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Microbiology OUT-OF-THE-BOX

Something from nothing: Microbial fieldotrophy from ambient field fluctuations

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Microbiology has long held that energy enters the cell through one of two channels: phototrophic capture of photons or chemotrophic oxidation of substrates. Both channels assume tangible energy carriers, namely photons of defined wavelength or chemicals held at fixed redox potentials. The dichotomy holds neatly for surface ecosystems but cannot fully explain microbial communities that thrive in energy-limited subsurface and extreme environments. Recent work points to a third option: the ambient fluctuations of physical fields, such as mechanical strain, temperature drift, and magnetic flicker, can themselves drive microbial metabolism, sometimes alongside conventional substrates and sometimes in their absence. The per-electron energy density is modest, but such fluctuations are ubiquitous and persistent, and their cumulative biological consequence may be larger than appreciated. This emerging energy acquisition mode has been termed fieldotrophy.[1] We note that "nothing" in our title is rhetorical: ambient field fluctuations do carry thermodynamically usable free energy, though at densities far below those of conventional photons or redox substrates. What is absent is not energy per se, but a recognized carrier in the classical sense, that is, a photon of defined wavelength or a chemical substrate at a fixed redox potential.

This article offers three structural additions. First, we propose a single constitutive relation in which the charge output of any transducer scales with the variation of the driving field, capturing every fieldotrophic modality under one expression. Second, we argue that photosynthesis is itself a special case of this relation rather than a separate trophic category. Third, we translate the unified picture into an actionable design principle, field regulation, that broadens conventional electric regulation of microbial electrochemical systems along three axes. Across these additions runs a common motif: microbes draw biologically useful something from what physics treats as energetic nothing.

Experimental evidence now spans all elementary field types.[1] Piezoelectric struvite under mechanical agitation drives autotrophic nitrate reduction by *Thiobacillus denitrificans* with water as the electron donor, achieving nearly complete nitrate removal over five cycles;[2] other piezoelectric minerals such as $BaTiO_3$ similarly support denitrifying and electrotrophic microorganisms.[1] The flexoelectric effect removes the non-centrosymmetric crystal requirement of conventional piezoelectricity: centrosymmetric MnO_2 nanoflowers, bent under strain gradients, generate electrons that drive *Rhodopseudomonas palustris* growth in the dark.[3] Pyroelectric and magnetoelectric transduction likewise sustain denitrification;[1] natural water evaporation through *R. palustris* biofilms supports autotrophic growth for at least 50 days via hydrovoltaic currents;[4] and interfacial effects at water-solid boundaries produce comparable results.[1] Individual modalities have been termed piezoelectrotrophy, magnetoelectrotrophy, and so on; fieldotrophy unites them and their cross-couplings.

A CONSTITUTIVE PICTURE: FROM FIELD FLUCTUATION TO MICROBIAL CONVERSION

A single three-layer architecture emerges (Figure 1A). First, an environmental field fluctuates in time: mechanical strain with currents, tides, and tectonic stress; temperature by several degrees in soils, surface waters, and at hydrothermal margins; magnetic flux both geomagnetically and anthropogenically (Figures 1B–E). Each fluctuation can be written as a variation ΔF in the relevant field intensity F.

Second, a coupling material (transducer) converts that variation into mobile electrons. The yield scales approximately as $Q \approx \alpha \cdot \Delta F$, where α is set by the symmetry and microstructure of the material. This is a first-order linearization: piezoelectric, pyroelectric, flexoelectric, magnetoelectric, and photoelectric transduction each obey different constitutive laws but share the same qualitative dependence of charge on field variation in the small-signal regime. This linearization is expected to hold when the field perturbation remains small relative to the characteristic limits of the transducer material. Whether and how the charge output deviates at larger amplitudes has not yet been systematically explored for most fieldotrophic modalities and will require dedicated experimental attention. Piezoelectricity requires non-centrosymmetric crystals, pyroelectricity a polar axis, and magnetoelectric coupling either a magnetoelectric material or a closed loop; flexoelectricity, arising from strain gradients, occurs in essentially any dielectric.[3] A defining feature of fieldotrophy is that electrons are generated extracellularly by abiotic transducers and captured by microorganisms via extracellular electron transfer.[1] In conventional phototrophy, the transducer (chlorophyll) and the cell are the same; in fieldotrophy, they remain separate. This difference in integration does not alter the underlying physics: in both cases a field fluctuation drives charge separation, and the resulting electrons enter central metabolism. Photosynthesis, viewed through this lens, represents one of the most highly optimized examples within the fieldotrophy spectrum, with quantum efficiencies and charge-separation rates that far exceed those of known abiotic mineral transducers. To illustrate: flexoelectric biohybrids reach mechanical-to-metabolic conversion efficiencies on the order of 10^{-3},[3] whereas natural photosynthesis operates at roughly 1%,[4] a gap of about three orders of magnitude. Our unifying claim thus concerns shared physical logic, not equivalence in performance.

Third, electrons reach cells through extracellular electron transfer conduits, including conductive minerals, redox shuttles, and multi-heme cytochrome nanowires documented across both Bacteria and Archaea.[5] Cryo-electron microscopy has shown that bacterial and archaeal nanowires, despite sharing no protein fold similarity, converge on a conserved heme stacking geometry (RMSD < 1.1 Å), indicating strong evolutionary selection for this arrangement.[5] Electrons enter via outer-membrane c-type cytochromes and porin–cytochrome assemblies, then pass into the quinone pool for carbon fixation, denitrification, and biomass synthesis. The essentiality of outer-membrane uptake has been confirmed genetically: a *Shewanella oneidensis* Δ*omcA*–Δ*mtrC* double mutant showed a ~66% decrease in flexoelectricity-driven nitrate reduction.[3] Because any transducer delivers the same bioavailable electron, distinct fluctuations converge on common downstream biology: transcriptomic and inhibitor studies show overlapping upregulation of multi-heme cytochromes, hydrogenases, Calvin–Benson–Bassham (CBB) cycle genes, and denitrification operons, and blocking the quinone pool, cytochrome bc_1 complex, or proton motive force each severely impairs field-driven metabolism.[2-4] This convergence implies that electroactivity, once considered a peculiarity of *Geobacter* and *Shewanella*, is broadly accessible across bacteria and archaea;[1,5] ambient fluctuations render this latent capacity useful in low-energy habitats.

Laboratory demonstrations show modest but measurable biomass accumulation: a 50% protein increase over 6 days for flexoelectric biohybrids[3] and an 82% biomass gain over 50 days for hydrovoltaic biofilms.[4] Hydrovoltaic growth has also been replicated with *T. denitrificans* and *Moorella thermoacetica*,[4] suggesting broad applicability. In natural settings, fieldotrophy likely operates closer to maintenance metabolism, consistent with the low per-electron energy density.[1] Its advantage lies not in intensity but in ubiquity and persistence.

GEOBIOLOGICAL IMPLICATIONS

The reach of fieldotrophy extends well beyond laboratory biohybrids. Two implications follow at the biosphere scale (Figure 1A). The first concerns biogeochemical cycling. Field-electron pathways have been demonstrated for both the carbon and nitrogen cycles, and the underlying physics offers no reason to exempt the sulfur, phosphorus, oxygen, or metal cycles. Global budgets remain incomplete, but the persistence of field fluctuations into habitats that light and chemistry cannot easily reach suggests a nontrivial

PREPROOF

Figure 1. Microbial fieldotrophy from ambient field fluctuations and its geobiological implications (A) Schematic of the conceptual cascade. Ambient field fluctuations (including solar irradiation, mechanical strain, temperature variation, and magnetic flicker) are converted into mobile electrons via photoelectric, piezoelectric, flexoelectric, pyroelectric, and magnetoelectric effects, following $Q \approx a \cdot \Delta F$. Electroactive microorganisms capture these electrons through outer-membrane cytochromes, conductive nanofilaments, or porin–cytochrome complexes. Electrons are channeled through the quinone pool to generate NAD(P)H and ATP, powering carbon fixation, denitrification, and biomass synthesis. At the biosphere scale, this cascade supports C and N cycling, with plausible extension to S, P, O, and metal cycles, and provides a thermodynamic link between abiotic geophysical processes and the origin of life. (B) Light irradiation at lake and ocean surfaces. (C) Mechanical perturbations from river flow, ocean waves, currents, and crustal movements. (D) Temperature variations across hydrothermal systems and volcanic margins. (E) Magnetic fluctuations from geomagnetic and anthropogenic sources.

contribution to long-term element cycling.

The second implication, deliberately more tentative, concerns the origin and energetic maintenance of early life. The pre-Great-Oxidation-Event Earth was poor in O_2 and complex organic substrates but rich in mechanical, tidal, hydrothermal, and magnetic fluctuations interfaced with quartz, sphalerite, sulfide, and clay minerals. Quartz, the most abundant piezoelectric mineral in the crust, would have been subjected continuously to tidal and tectonic stress; pyroelectric minerals such as tourmaline near hydrothermal gradients could have generated electrons on mineral surfaces well before photosynthetic reaction centers evolved. Cytochrome nanowire homologs already found in deep-sea hydrothermal archaea[5] are consistent with long-range electron transfer being an ancient metabolic capability. These abiotic fluctuations constitute a thermodynamically modest yet continuously available electron supply, providing a plausible energetic supplement to the chemiosmotic and photochemical scenarios proposed for the origin of life. Testing these claims will require convergent evidence: *in situ* electrochemical profiling of field-generated electron fluxes in subsurface sediments; isotopic tracers (^{13}C-bicarbonate, ^{15}N-nitrate) following protocols validated in laboratory biohybrid systems[3,4] to quantify field-driven assimilation in controlled mineral–microbe assemblages; and metagenomic surveys of communities on piezoelectric and pyroelectric minerals where conventional energy sources are absent.

FROM UNDERSTANDING TO DESIGN: FIELD REGULATION

Recognizing fieldotrophy as a unified pathway has direct design implications. The natural design vector is field regulation, which generalizes electric regulation of microbial electrochemical systems along three axes: the energy source broadens from electricity alone to mechanical, thermal, magnetic, light, hydrovoltaic, and triboelectric fields in parallel; the regulating modality shifts from a single applied electric field to coordinated multi-field control; and the active site expands from a planar electrode to a three-dimensional transducer–microbe community pervading the entire reaction volume. Piezo-, pyro-, and flexo-responsive materials, nanobiointerfaces that buffer fast physical kinetics against slower biology, and microbial chassis with promiscuous electron uptake have each been demonstrated;[1–3] their integration is the next step. Concrete returns are already visible: a piezoelectric biohybrid driven by mechanical agitation delivered a 117% increase in nitrate removal from real wastewater,[2] and analogous gains appear plausible for carbon sequestration, pollutant degradation, and field-regulated biomanufacturing. The goal in each case is the same: to harvest biologically useful something from what otherwise dissipates as energetic nothing.

As stated in the *Daodejing*: "the myriad creatures of the world arise from Being, and Being from Non-being". Wherever conventional energy carriers are absent or scarce, microbial life appears to have learned to draw what it needs from the ambient fluctuations that physics dismisses as noise, making something from nothing.

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AUTHOR CONTRIBUTIONS

Shungui Zhou conceived the idea. Shungui Zhou and Jiangtao Gao prepared the manuscript. Guoping Ren drew a picture. Jie Ye revised the manuscript. All the authors have approved the final version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Correction Proof