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Anaerobic microbiomes: Hidden infrastructure for resilient and carbon-neutral water systems

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Contemporary water management prioritizes macroscale engineering metrics and bulk water quality indicators, often overlooking the microbial processes that sustain water system functioning. Here, we propose a conceptual shift: anaerobic microbiomes should be recognized as 'hidden ecological infrastructure'. Across natural aquatic habitats and engineered wastewater systems, these dynamic, cross-kingdom consortia regulate key biogeochemical fluxes and contribute to functional resilience. Despite their shared metabolic foundations, natural and engineered microbiomes remain largely separate subjects of research and management. Bridging this divide chasm requires a unified framework centered on conserved anaerobic pathways. Such a framework would extend beyond assessments of individual functions to incorporate complex syntrophic networks into water research and management. A deeper understanding of this hidden infrastructure could inform strategies to manage greenhouse gas fluxes, advance carbon-neutral water treatment and strengthen ecological resilience under interacting global stressors.

INTRODUCTION

Aquatic ecosystems are major sites of biogeochemical activity, where microbial processes regulate organic-carbon turnover, nitrogen transformations, and the speciation and mobility of metals and metalloids. However, their functioning is changing rapidly under interacting anthropogenic pressures, including climate change, eutrophication, habitat degradation, and intensive resource exploitation.[1,2] Anaerobic microbiomes mediate key redox-driven processes within these ecosystems. Through the coordinated activities of hydrolytic, sulfate-reducing, denitrifying and iron-reducing bacteria, together with acetogens and methanogenic archaea, these consortia decompose and transform complex organic matter, producing volatile organic intermediates, inorganic nutrients and reduced end-products, including methane.[3]

Natural aquatic ecosystems and engineered wastewater systems share many core anaerobic metabolic processes: those occurring in anoxic sediments often have functional counterparts in wastewater treatment systems. In both settings, interconnected microbial networks mediate organic-matter degradation, nitrogen transformations and methanogenesis, supporting biogeochemical functioning in natural habitats and low-carbon wastewater treatment. The resilience of these systems therefore depends, in part, on the capacity of anaerobic microbial consortia to maintain or recover function in response to fluctuating oxygen availability, episodic nutrient inputs, temperature shifts and pollutant stress.[4,5]

Despite their central role in global biogeochemical processes, anaerobic microbial consortia are often treated as background components of aquatic systems. In this Perspective, we propose conceptualizing these consortia as 'hidden ecological infrastructure' (Figure 1). These metabolically active networks regulate carbon turnover, nutrient transformations and contaminant fate under changing redox conditions. This framing emphasizes the persistence, organization and interdependence of microbial networks that sustain system-level biogeochemical functions and support recovery from disturbance. By linking functional redundancy and network interactions to ecological resilience across natural and engineered aquatic systems, the framework provides a mechanistic basis for using insights from natural ecosystems to inform carbon-neutral wastewater management strategies.

ANAEROBIC MICROBIOMES AS HIDDEN ECOLOGICAL INFRASTRUCTURE FOR AQUATIC RESILIENCE

In oxygen-depleted environments, anaerobic microbial processes mediate key biogeochemical transformations and influence the speciation, mobility and bioavailability of metals and metalloids. Depending on redox conditions and mineral associations, these processes can immobilize such contaminants through precipitation or promote their mobilization through reductive mineral dissolution. For example, in anoxic wetland sediments, sulfate-reducing bacteria produce sulfide that reacts with dissolved metal ions to form sparingly soluble metal sulfides, thereby reducing metal mobility.[1,3] Conversely, under strongly reducing conditions, iron-reducing bacteria can promote the reductive dissolution of arsenic-bearing iron minerals, releasing arsenic into porewater and increasing its mobility and potential bioavailability.[6]

Across natural and engineered aquatic systems, anaerobic microbial consortia regulate carbon fluxes, nutrient cycling and greenhouse-gas dynamics, collectively functioning as a form of 'hidden ecological infrastructure'. Syntrophic interactions and coordinated metabolite exchange sustain this infrastructure.[5] However, a high degree of metabolic interdependence can also increase community sensitivity to environmental perturbations.[7] Transient oxygen exposure, fluctuations in organic-matter loading and shifts in nutrient supply can trigger rapid functional responses in anoxic sediment microbiomes. The resulting responses may include altered methanogenesis, disrupted coupling among nitrogen-transformation processes and reduced rates of anaerobic carbon oxidation. Under defined environmental conditions, such community-level metabolic shifts may provide early-warning signals of emerging instability associated with hypoxia or harmful algal blooms.[2] Monitoring temporal changes in the composition, interactions and metabolic activity of anaerobic microbiomes could therefore provide sensitive indicators of emerging ecosystem instability.

Although the metabolic capabilities of many individual microbial taxa have been extensively characterized. By contrast, the syntrophic interactions and network structures that sustain ecosystem-scale biogeochemical processes remain poorly resolved. This knowledge gap limits our ability to explain and predict the functional resilience of anaerobic microbiomes. Natural aquatic habitats and engineered wastewater systems are increasingly face interacting environmental stressors, with nutrient supply, organic-matter loading, redox conditions and temperature varying concurrently across space and time. How complex metabolic interdependencies enable anaerobic microbiomes to maintain function under these combined perturbations remains unclear.

ANAEROBIC MICROBIOMES AS HIDDEN ECOLOGICAL INFRASTRUCTURE FOR CARBON-NEUTRAL WATER SYSTEMS

Anaerobic microbiomes play a central role in determining the fate of

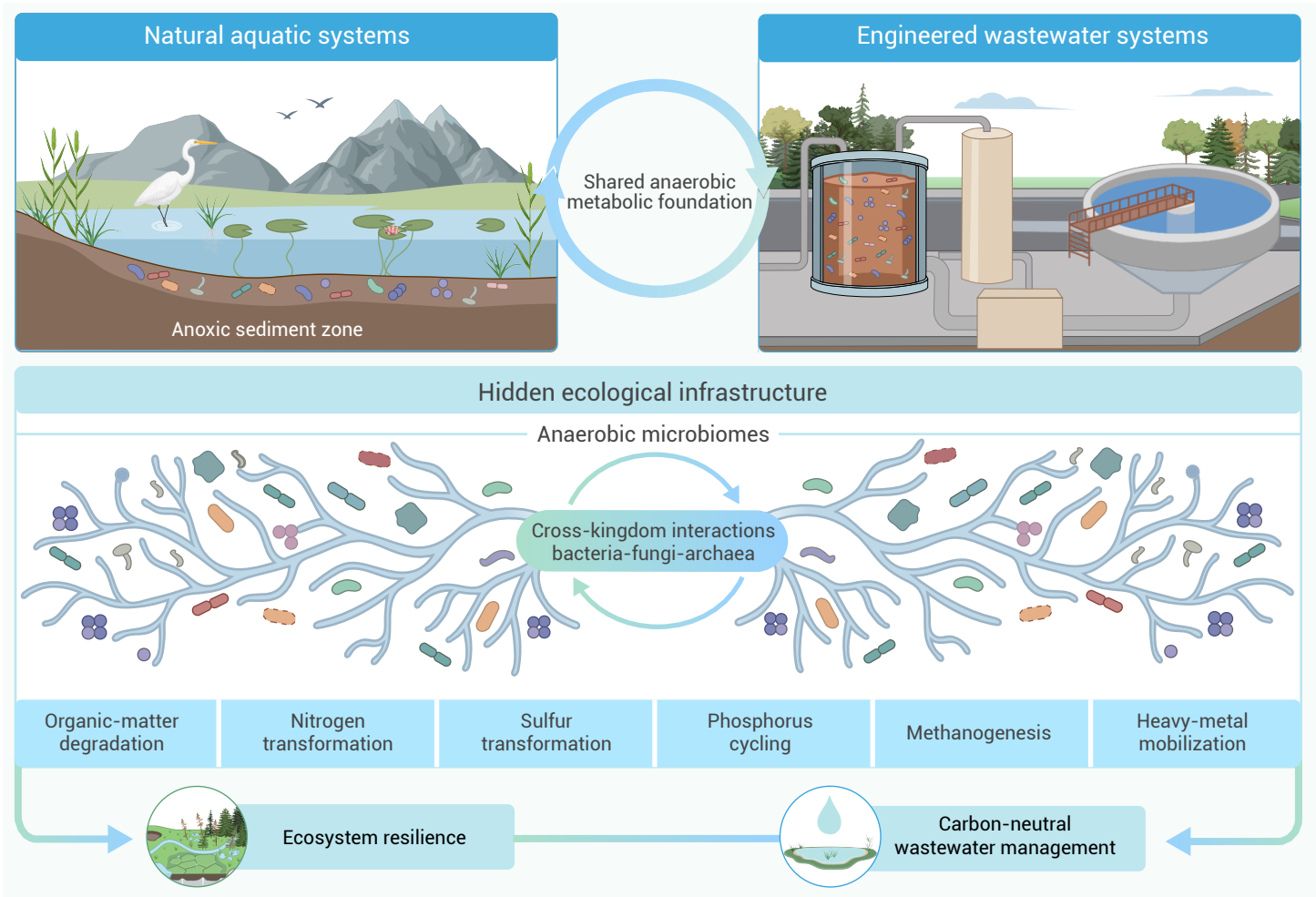


Figure 1. Hidden ecological infrastructure linking natural and engineered aquatic systems Anaerobic microbiomes constitute a form of 'hidden ecological infrastructure' across natural and engineered aquatic systems. Through complex syntrophic interactions, these microbial consortia mediate organic-matter degradation, nitrogen transformations, methane cycling and contaminant transformation in anoxic sediments, wetlands, reservoirs and anaerobic wastewater-treatment reactors. These shared metabolic processes provide a functional bridge between natural aquatic ecosystems and engineered wastewater-treatment systems, with implications for ecosystem resilience and carbon-neutral wastewater management.

organic carbon in anoxic sediments and water bodies. Through coupled metabolic processes, these consortia influence carbon partitioning among particulate and sedimentary reservoirs, dissolved carbon pools and biogenic methane. Methanogenesis is a terminal pathway in the anaerobic organic matter degradation. In some anoxic environments, it may become increasingly important as alternative electron acceptors, such as nitrate, ferric iron and sulfate, are depleted. However, the relative importance and sequence of these processes depend on substrate availability and local environmental or reactor operating conditions. Under electron-acceptor-limited conditions, carbon flow can shift towards fermentative and methanogenic pathways, with methanogenic archaea converting major fermentation products, particularly acetate and H_2/CO_2, into methane. Unless oxidized or captured, this methane can escape to the atmosphere and contribute to climate warming.[8]

Anaerobic carbon cycling encompasses both methane production and methane consumption. Methanotrophic consortia can act as biological filters oxidizing methane in anoxic habitats and engineered reactors, and thereby reducing the fraction released to the atmosphere. In engineered wastewater systems, anaerobic methane oxidation (AOM) and anammox processes can be integrated at the reactor level to enable the concurrent removal of methane and reactive nitrogen.[9] Anaerobic methanotrophs oxidize methane, whereas anammox bacteria convert ammonium and nitrite into dinitrogen gas. Anaerobic microbiomes should therefore not be viewed solely as sources of methane. Rather, their combined methane-producing and methane-consuming activities help determine net methane fluxes across natural and engineered aquatic systems.

INTEGRATING AQUATIC RESILIENCE AND CARBON NEUTRALITY THROUGH A UNIFIED ANAEROBIC MICROBIOME FRAMEWORK

Current research and management paradigms often treat natural aquatic habitats and wastewater-treatment systems as separate domains. Yet both are underpinned by many shared anaerobic metabolic interactions. A unified microbiome framework would enable comparisons of how anaerobic microbial networks regulate carbon turnover, methane cycling and nutrient transformations, and how they respond to environmental stress across anoxic sediments, wetlands, reservoirs and anaerobic reactors. Wastewater treatment systems have traditionally been optimized for high treatment rates and operational efficiency. Their long-term functional resilience—the capacity to maintain or recover function in response to disturbance—also depends on the stability of the microbial interactions that sustain treatment processes. Applying principles of functional redundancy derived from natural ecosystems could therefore strengthen reactor resilience to concurrent perturbations, including shifts in redox conditions, episodic nutrient inputs, temperature fluctuations and chemical stress. Conversely, wastewater treatment reactors offer experimentally tractable platforms for resolving microbial interactions, metabolic thresholds and disturbance responses, thereby providing testable insights into the functioning of natural aquatic ecosystem functioning.

Although effluent discharge and water reclamation connect natural aquatic ecosystems with engineered wastewater systems through flows of water and materials, microbiome research in these settings remains largely compartmentalized. Within a unified framework, a key priority is to identify the metabolic thresholds governing whether fermentation intermediates are converted to methane or retained in recoverable products. Microbial chain

elongation, for example, competes with methanogenesis for fermentation intermediates, redirecting carbon towards medium-chain fatty acids.[10] Identifying shared functional biomarkers across these connected environments could improve monitoring of greenhouse gas emission risks and support integrated assessments of ecological condition and treatment performance.

Future strategies should focus on community-level interactions alongside the functions of individual taxa. Translating the concept of anaerobic microbiomes as 'hidden ecological infrastructure' into practice will require approaches that sustain syntrophic networks. Ecological principles, including functional redundancy, can guide efforts to maintain community function under dynamic environmental conditions. Such approaches must account for steep redox gradients and complex interactions across microbial domains. Engineering interventions could regulate electron-acceptor availability and substrate supply to sustain the metabolic interdependencies that support system function. Strengthening this microbial infrastructure could promote both aquatic ecosystem resilience and progress towards carbon-neutral wastewater management. Maintaining reliable function under changing environmental and operational conditions could also reduce the risk of secondary impacts, including eutrophication and unintended gas emissions.

CONCLUSION

Across natural aquatic habitats and engineered wastewater systems, anaerobic microbiomes form the 'hidden ecological infrastructure' that regulates carbon turnover, nutrient transformations and greenhouse-gas fluxes through interconnected metabolic networks. A unified microbiome framework would connect these traditionally separate domains through their shared anaerobic metabolic processes. A central challenge is to understand and sustain the functional resilience of these networks under multiple, interacting environmental perturbations. Future interventions should apply ecological engineering principles to support syntrophic networks while limiting unintended methane emissions. Characterizing anaerobic microbiomes as dynamic quantifiable networks could guide aquatic ecosystem protection and advance carbon-neutral wastewater management.

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AUTHOR CONTRIBUTIONS

Jianfeng Liu: Investigation, Writing-review and editing; Ayesha Gulzar: Investigation, Writing-Original Draft; Xiao Liu: Writing-review and editing; Min Zhan: Writing-review and editing; Bin Liu: Conceptualization, Investigation, Writing-review and editing, Funding acquisition. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.