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Hematite Promotes Methanogenic Degradation of Petroleum Hydrocarbons by a Thermophilic Microbial Consortium: Evidence for Iron Dissolution, Intracellular Precipitation, and Electron

YUAN LIU[1], YUEYI HUANG[2], ZHUO ZHOU[3], LEI CHENG[2] AND HAILIANG DONG[1]

[1]China University of Geosciences, Beijing

[2]Key Laboratory of Development and Application of Rural Renewable Energy, Chengdu Biogas Institute, Ministry of Agriculture and Rural Affairs

[3]Key Laboratory of Development and Application of Rural Renewable Energy, Chengdu Biogas Institute, Ministry of Agriculture and Rural Affairs, China

The mechanisms by which iron minerals facilitate methanogenic degradation of petroleum hydrocarbons in high-temperature oil reservoirs remain poorly understood. Here, we investigated the role of nano-hematite (Fe_2O_3) in promoting methanogenic hydrocarbon degradation by a thermophilic (55°C) consortium SK, originally enriched from the Shengli oil field [1].

Hematite addition substantially enhanced methane production, yielding approximately twice the methane compared to mineral-free controls. A positive correlation between Fe(III) reduction and methanogenesis suggested direct coupling of these processes. GC-MS analysis of residual crude oil revealed that hematite promoted more extensive degradation of n-alkanes and alkylcyclohexanes, with significantly lower relative abundances of these compounds in the SK+Oil+Fe_2O_3 treatment compared to SK+Oil alone. In contrast, alkyltoluene abundances showed minimal differences across treatments, indicating compound-specific degradation patterns.

X-ray diffraction (XRD) detected no secondary crystalline minerals following incubation. However, transmission electron microscopy (TEM) revealed amorphous iron-containing nanoparticles associated with cell envelopes and accumulated intracellularly. Elemental analysis showed striking compartmentalization: intracellular iron content reached 1–10% in the hematite-amended treatment versus <0.5% in the unamended control. Electron Energy Loss Spectroscopy (EELS) revealed that the amorphous particles surrounding cells contained Fe, O, N, and Ca, whereas the intracellular iron-containing particles contained Fe, O, N, S, P, and Ca. Atomic force microscopy (AFM) detected weak current signals at iron particles along cell membrane edges, implying possible electron transfer capacity.

We propose that hematite promotes methanogenic hydrocarbon degradation through a multi-step mechanism: (1) reductive dissolution of crystalline Fe_2O_3, (2) cellular uptake of dissolved iron, (3) intracellular precipitation as amorphous iron-sulfur/iron-phosphorus nanoparticles, and (4) electron transfer mediated by these biogenic nanoparticles—possibly as electron conduits or storage shuttles—facilitating syntrophic partnerships between hydrocarbon degraders and methanogens. This "dissolution-precipitation-electron transfer" cascade expands our understanding of mineral-microbe interactions in deep subsurface environments.

[1] Cheng, L., He, Q., Ding, C., Dai, L. R., Li, Q., & Zhang, H. (2013). Novel bacterial groups dominate in a thermophilic methanogenic hexadecane-degrading consortium. FEMS microbiology ecology, 85(3), 568-577.