

Cost Estimation of Coal Utilization Technology for Coal Bed Methane (CBM) Using H_2O_2

Heru Suharyadi^{1*}, Shofa Rijalul Haq¹, Tiara Juniar², Hizkiel Purba¹, Farish Rajabi¹,
Gede Ari Subyakta¹

¹ Mining Engineering Department, UPN "Veteran" Yogyakarta

² Economics Department, UPN "Veteran" Yogyakarta

Received : August 7, 2026

Revised : August 16, 2026

Accepted : August 18, 2026

Online : October 7, 2026

Abstract

Indonesia holds 31.95 billion tonnes of coal reserves dominated by low-rank grades, while the 2060 net-zero-emission commitment demands reduced conventional coal use. Hydrogen peroxide-assisted coal bed methane (CBM) technology converts coal into methane within the seam without lifting it to the surface. Its effectiveness is proven at laboratory scale, yet no operating cost estimate exists. This study develops one and identifies the cost-determining components. We built a bottom-up deterministic model from secondary data for a notional installation processing one tonne of low-rank coal per year in the South Sumatra Basin, Indonesia, at 2025–2026 price levels in rupiah. Capital expenditure was excluded as the technology has never been deployed commercially. Reagent requirements followed a published solid-to-liquid ratio of 17 g lignite per 4 L of 0.3 percent H_2O_2 solution, yielding 235,294.12 L per tonne. The two unit bases were held separately: annually fixed and volume-proportional. The results total IDR 11,126,119,382, comprising IDR 8,345,589,114 in fixed cost (75.01 percent) and IDR 2,780,530,269 per tonne in solution cost (24.99 percent). Theoretically, hydrogen peroxide contributes only 0.165 percent of total cost, while diluent water contributes 97.32 percent of solution cost, contradicting the assumption that oxidant efficiency governs MECBM economics; geometry, not chemistry, governs the economics. Practically, the study redirects optimization effort towards the solid-to-liquid ratio and the choice of diluent medium.

Keywords: Coalbed Methane, Hydrogen Peroxide, Cost Estimation, Low-Rank Coal, Solid-To-Liquid Ratio

INTRODUCTION

Coal remains central to Indonesia's energy system. National reserves stand at 31.95 billion tonnes, dominated by low-calorific grades amounting to 67.33 billion tonnes (Badan Geologi, 2025), and coal holds the largest share of the primary energy mix at 40.46 percent (Dewan Energi Nasional, 2023). Its use remains conventional surface mining followed by direct combustion, which requires large-volume overburden removal and produces substantial carbon dioxide emissions, conflicting with the 2060 net-zero emissions commitment.

Coal Bed Methane (CBM) offers a different pathway for the same resource. Coal is converted into methane within the seam rather than lifted to the surface, and CBM combustion releases far less CO_2 , NO_x , SO_x , and mercury than conventional hydrocarbons (Barnhart et al., 2017). Indonesia's prospective CBM resources are estimated at 453.3 TCF, the South Sumatra Basin being the largest at 183 TCF (Stevens & Hadiyanto, 2004).

Hydrogen peroxide stimulation is the most recent development along this pathway. Rather than adding nutrients or microorganisms, H_2O_2 chemically solubilizes coal macromolecules, making methanogenic substrates available much more rapidly (Haq et al., 2018). Work on improving biogenic methane yield has advanced rapidly (Wang et al., 2023; Chen et al., 2023; Zhang et al., 2024), yet it shares a common boundary: such studies stop at the geochemical and microbiological level (Davis & Gerlach, 2018), reporting yield but not the cost of achieving it.

Copyright Holder:

© Suharyadi, Haq, Juniar, Purba, Rajabi & Subyakta. (2026)
Corresponding author's email: heru.suharyadi@upnyk.ac.id

This Article is Licensed Under:



Two questions therefore remain: what it costs to operate this technology, and which component most determines that cost. The second matters more, because it determines where engineering effort should be directed. Without it, optimization proceeds on assumptions, and the prevailing assumption is that oxidant efficiency governs MECBM economics (Park & Liang, 2016; Xu et al., 2023).

This study addresses that gap through a bottom-up deterministic operating cost estimate. Five boundary conditions define its scope. The functional unit is one tonne of low-rank coal processed per year by a notional H_2O_2 injection installation. Capital expenditure is excluded because the technology has never been deployed commercially and no engineering cost basis exists for a full-scale facility, so the estimate is a lower bound.

The base year and currency are 2025–2026 price levels in Indonesian rupiah, with reagent prices accessed on 25 May 2026. The geographic context is the South Sumatra Basin, Indonesia, which holds the country's largest CBM resource and whose low-rank coal is most responsive to H_2O_2 oxidation. The modeling approach is deterministic and bottom-up, holding two unit bases separate and testing them with a one-factor-at-a-time sensitivity analysis.

Within those boundaries, this study aims to prepare an operating cost estimate with the unit basis appropriate to each component group held separate, to identify the components that most determine cost magnitude, and to formulate the most consequential direction for cost reduction.

LITERATURE REVIEW

Before building a cost model, the process must be specified: what reaction takes place, what materials it consumes, and in what proportions.

Mechanism and Theoretical Basis

Under the microbially enhanced coalbed methane concept, methanogenic archaea utilize only simple carbon compounds: acetate, formate, and CO_2/H_2 supplied by fermentation and acetogenesis (Park & Liang, 2016). Coal solubilization is the rate-limiting step, and hydrogen peroxide acts here, cleaving the coal macromolecule and releasing short-chain organic acids into the liquid phase. Microbial treatment also alters coal pore structure and improves reservoir permeability (Gao et al., 2022), while coal position within a block affects methane yield (Yan et al., 2023).

Column experiments flowing a dilute 0.3 percent solution, which is already effective at subsurface temperatures, through pulverized lignite yielded nearly $6 \text{ cm}^3 \text{ CH}_4$ per gram over 130 days (Haq et al., 2018). Notably, the highest yield of $5.92 \text{ cm}^3/\text{g}$ was obtained without minerals or a reducing agent, whereas adding both lowered it to $4.02 \text{ cm}^3/\text{g}$, indicating that a nutrient medium is not required as long as the reaction pH is neutralized.

Two properties underpin the selection of H_2O_2 : it decomposes into O_2 and H_2O , leaving no polluting residue; and its effectiveness depends strongly on coal rank, peaking in lignite, which suits the low-calorific reserves that dominate national resources.

Field application is formulated as subsurface cultivation and gasification: drilling and hydraulic fracturing, injection, methanogen cultivation, and methane production (Aramaki et al., 2017). Pilot trials have not reached commercially viable yields, and recent work extends the concept towards coupling biomethane enhancement with carbon dioxide storage (Li et al., 2026; Niu et al., 2024).

RESEARCH METHOD

Research Design and Data Sources

This study uses a quantitative descriptive approach based on bottom-up deterministic cost

modeling of secondary data; no laboratory or field measurements were conducted. Table 1 lists the data sources and the equation in which each is used.

Table 1. Data Sources and Their Use in the Cost Model

Parameter group	Source	Used in
Solid-to-liquid ratio, methane yield, nutrient medium composition	Haq et al. (2018)	Eq. (1), (2), (4), (8)
Installation labor cost	Sarhosis et al. (2016)	Eq. (5)
Generator capacity and power consumption	Munawar et al. (2013)	Eq. (5)
Produced water volume	Rice & Nuccio (2000)	Eq. (5)
Reagent and distilled water unit prices	Chemical suppliers, 25 May 2026	Eq. (6)

The reference coal is low-rank coal from the South Sumatra Basin ([Stevens & Hadiyanto, 2004](#)), adopted because H_2O_2 effectiveness depends strongly on coal rank.

Cost Model Formulation

The model computes the annual operating cost of an installation processing a coal mass m_{coal} (tonnes per year) in four steps: scaling the solution requirement, converting it into reagent quantities, costing each, and aggregating the two unit bases. The solid-to-liquid ratio from column experiments is:

$$RL/S = VL / mS \quad (1)$$

where VL is the volume of 0.3 percent H_2O_2 solution (L), and mS is the mass of coal (g). The experiment used 17 g of lignite with a cumulative effluent volume of 4 L ([Haq et al., 2018](#)), giving $RL/S = 0.23529$ L/g. Scaling to an arbitrary coal mass:

$$V_{solution} = RL/S \times m_{coal} \times 10^6 \quad (2)$$

For one tonne, $V_{solution} = 235,294.12$ L. The mass of commercial H_2O_2 of concentration w required is:

$$m_{H_2O_2} = (V_{solution} \times \rho_{solution} \times C) / w \quad (3)$$

with $\rho_{solution} \approx 1$ kg/L, $C = 0.003$, and $w = 0.50$, giving 1,686.73 kg per tonne at a density of 1.195 kg/L. The mass of the i -th nutrient medium reagent follows from its prescribed concentration:

$$m_i = C_i \times V_{solution} \quad (4)$$

Annually fixed cost comprises four components incurred once per year regardless of tonnage:

$$FC = Clabour + Celectricity + Cfuel + Cwater \quad (5)$$

Volume-proportional cost sums each reagent quantity multiplied by its unit price H_i , including the diluent water:

$$VC = \sum_i (m_i \times H_i) \quad (6)$$

Total annual operating cost is therefore:

$$TC = FC + VC \times m_{\text{coal}} \quad (7)$$

Equation (7) is the central formulation. It makes explicit why the two bases must be held separate: FC is independent of m_{coal} whereas VC scales linearly with it, so merging them would make fixed cost appear very large at small tonnage and negligible at large tonnage even though its magnitude never changes. Solution cost per unit of methane is:

$$c_{\text{CH}_4} = VC / Y \quad (8)$$

where Y is the specific methane yield of 5.92 m³ CH₄ per tonne (Haq et al., 2018).

Sensitivity Analysis and Assumptions

Sensitivity was assessed by the one-factor-at-a-time method. Each parameter p_j was varied by ± 50 percent while the others were held at the base value, and its effect was expressed as the resulting percentage change in VC:

$$S_j = [VC(1.5 p_j) - VC(0.5 p_j)] / (2 \times VC_{\text{base}}) \times 100 \% \quad (9)$$

Five parameters were tested: the solid-to-liquid ratio and the unit prices of distilled water, NaHCO₃, H₂O₂, and MgCl₂·6H₂O.

Five assumptions apply: the solid-to-liquid ratio scales proportionally with coal mass; the methane yield of 5.92 m³ per tonne is attainable at reservoir conditions although the source experiments were at atmospheric pressure; solution density is 1 kg/L; reagent prices are constant; and capital expenditure is excluded per Section I. As field well operating costs are also excluded, the results are a lower bound.

FINDINGS AND DISCUSSION

Applying Equations (1) to (7) to the data in Table 1 yields the results below: first the aggregate split between the two bases, then the disaggregation, then sensitivity.

Cost Structure by Unit Basis

The operating cost of an installation processing one tonne of coal in its first year amounts to IDR 11,126,119,382 and comprises two groups with different unit bases (Table 2).

Table 2. Operating cost structure of hydrogen peroxide-assisted CBM technology

Group	Unit basis	Value (IDR)	Share (%)
Installation fixed cost	per year	8,345,589,114	75.01
Solution and reagent cost	per tonne of coal	2,780,530,269	24.99
Total	per tonne-year	11,126,119,382	100.00

Figure 1 presents a breakdown of all constituent components.

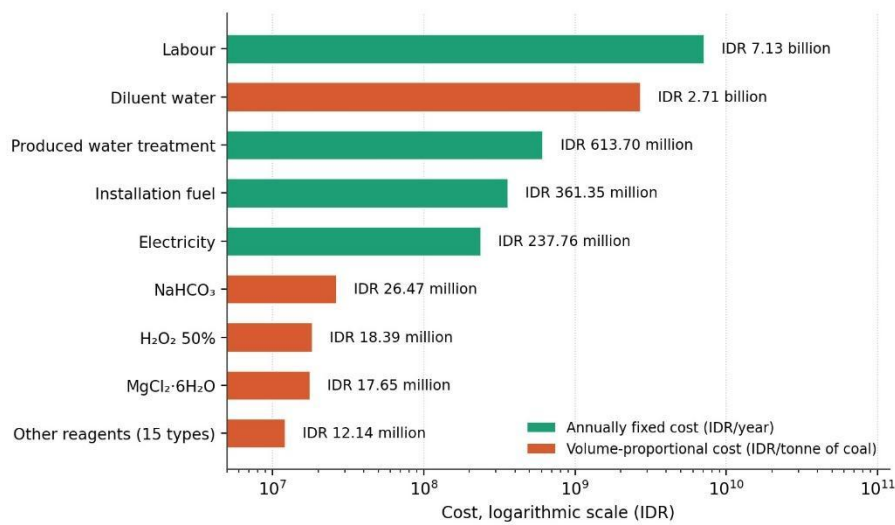


Figure 1. Cost component breakdown by unit basis

Source: authors' analysis

Breakdown of annually fixed cost

Table 3. Installation Fixed Cost Per Year

Component	IDR per year	Share (%)
Labour	7,132,782,000	85.47
Produced water treatment	613,698,955	7.35
Installation fuel	361,348,759	4.33
Electricity	237,759,400	2.85
Total	8,345,589,114	100.00

Labor contributes 85.47 percent of this group. The total group size does not change with the coal tonnage processed, as long as installation capacity is not exceeded.

Breakdown of Solution Cost Per Tonne of Coal

One tonne of coal requires 235,294.12 liters of solution, from Equations (1) and (2). Table 4 gives the breakdown.

Table 4. Cost of 0.3 percent H₂O₂ solution per tonne of coal

Component	Quantity	IDR per tonne	Share (%)
Diluent water	233,884 L	2,705,882,380	97.316
NaHCO ₃	588.24 kg	26,470,589	0.952
H₂O₂ 50%	1,686.73 kg	18,385,357	0.661
MgCl ₂ ·6H ₂ O	117.65 kg	17,647,059	0.635
Other reagents (15 types)	—	12,144,884	0.436
Total	235,294.12 L	2,780,530,269	100.00

solution

Diluent water contributes 97.32 percent of solution cost, whereas hydrogen peroxide, the core of the technology, contributes merely 0.661 percent, or 0.165 percent of total cost. At a specific methane yield of $5.92 \text{ m}^3 \text{ CH}_4$ per tonne of coal, applying Equation (8) gives a solution cost of IDR 469.68 million per cubic meter of methane generated.

Cost Behavior with Respect to Tonnage

Because the two bases respond differently to tonnage, their relative weight shifts as the installation scales. Because the two groups behave differently with respect to tonnage, the composition of total cost shifts as the coal processed increases. Figure 2 presents this behavior.

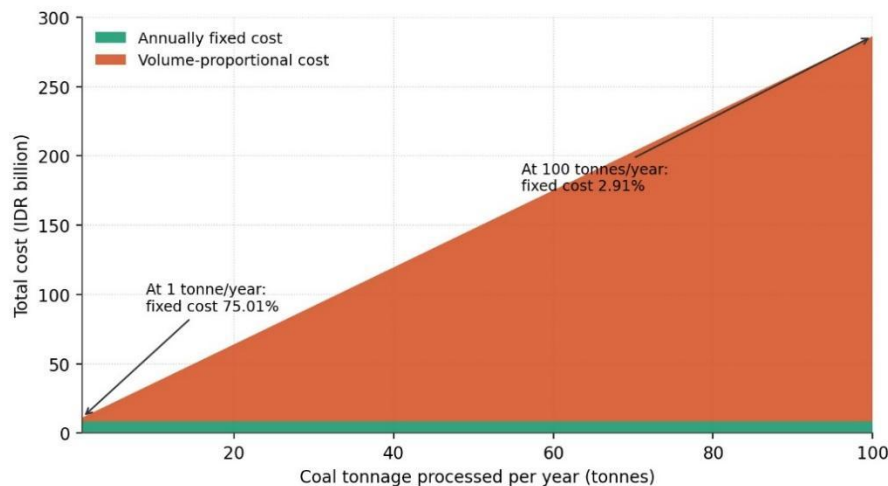


Figure 2. Behavior of Total Cost with Respect to Annual Coal Tonnage

Source: authors' analysis

At one tonne per year, fixed cost contributes 75.01 percent of the total; at ten tonnes, it falls to 23.09 percent; and at one hundred tonnes, it falls to 2.91 percent, while its absolute value remains unchanged. Solution cost remains fixed at IDR 2,780,530,269 per tonne, regardless of tonnage. The two become equal at 3.0 tonnes per year, the threshold below which capacity selection governs cost and above which reagent consumption does.

Sensitivity Analysis

The composition above rests on unit prices and one geometric parameter; testing each establishes which merit verification.

Table 5. Effect of ± 50 percent Parameter Variation on Solution Cost

Rank	Parameter	Effect
1	Solid-to-liquid ratio	$\pm 50.000\%$
2	Diluent water price	$\pm 48.658\%$
3	NaHCO_3 price	$\pm 0.476\%$
4	Price of 50 percent H_2O_2	$\pm 0.331\%$
5	$\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ price	$\pm 0.317\%$

The two leading parameters account for 99.3 percent of total variation. Hydrogen peroxide,

hitherto the focus of efficiency efforts, ranks fourth with an effect below one-third of one per cent.

Discussion

Taken together, these results run against the prevailing assumption in the MECBM literature.

The paradox of a technology named after hydrogen peroxide.

Efforts to reduce MECBM costs have targeted oxidant efficiency, whether through lower concentration or cheaper agents (Park & Liang, 2016; Xu et al., 2023). These results show that direction is almost inconsequential: even if hydrogen peroxide were free, total cost would fall by only 0.165 percent. What matters is a far simpler question: which water is used to dilute the solution, and how much.

The dominance of diluent water originates in the solid-to-liquid ratio.

The requirement of 233,884 liters of water per tonne follows directly from the ratio of 0.23529 L/g, which reflects full-immersion conditions with finely ground coal fully submerged. Under *in situ* injection, solution contacts only fracture surfaces, so the effective field ratio is almost certainly lower. That ratio therefore ranks first in the sensitivity analysis, ahead of any unit price, because every reagent quantity derives from it through Equations (2) and (4).

Implications and excluded costs.

Because fixed cost dilutes with tonnage whereas solution cost does not, design must separate two problems: selecting a capacity sufficient to spread fixed costs, and reducing the solution requirement per tonne. The estimate covers solution production only; it excludes field well operating costs, the dewatering generator at roughly 392 kWh per day per well (Munawar et al., 2013), drilling, fracturing, pipelines, and gas compression (Sarhosis et al., 2016), as well as depreciation. The figures are therefore a lower bound.

CONCLUSIONS

The operating cost estimate comprises two groups with different unit bases. Installation cost is annually fixed at IDR 8,345,589,114, with labor contributing 85.47 percent. Solution cost is volume-proportional at IDR 2,780,530,269 per tonne, equivalent to IDR 469.68 million per cubic meter of methane. For an installation processing one tonne in its first year, the total is IDR 11,126,119,382, of which fixed cost accounts for 75.01 percent.

The main finding is the composition of solution cost. Hydrogen peroxide, which gives the technology its name, contributes merely 0.661 percent, whereas diluent water contributes 97.32 percent. Sensitivity analysis confirms the pattern: the solid-to-liquid ratio and the diluent water price together determine 99.3 percent of cost variation. In contrast, the hydrogen peroxide price has an effect below one-third of one per cent.

Theoretically, this contradicts the assumption that oxidant efficiency governs MECBM economics and shows that geometry, rather than chemistry, is the governing parameter. Practically, it shifts optimization from oxidant chemistry to the diluent medium and injection ratio, and provides the first quantified cost basis against which field configurations can be judged.

LIMITATIONS & FURTHER RESEARCH

Three limitations bound these results: the solid-to-liquid ratio derives from full-immersion laboratory conditions; the methane yield is untested at reservoir pressure; and capital and field well operating costs are excluded. Further research should prioritize testing the ratio–yield relationship across a far lower ratio range, then assess whether well-produced water can serve as the diluent medium, and determine the capacity at which fixed costs are adequately diluted.

REFERENCES

- Aramaki, N., Tamamura, S., Ueno, A., Badrul, A. A., Murakami, T., Tamazawa, S., Yamaguchi, S., Aoyama, H., & Kaneko, K. (2017). Experimental investigation on the feasibility of industrial methane production in the subsurface environment via microbial activities in northern Hokkaido, Japan: A process involving subsurface cultivation and gasification. *Energy Conversion and Management*, 153, 566–575. <https://doi.org/10.1016/j.enconman.2017.10.017>
- Badan Geologi. (2025). National mineral and coal resource and reserve balance 2025. Ministry of Energy and Mineral Resources. <https://geologi.esdm.go.id>
- Barnhart, E. P., Davis, K. J., Varonka, M., Orem, W., Cunningham, A. B., Ramsay, B. D., & Fields, M. W. (2017). Enhanced coal-dependent methanogenesis coupled with algal biofuels: Potential water recycle and carbon capture. *International Journal of Coal Geology*, 171, 69–75. <https://doi.org/10.1016/j.coal.2017.01.001>
- Chen, R., Bao, Y., & Zhang, Y. (2023). A review of biogenic coalbed methane experimental studies in China. *Microorganisms*, 11(2), 304. <https://doi.org/10.3390/microorganisms11020304>
- Davis, K. J., & Gerlach, R. (2018). Transition of biogenic coal-to-methane conversion from the laboratory to the field: A review of important parameters and studies. *International Journal of Coal Geology*, 185, 33–43. <https://doi.org/10.1016/j.coal.2017.11.006>
- Dewan Energi Nasional. (2023). *Indonesia energy outlook 2023*. Secretariat General of the National Energy Council. <https://den.go.id>
- Gao, D., Guo, H., Guo, B., Tan, K., & Ren, H. (2022). Impact of microbially enhanced coalbed methane on the pore structure of coal. *Frontiers in Earth Science*, 10, 869917. <https://doi.org/10.3389/feart.2022.869917>
- Haq, S. R., Tamamura, S., Ueno, A., Tamazawa, S., Aramaki, N., Murakami, T., Alam, A. K. M. B., Igarashi, T., & Kaneko, K. (2018). Biogenic methane generation using solutions from column reactions of lignite with hydrogen peroxide. *International Journal of Coal Geology*, 197, 66–73. <https://doi.org/10.1016/j.coal.2018.08.007>
- Li, Y., Shuai, L., & Zhang, Q. (2026). Microbial metabolic pathways for synergistic biomethane augmentation and CO₂ sequestration in coalbed systems: A mini-review. *Microorganisms*, 14(3), 566. <https://doi.org/10.3390/microorganisms14030566>
- Munawar, A., Hendromurti, D., Dewi, P. R., Foglio, G., & Schupp, B. (2013). Dewatering facilities for CBM resource appraisal, lesson learn from Sanga-Sanga coalbed methane field, East Kalimantan (IPA13-E-120). In Proceedings of the Indonesian Petroleum Association 37th Annual Convention and Exhibition. Indonesian Petroleum Association.
- Niu, Y., Wang, Z., Xiong, Y., Wang, Y., Chai, L., & Guo, C. (2024). Exploring the potential of microbial coalbed methane for sustainable energy development. *Molecules*, 29(15), 3494. <https://doi.org/10.3390/molecules29153494>
- Park, S. Y., & Liang, Y. (2016). Biogenic methane production from coal: A review on recent research and development on microbially enhanced coalbed methane (MECBM). *Fuel*, 166, 258–267. <https://doi.org/10.1016/j.fuel.2015.10.121>
- Rice, C. A., & Nuccio, V. (2000). Water produced with coal-bed methane (Fact Sheet FS-156-00). U.S. Geological Survey. <https://doi.org/10.3133/fs15600>
- Sarhosis, V., Jaya, A. A., & Thomas, H. R. (2016). Economic modelling for coal bed methane production and electricity generation from deep virgin coal seams. *Energy*, 107, 580–594. <https://doi.org/10.1016/j.energy.2016.04.056>
- Stevens, S. H., & Hadiyanto, H. (2004). Indonesia: Coalbed methane indicators and basin evaluation (SPE-88630-MS). In SPE Asia Pacific Oil and Gas Conference and Exhibition. Society of Petroleum Engineers. <https://doi.org/10.2118/88630-MS>

- Wang, Y., Bao, Y., & Hu, Y. (2023). Recent progress in improving the yield of microbially enhanced coalbed methane production. *Energy Reports*, 9, 2810–2819. <https://doi.org/10.1016/j.egyr.2023.01.107>
- Xu, F., Hou, W., Xiong, X., Xu, B., Wu, P., Wang, H., Feng, K., Yun, J., Li, S., Zhang, L., Yan, X., Fang, H., Lu, Q., & Mao, D. (2023). The status and development strategy of coalbed methane industry in China. *Petroleum Exploration and Development*, 50(4), 765–783. [https://doi.org/10.1016/S1876-3804\(23\)60427-6](https://doi.org/10.1016/S1876-3804(23)60427-6)
- Yan, L., Gong, K., Guo, H., Zhang, Y., Huang, Z., & Urynowicz, M. (2023). Biogenic methane production from lignite in cube: Comparison of the inner and outer part of coal. *Fuel*, 346, 128370. <https://doi.org/10.1016/j.fuel.2023.128370>
- Zhang, N., Yin, X., Wang, Z., Liu, H., Huang, M., Wang, H., Liang, D., & Hu, J. (2024). Research progress on the mechanism and influencing factors of microorganisms to increase coal bed methane production. *Chinese Journal of Process Engineering*, 24(11), 1–11.