

Perspective

Coupled microbial-geochemical reactions in underground hydrogen storage systems: From hydrogen loss to a cyclically perturbed reactive system

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Keywords:

Underground hydrogen storage
hydrogen loss
microbial activity
geochemical reactions
cyclic operation

Cited as:

Lin, J., Li, H., Zhao, Z., Wang, Y., Ali, M. Coupled microbial-geochemical reactions in underground hydrogen storage systems: From hydrogen loss to a cyclically perturbed reactive system. *Advances in Geo-Energy Research*, 2026, 22(1): 91-94.
<https://doi.org/10.46690/ager.2026.10.08>

Abstract:

Underground hydrogen storage involves repeated cycles of hydrogen injection and withdrawal, which change how formation fluids, minerals and microorganisms interact. Microbial hydrogen consumption and abiotic geochemical reactions are often treated separately, but in a storage reservoir they are connected through substrate supply, solution chemistry and mineral interfaces. Although direct reactions between hydrogen and formation minerals are slow at reservoir temperatures, fluid-mineral interaction can alter the fluid chemistry, the availability of microbial substrates, and the stability of secondary minerals associated with microbial activity. Because chemical and biological changes carry over from one storage cycle to the next, reservoir reactivity can change cumulatively: hydrogen consumption may decline, persist or recover as substrates, pH and microbial communities change. Cycle frequency, shut-in duration, cushion gas composition and fluid chemistry give operators some control over this evolution, but the conditions that minimize hydrogen loss do not necessarily minimize gas contamination or formation damage. Assessing these effects requires distinguishing among hydrogen loss pathways, multi-cycle experiments, in situ characterization and long-term monitoring to identify cumulative changes and help define operating limits.

1. Introduction

Underground hydrogen storage (UHS) offers a means of balancing intermittent renewable generation against demand, including seasonal fluctuations. The performance of depleted hydrocarbon reservoirs and aquifers as storage sites depends on how hydrogen interacts with formation fluids, minerals and microorganisms. Unlike permanent CO₂ storage, UHS requires repeated recovery of the injected gas, and unlike natural gas storage, it must also account for hydrogen-specific reactivity (Hematpur et al., 2023). Yet quantitative under-

standing of coupled geochemical and microbial processes under cyclic operation remains limited. Injected hydrogen acts as an electron donor for hydrogenotrophic microorganisms, such as methanogens, acetogens, sulfate reducers and iron reducers, and can, in principle, drive abiotic reduction of sulfate-, carbonate- and Fe(III)-bearing phases (Thaysen et al., 2021; Aftab et al., 2026). Hydrogen-consuming reactions are commonly classified as abiotic or biotic, but we argue here that the two are connected through substrate supply, solution chemistry and mineral interfaces. Building on assessments

of hydrogen loss, purity and recovery, this perspective treats the reservoir as an evolving reaction network rather than a passive container, in which the state left by one storage cycle sets the initial conditions of the next. The central question is therefore not only how much hydrogen is lost, but how the coupled reaction pathways evolve across cycles and whether their evolution can be managed through operational strategies.

2. Coupled microbial-geochemical reactions

Whether microbial and abiotic hydrogen sinks can be evaluated independently depends on their relative reaction kinetics and the chemical species through which they interact. Several proposed abiotic H_2 -consuming redox pathways involving sulfate, carbonate and Fe-bearing phases can be thermodynamically favorable under modeled reservoir conditions but are kinetically limited at typical UHS temperatures of 30-90 °C (Alanazi et al., 2026). Arrhenius extrapolation of sulfate reduction rates by H_2 measured at 250-300 °C to storage temperatures gives an abiotic half-life for aqueous sulfate far longer than any operational timescale (Truche et al., 2009). Likewise, Truche et al. (2010) observed reduction of pyrite to pyrrhotite by H_2 between 90 and 180 °C, but at 90 °C, aqueous sulfide production was measurable only with ultrafine, high-surface-area pyrite.

Taken together, these rates imply that under UHS conditions where temperature, salinity and electron-acceptor availability permit microbial activity, microbial pathways are likely to account for most reactive hydrogen consumption, whereas direct abiotic consumption may become more important only where microbial activity is limited or reactive minerals are abundant and accessible. Yet a difference in rates does not make the pathways independent: on operational timescales, the coupling between microbial metabolism and secondary mineral reactions may matter more than direct H_2 -mineral reactions.

This coupling operates through three interacting mechanisms. (i) Substrate supply: fluid-mineral reactions control the supply of electron acceptors and inorganic carbon to hydrogenotrophic microorganisms. Dissolution of sulfate-bearing minerals provides sulfate for sulfate reduction; carbonate dissolution supplies dissolved inorganic carbon (DIC), which serves as both carbon source and electron acceptor for methanogens and acetogens; and Fe(III)-bearing phases support H_2 -dependent microbial iron reduction. (ii) Solution chemistry: microbial metabolism alters pH, alkalinity and redox conditions, thereby shifting mineral saturation states and promoting dissolution or precipitation. (iii) Mineral interfaces: mineral surfaces provide attachment sites and reactive surface areas, while biofilms can limit surface accessibility and mass transfer. These effects can oppose one another. For example, for methanogenesis and acetogenesis, DIC consumption favors carbonate dissolution, whereas the associated pH increase favors carbonate precipitation. The direction and magnitude of these feedbacks therefore depend on mineralogy, formation water chemistry and operating conditions.

3. Coupled reactions under multi-cycle injection and withdrawal

Coupled microbial-geochemical reactions affect recovery efficiency, gas quality, reservoir permeability, wettability and wellbore integrity in UHS (Tao et al., 2025; Vedadi et al., 2026). The coupled reactions also create trade-offs, as an increase in pH may slow microbial hydrogen consumption but favor carbonate precipitation, while iron-sulfide formation may remove H_2S from the gas phase but reduce permeability.

Under cyclic UHS operation, the microbial-mineral system is unlikely to return to its initial state after each injection-withdrawal cycle (Kabbaj et al., 2026). Repeated cycling changes reservoir pressure, hydrogen availability, gas-water contact and fluid mixing (Gao et al., 2023), while flow hysteresis modifies H_2 and brine contact with reactive mineral surfaces (Lysy et al., 2022). The resulting reactions alter substrate supply, solution chemistry and mineral interfaces, leaving conditions that affect the next cycle. A field trial already shows such carry-over in the microbial state: in the Lehen depleted gas reservoir (Austria), Hellerschmied et al. (2024) found that one cycle of 10% H_2 mixture storage doubled the DNA-based relative abundance of methanogens in reservoir brine, and that methanogens made up 61% of the active community (RNA-based) during withdrawal. These are relative abundances, not reaction rates.

The reservoir can therefore be conceptualized as an evolving reactive system, in which hydrogen consumption, reaction pathways and microbial-mineral feedback depend on operational history as well as on instantaneous conditions (Fig. 1). Such evolution need not be monotonic. Depletion of reactive substrates or electron acceptors, pH shifts beyond ranges favorable for microbial activity, and accumulation of inhibitory products such as H_2S may reduce hydrogen consumption. Decline is not inevitable: in the mesocosms of Hellerschmied et al. (2024), conversion rates did not decline over 14 successive H_2 supply cycles, indicating that repeated supply can sustain the active community. Renewed substrate supply by brine influx, or enrichment of hydrogenotrophic communities, may likewise restore previously limited pathways.

For prediction, the end of a cycle is better represented by a set of inherited state variables than by a single H_2 -loss percentage: aqueous sulfate and DIC inventories, pH and alkalinity, dissolved or precipitated sulfide, viable community activity, reactive mineral surface area, and gas-water saturation history. Describing a site this way also turns microbial and geochemical risk into measurable criteria rather than a general hazard, as recent site-selection frameworks have urged (Duah et al., 2026). Because these variables can move in different directions, whether microbial activity recovers or becomes self-limiting over successive cycles is a site-specific, testable hypothesis rather than a general rule.

The injection-withdrawal schedule that drives this evolution may also be used to manage how these reactions evolve across storage cycles. Cycle frequency and shut-in duration determine the residence time of hydrogen in contact with reactive substrates and microbial communities. Shorter storage periods may reduce consumption per cycle, but repeated injection

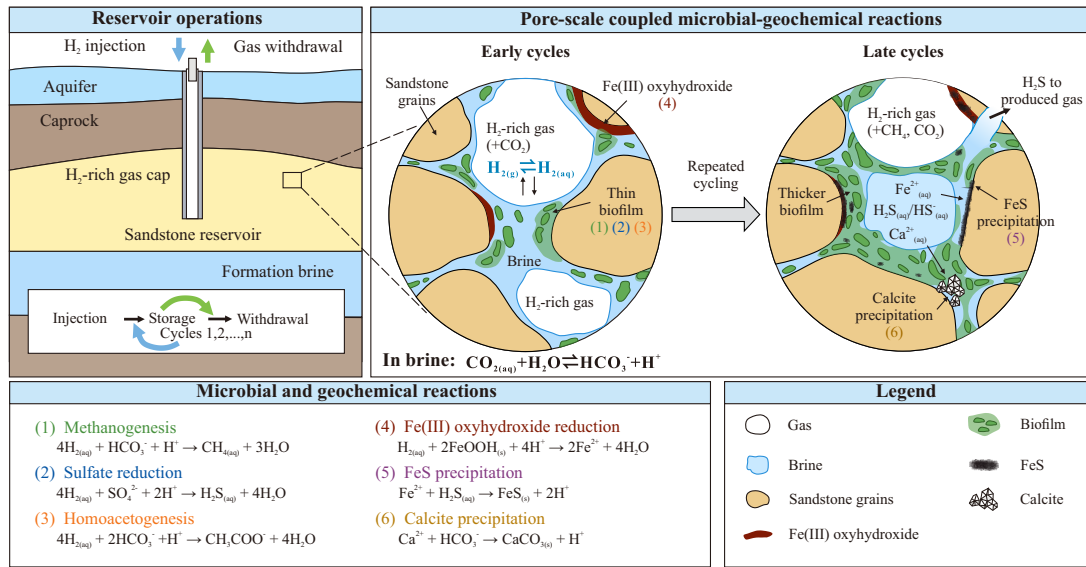


Fig. 1. Coupled microbial-geochemical reactions under cyclic H₂ injection and withdrawal in underground hydrogen storage.

tions may increase cumulative consumption when CO₂ is co-injected in each cycle (Hemme and van Berk, 2018). Reactive-transport simulations and the CO₂ consumption observed at Lehen indicate that CO₂ cushion gas enhances methanogenic H₂ conversion and reduces H₂ recovery (Hemme and van Berk, 2018; Hellerschmied et al., 2024). CH₄ or N₂ may therefore be preferable where methanogenesis is a concern, subject to their different trade-offs in mixing, displacement, deliverability and required withdrawal purity (Zhang et al., 2026). Fluid chemistry provides a further control, as salinity and pH constrain microbial activity and biocides can suppress H₂-consuming populations (Thaysen et al., 2021); raising pH or alkalinity to limit hydrogen consumption may, however, promote carbonate precipitation.

4. Key challenges

Research on UHS needs to extend beyond quantifying hydrogen loss to examining coupled microbial-geochemical reactions under cyclic operation. Four challenges are particularly important:

(1) **Hydrogen loss pathways and coupled feedbacks.** A decrease in gas-phase hydrogen does not necessarily indicate reactive consumption; in the Lehen trial, migration into the cushion gas accounted for an estimated 40% of the unrecovered H₂ (Hellerschmied et al., 2024). Mass and electron balances should account for dissolved and residual H₂, leakage and mixing with cushion gas before the remainder is assigned to reaction. Live and sterile controls (autoclaved or inhibitor-treated, with the treatment shown not to alter pH, redox state or mineral reactivity), combined with time-resolved measurements of CH₄, H₂S, acetate, sulfate, DIC and dissolved iron (Mura et al., 2024), distinguish biotic and abiotic pathways more reliably than gas composition alone. Likewise, a new mineral phase alone does not demonstrate direct abiotic H₂ consumption without paired fluid, mineral and microbial evidence.

(2) **Multi-cycle experiments and cumulative effects.** Whether the system exhibits hysteresis, recovery or irreversible accumulation across cycles must be tested directly. Representative experiments should combine formation brine, reservoir rock and indigenous communities at reservoir pressure and temperature, sample at the same point in every cycle, and vary residence time, pressure swing, brine renewal and CO₂ supply separately so that a rate change is not attributed to microbial adaptation by default.

(3) **In situ characterization and multiscale prediction.** In situ characterization is constrained by reservoir pressure, temperature, salinity, sampling disturbance and contamination risk. Kinetic parameters should be constrained with indigenous microbial communities, rock heterogeneity and gas-liquid mass transfer taken into account, and coupled reactive-transport models validated against independent cyclic datasets rather than extrapolated from batch results. Harmonized field-brine handling and multi-laboratory testing protocols would make microbial rate estimates more comparable.

(4) **Long-term risks and operating limits.** A stable cyclic response does not necessarily indicate a safe system state. Time-series field monitoring is required to identify cumulative risks and renewed reactivity, and to establish site-specific early-warning indicators and operating limits with quantified uncertainty. Candidate indicators include rising CH₄ or H₂S in produced gas, persistent sulfate or DIC depletion, pH and alkalinity drift, and loss of injectivity at comparable pressure and rate; each has more than one possible cause, so intervention thresholds require repeated-cycle baselines and confirmatory fluid or microbial measurements.

5. Conclusions and Implications

The main conclusions are as follows:

Microbial and abiotic reactions are mechanistically distinct but dynamically coupled. Because direct hydrogen-mineral reactions are slow at reservoir temperatures, the abiotic contribu-

tion is expressed mainly through secondary mineral reactions driven by microbially modified fluid chemistry, which feed back on microbial hydrogen consumption through substrate supply, solution chemistry and mineral interfaces. Therefore, the coupled reaction network rather than any of its individual components is the appropriate unit for evaluation.

Under repeated injection and withdrawal, the reservoir does not reset between cycles. The geochemical state, microbial community and mineral surfaces inherited from one cycle set the initial conditions of the next, so hydrogen consumption may decline, persist or recover over time, and evaluation should therefore extend beyond the hydrogen consumed in any single cycle.

Cycle frequency, shut-in duration, cushion gas composition and fluid chemistry act through the same coupled pathways and can therefore be used to manage reaction evolution. However, the conditions that minimize hydrogen loss do not necessarily minimize gas contamination or formation damage.

Acknowledgements

The authors acknowledge the financial support from National Natural Science Foundation of China (No. 42602177), the National Engineering Research Center of Offshore Oil and Gas Exploration (No. 202522409669) and the 2025 AAPG Foundation Grants-in-Aid Program (Wallace E. Pratt Memorial Grant).

Conflicts of interest

The authors declare no competing interest.

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