driven by the synergistic interactions of multiple microbial groups. Its efficiency is jointly constrained by the initial hydrolysis and degradation of coal organic matter and the degree of metabolic cooperation among microbial populations.
- (2) Microbial stimulation and bioaugmentation techniques can enhance methane production to a certain extent; however, their effectiveness is often limited by restricted spatial influence and insufficient long-term stability.
- (3) Mixed microbial consortia from different sources can improve methane generation efficiency through metabolic complementarity and enhanced community-level cooperation, thereby optimizing the anaerobic degradation pathway. This approach represents a key direction for future research.
- (4) The large-scale application of CBM bioengineering remains challenged by reservoir heterogeneity, slow microbial kinetics, and limited process controllability. These issues require further resolution through technological optimization and interdisciplinary integration.

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