Modular Biofilters with Iron-Mediated Nitrogen Removal for Onsite Wastewater Treatment

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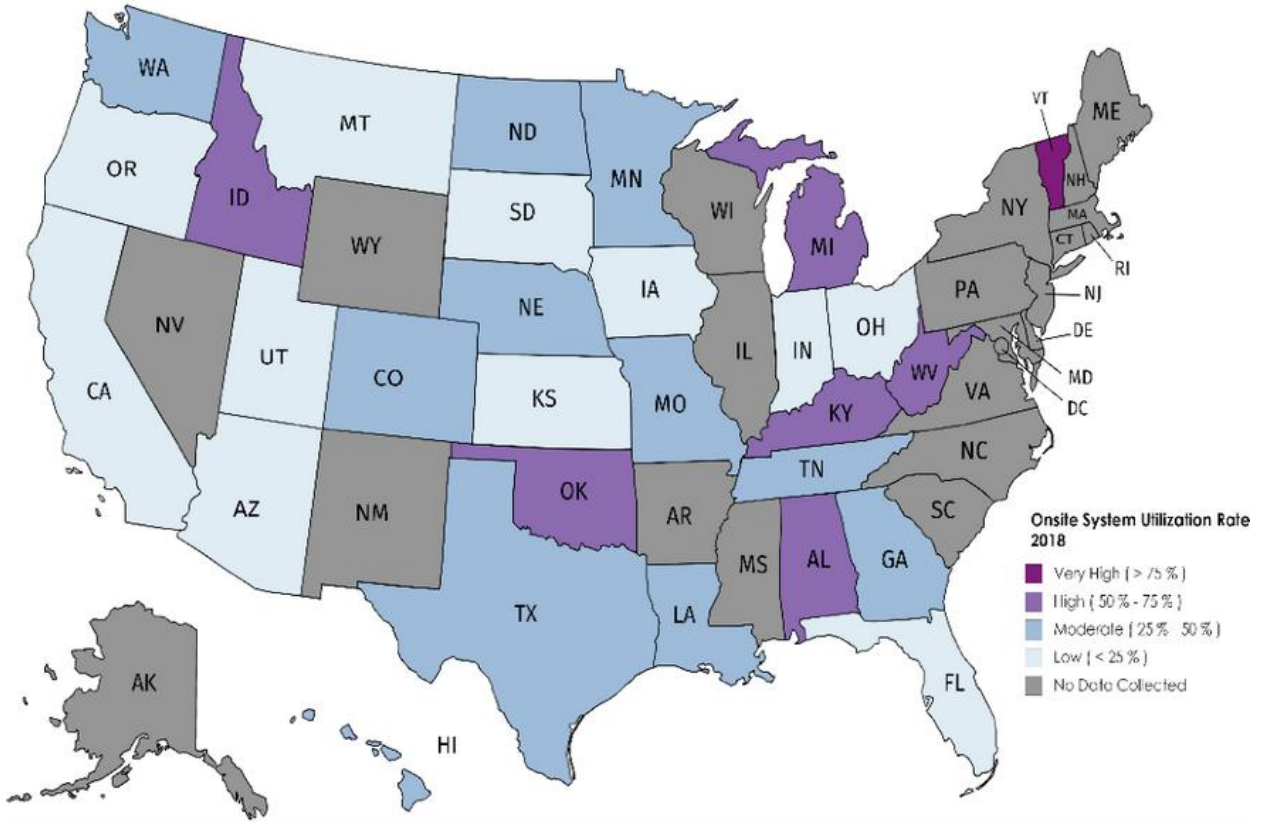
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Onsite Wastewater Treatment Systems (OWTS)

- Over **25%** of US population relies on OWTS
- Limited data available to locate, evaluate, maintain, and improve OWTS



Cesspools in Hawai‘i

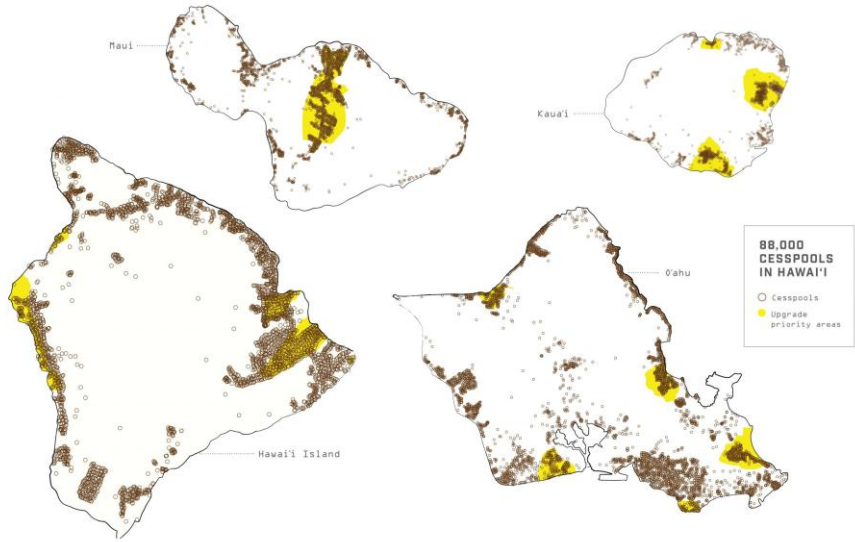
83,000 cesspools releasing 53 million gallons/day of untreated sewage into coastal and groundwater systems

State Act 125 (2017) mandates conversion, upgrade, or sever connection of all cesspools by **2050**

Senate Bill 1232 (2025) establishes a 3-year pilot program within UH WRRC to test and evaluate new technologies

Estimated financial burden over **$2 billion**

Opportunity for innovation of adaptive and cost-effective onsite biotechnologies



UH Sea Grant / WAI



Punaluu, Hawai‘i DLNR

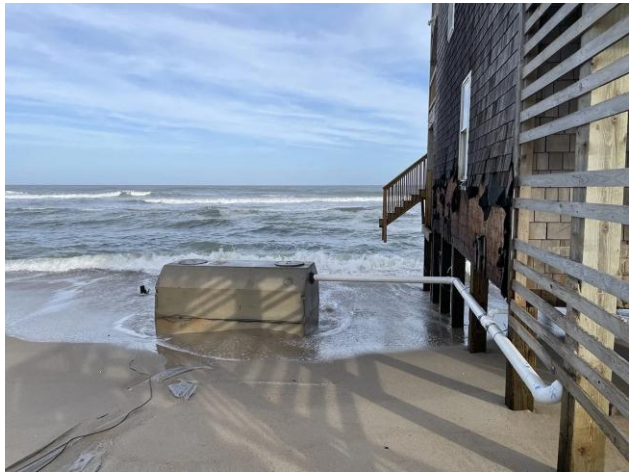
Climate Vulnerability of Coastal OWTS

- Sea-level rise, flooding, and sea water intrusion
- More frequent extreme weathers (hurricanes, droughts etc.)
- High costs and limited maintenance capacity
- Widespread reliance on septic

Only 31% of Pacific Islander have adequate sanitation

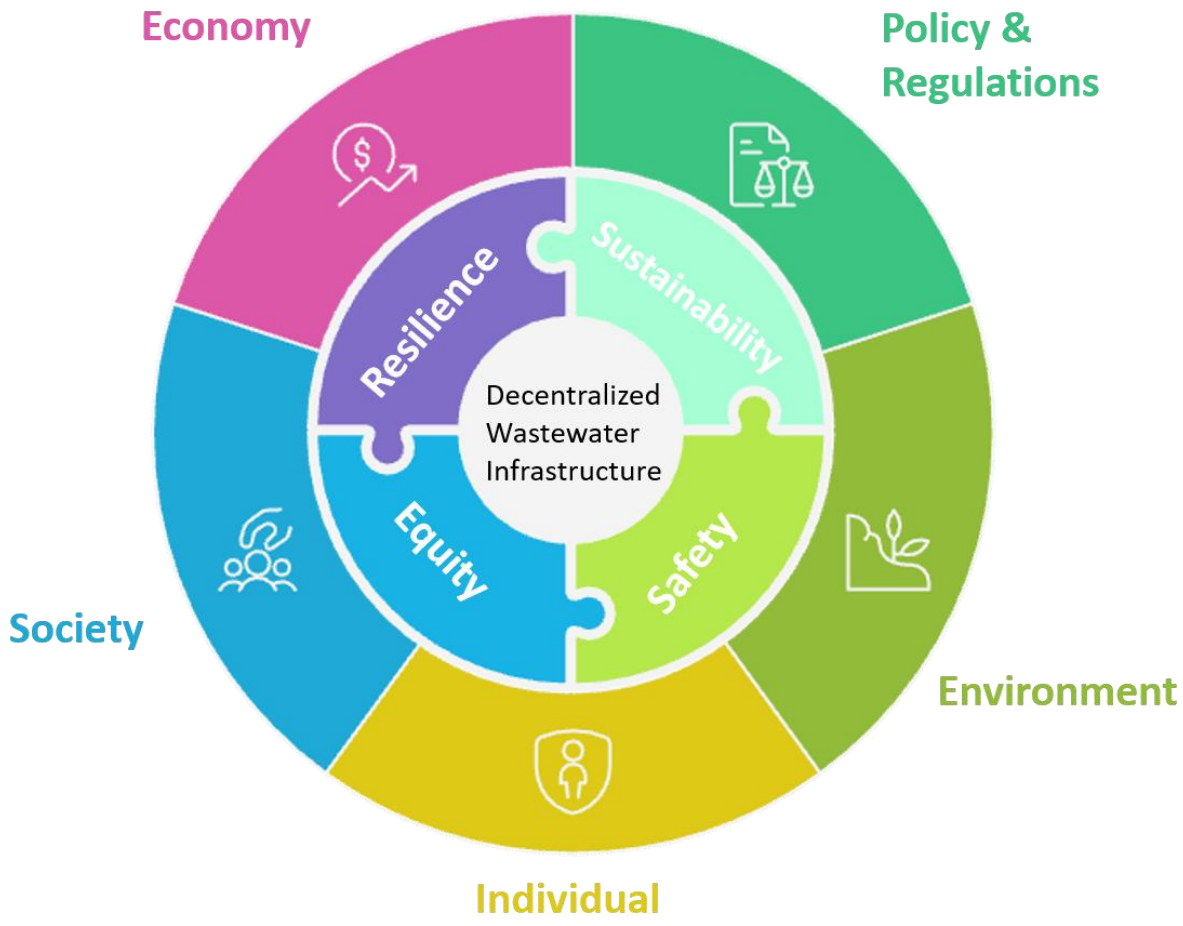


Waialua, HI, March 2026



Rodanthe, NC. National Park Service

Resilient, Equitable, Safe, and Sustainable (RESSI-H2O) OWTS



NSF Convergence Accelerator

VISIONS & VOICES

The Pressing Need for Resilient, Equitable, Safe, and Sustainable Decentralized Wastewater Solutions for the Pacific Islands

June 3, 2024 · Cesspool, Economy, Environment, Stories, Wastewater, Water

Nora Nelson, Robert Bair, Stuart Coleman, Christina Comfort, Stephen Gasteyer, Joyce Huang, Chris McKay, Allan Smith, Zhiyue Wang, Tao Yan, Paul Young, and Daniel Yeh.

Islands are unique environments with a number of resource constraints. Island water resources are vulnerable to myriad threats, including freshwater depletion due to groundwater pumping and aquifer contamination primarily as a result of saltwater intrusion (UNESCO-IHP and UNEP 2016; Spellman et al. 2021). The World Health Organization (WHO) estimates that only 31% of the population in the Pacific Islands has access to adequate sanitation (WHO 2015). The UNICEF/WHO Joint Monitoring Program on Water and Sanitation identifies numerous threats and climate risks to equitable,

Pacific Islands Report, 2024

RESSI-H2O Design of OWTS

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Conventional Infrastructure

✗ Insufficient treatment

✗ Percolation through soil

✗ High replacement cost

✗ Vulnerable to climate change

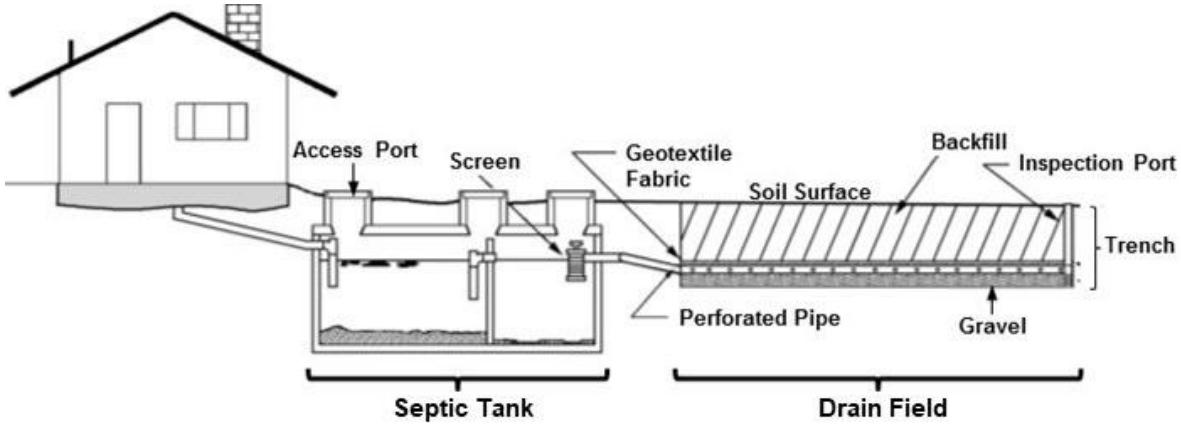
Next-generation Design

✓ Low cost, low maintenance

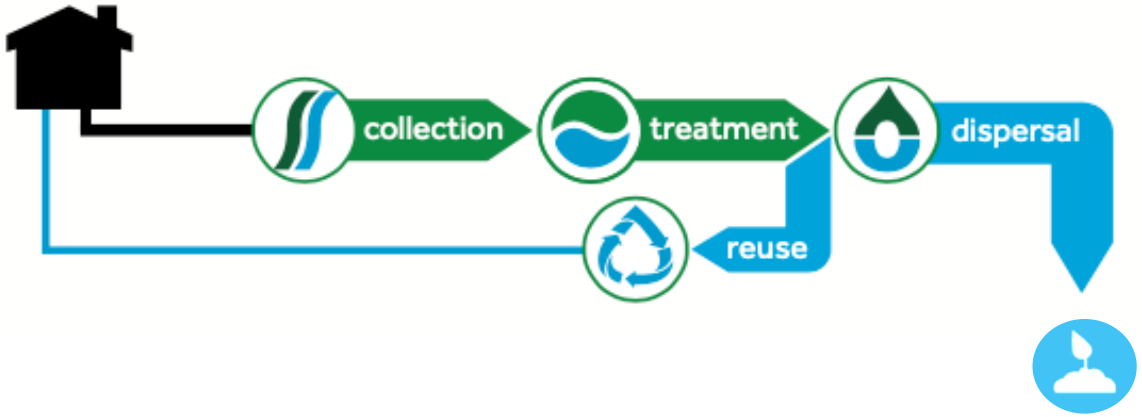
✓ Nutrient removal

✓ Above-ground structure

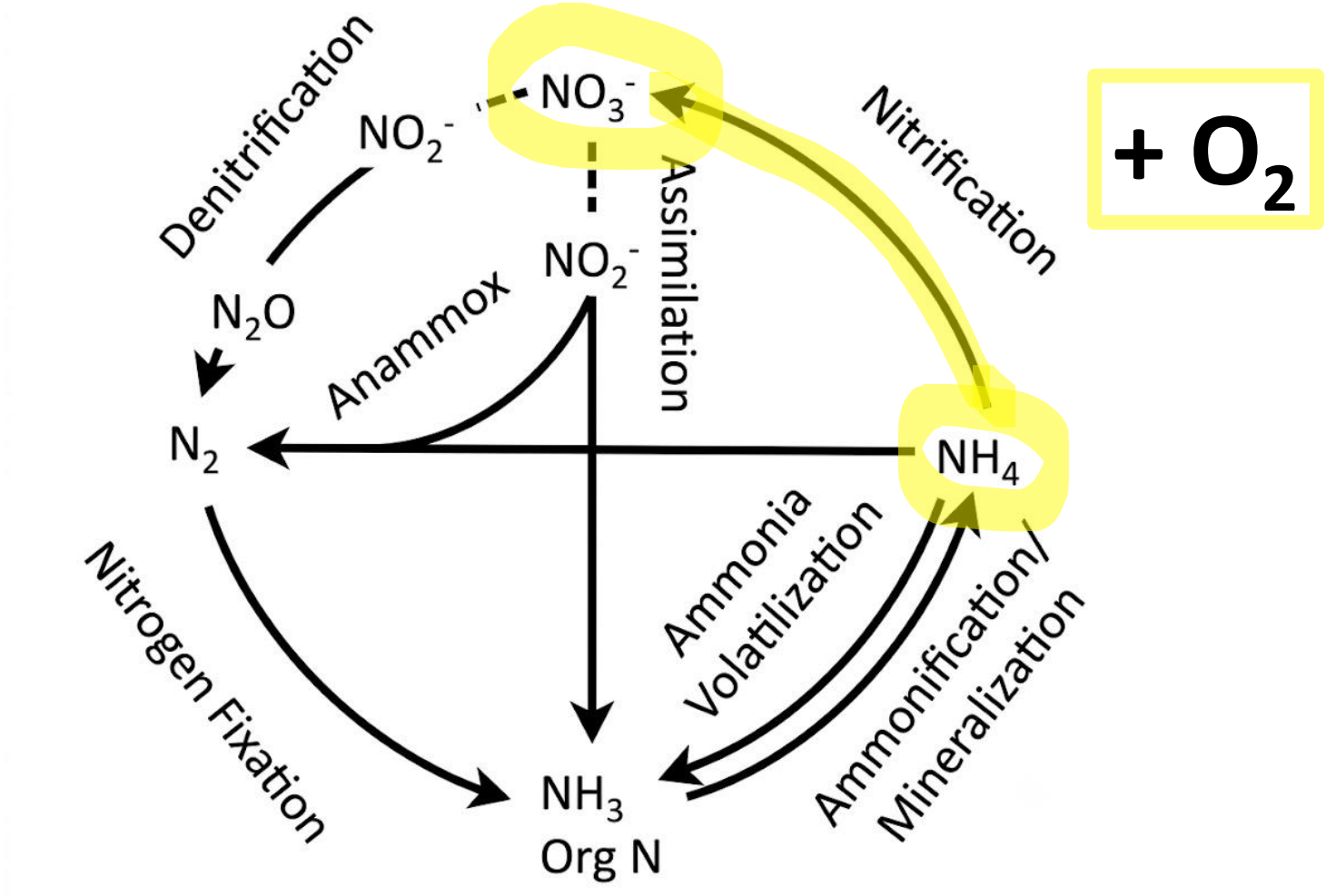
✓ Water reuse & resource recovery



Sergio M. Abit Jr., adapted from CIDWT

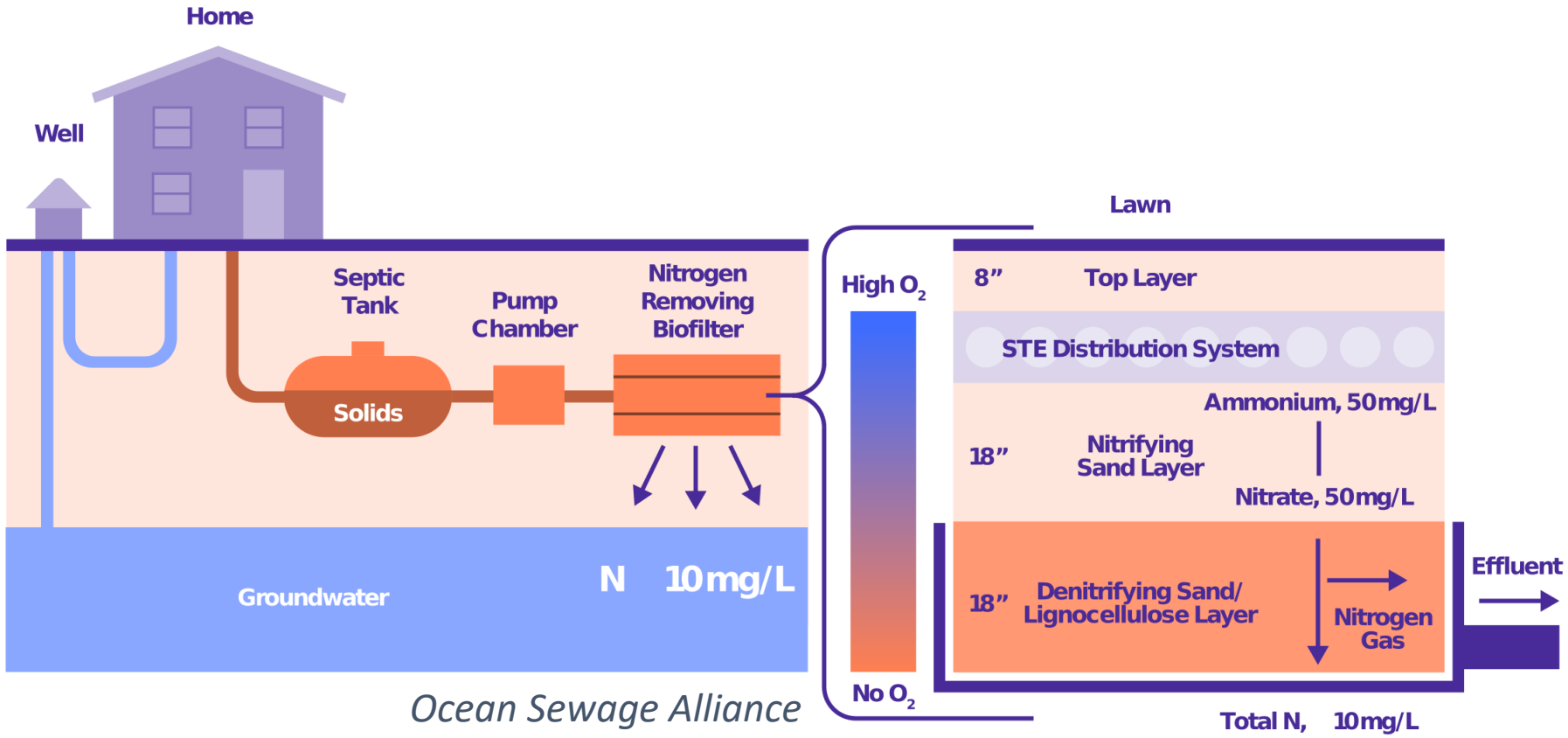


Microbial Nitrogen Removal Pathways



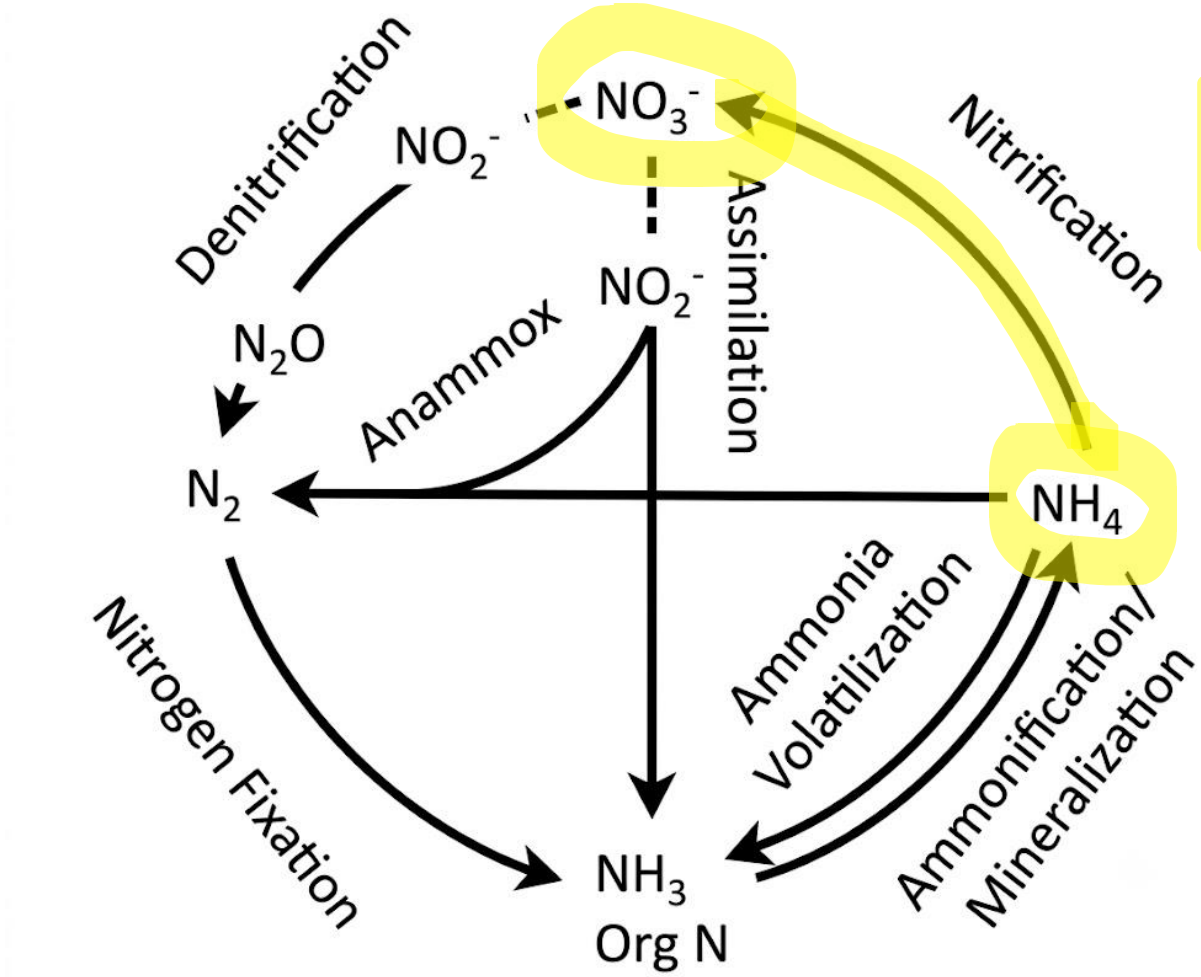
+ O_2

Conventional N-Removal Biofilters



- Only **32%** of total U.S. land area has soils suitable for absorption systems (U.S. EPA, 1999)
- Only **10 – 40%** of TN can be removed (Chen et al., 2022)

Microbial Nitrogen Removal Pathways



+ O_2

Fe

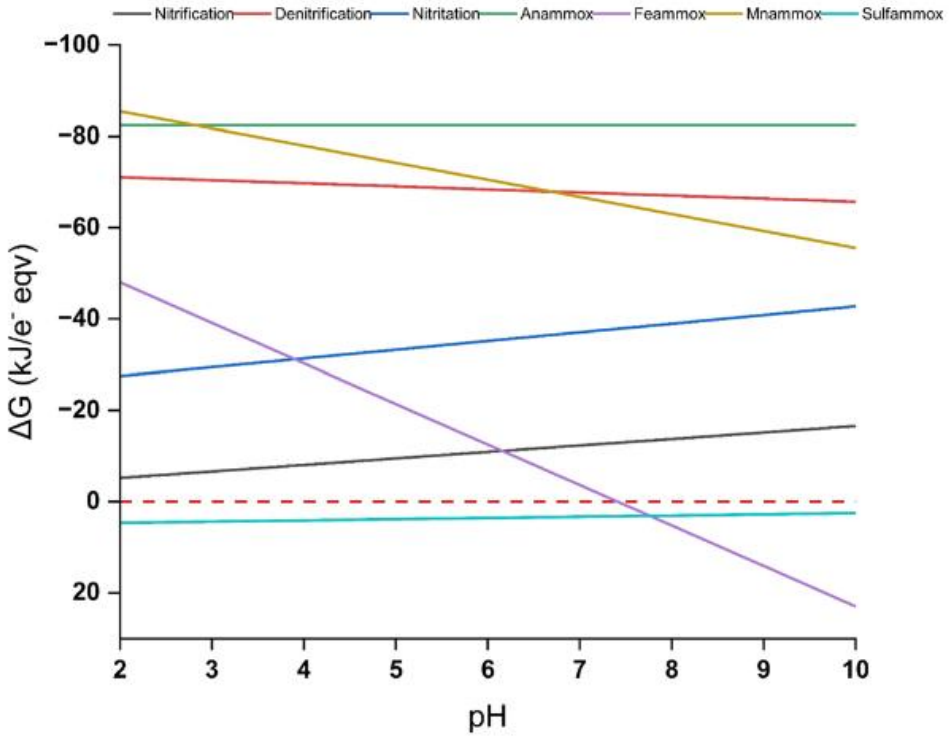
Mn

S

Alternative Electron Acceptors

- **R**obust **E**-acceptors for **N**itrogen **E**limination from **W**astewater (RENEW)

Thermodynamic & Kinetic feasibility



Environmental Science Water Research & Technology

ROYAL SOCIETY OF CHEMISTRY

PERSPECTIVE

Check for updates

Cite this: *Environ. Sci.: Water Res. Technol.*, 2026, **12**, 816

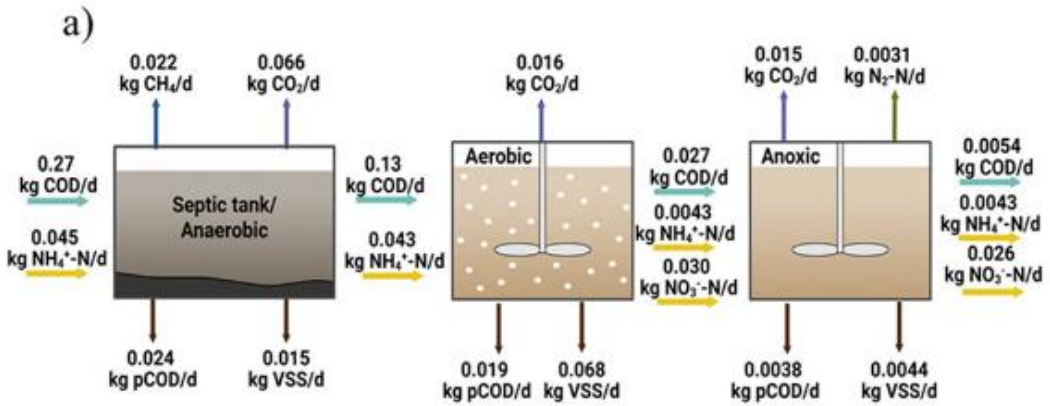
What to breathe? Steering microbial electron acceptors for sustainable onsite wastewater treatment

Bikal Kunwar, [a] Rishabh Shukla, [a] Zhiyue Wang *[ab] and Daniel Yeh[c]

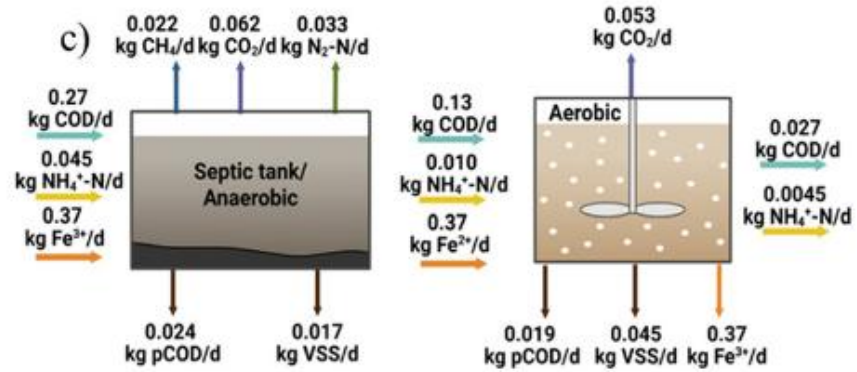
Alternative Electron Acceptors

- **R**obust **E**-acceptors for **N**itrogen **E**limination from **W**astewater (RENEW)

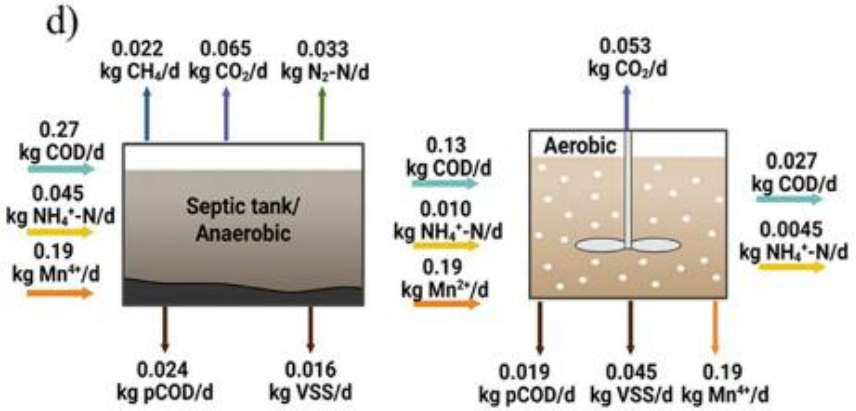
Baseline: Nitrification + Denitrification



Feammox



Mnammox



Kunwar et al., ESWRT, 2026

Alternative Electron Acceptors

- **Fe-mediated N Removal**

Advantages

- ✓ Potentially high N-removal rate

  (7.16 g NH_4^+-N $gVSS^{-1}$ d^{-1})

- ✓ Low sludge production

  (**~10x** lower than baseline)

- ✓ Low oxygen demand

  (0.025 kgO_2/d, **~5x** lower than baseline)

- ✓ Lower GHG emission (no nitrification)

Kunwar et al., ESWRT, 2026

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Challenges

- ❑ Iron supplementation (11.2 kgFe/kgN)

- ❑ Slow growth (μ_{max} = 0.48 d^{-1})

Kunwar et al., ESWRT, 2026

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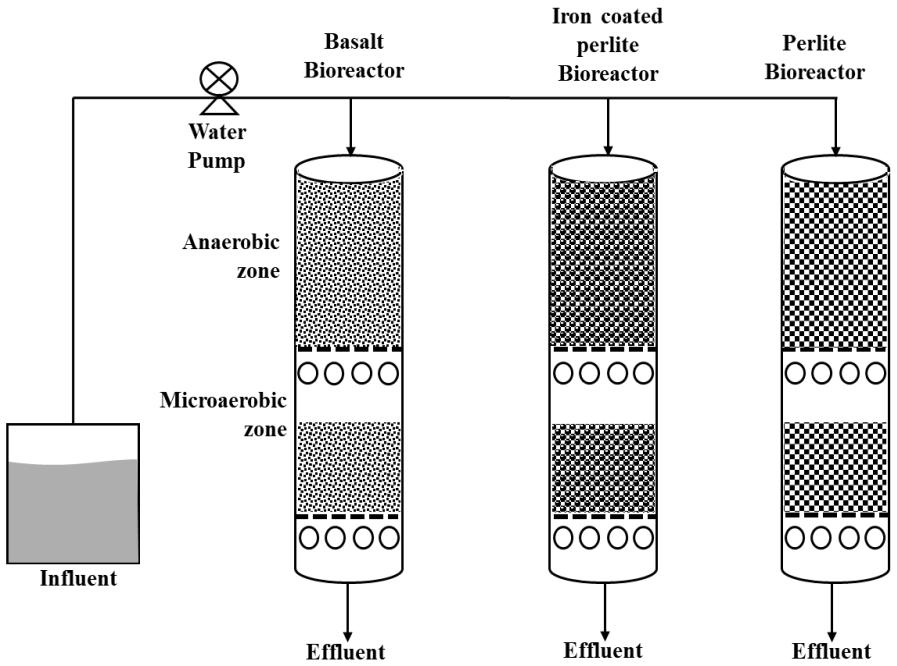
  → recycling of Fe

- ❑ Slow growth (μ_{max} = 0.48 d^{-1})

  → biofilm system

Kunwar et al., ESWRT, 2026

Iron Cycling Biofilters (ICB)



[Patent Pending]



1st US ICBM (1957)

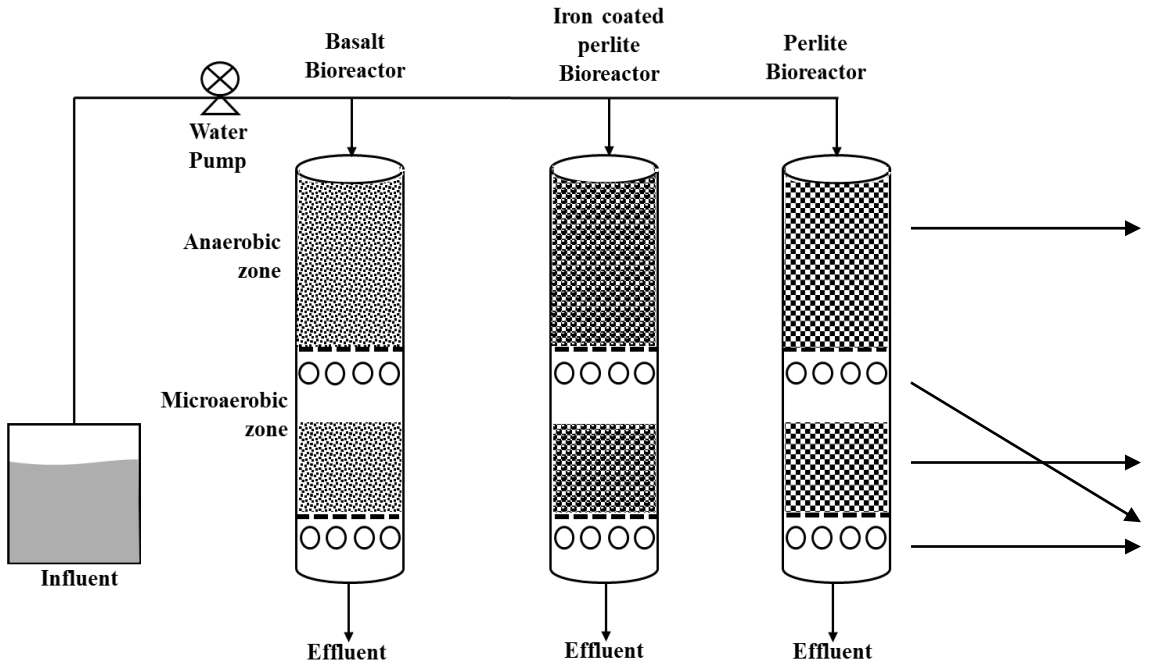
ACS ES&T Engineering

pubs.acs.org/estengg Article

Iron as an Electron Reservoir in Two-Zone Biofilters for Robust Nitrogen Removal

Rishabh Shukla, Zhiyue Wang,* Min Ki Jeon, and Tao Yan

Iron Cycling Biofilters (ICB)



[Patent Pending]


Basalt


Perlite

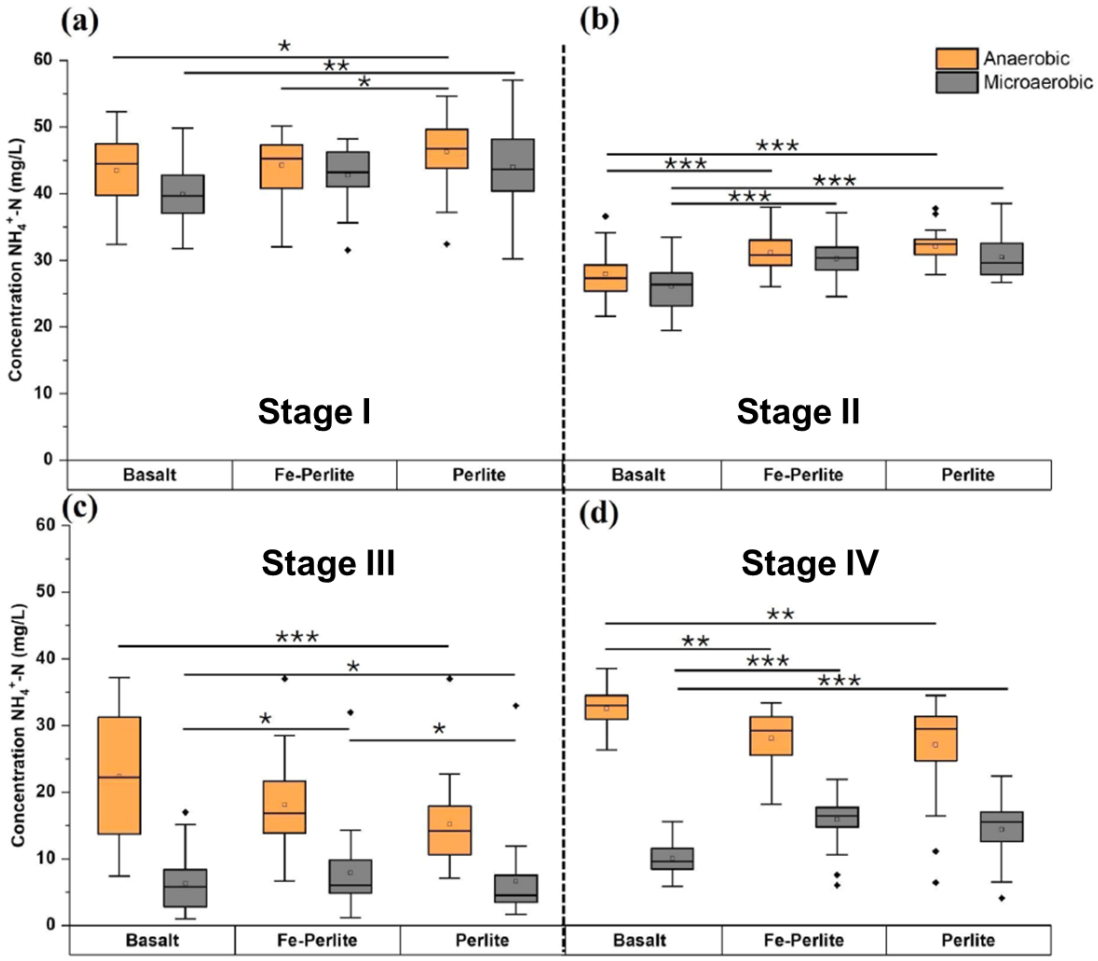

Iron Coated Perlite



Treatment Performance

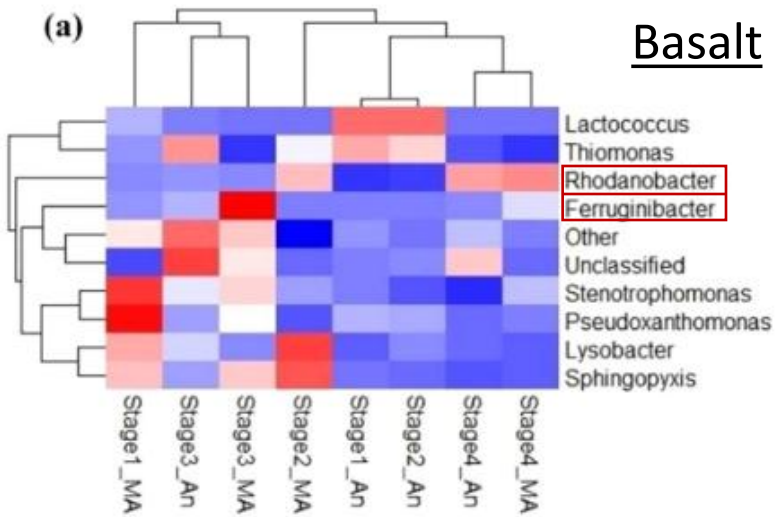
- Basalt-packed biofilters achieved the highest efficiencies for N-removal under
  - Low alkalinity (Stage II)
  - High C/N (Stage IV)

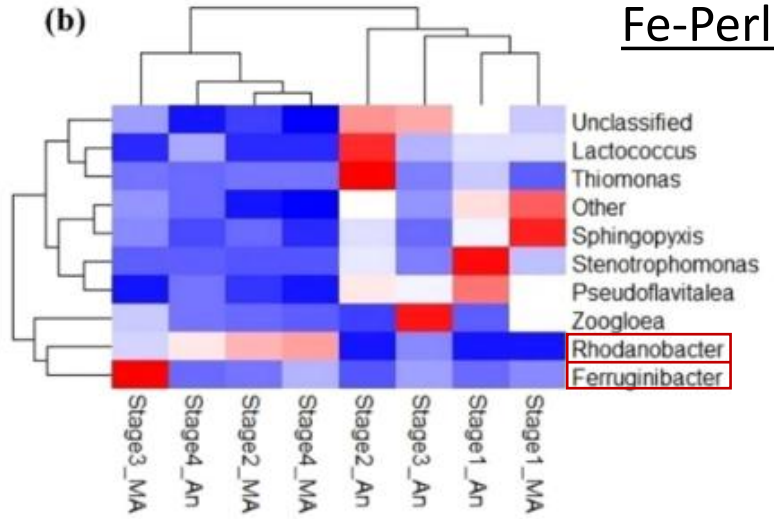
Shukla et al., ES&T Engineering, 2026

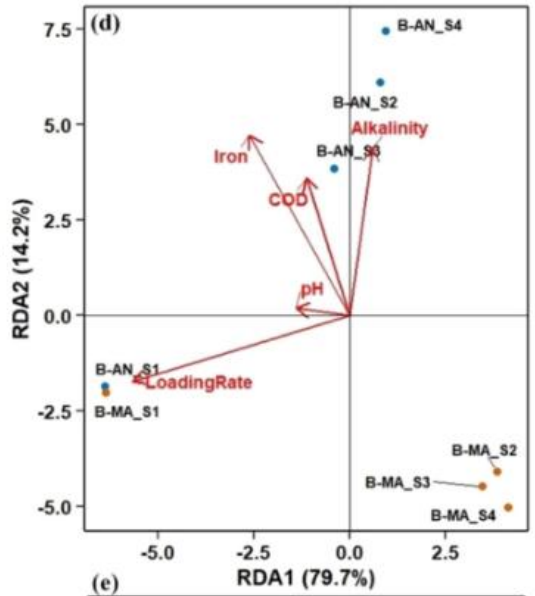


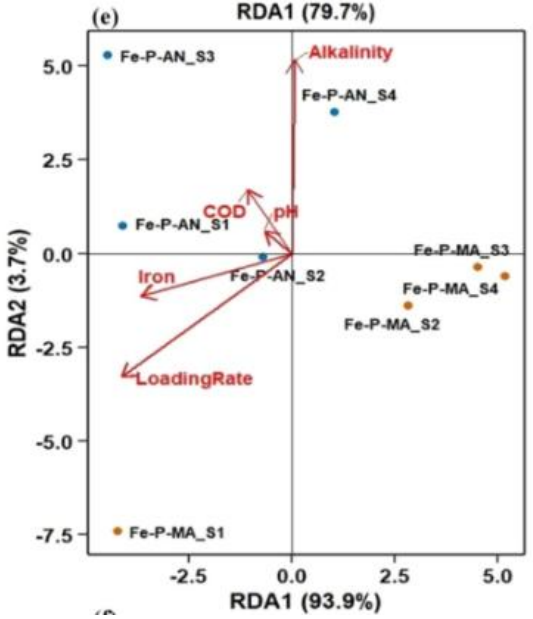
*BNR performance in biofilters. Comparison between groups with ANOVA test *p<0.05, **p<0.01, ***p<0.001 (n=35)*

Microbial Community Composition (16S rRNA)

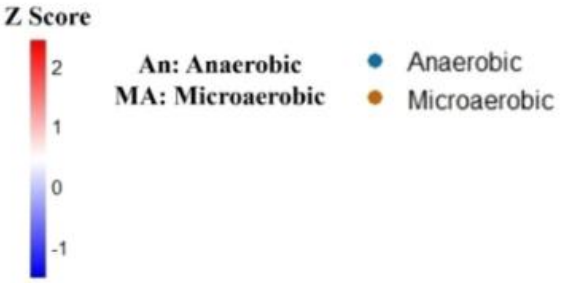






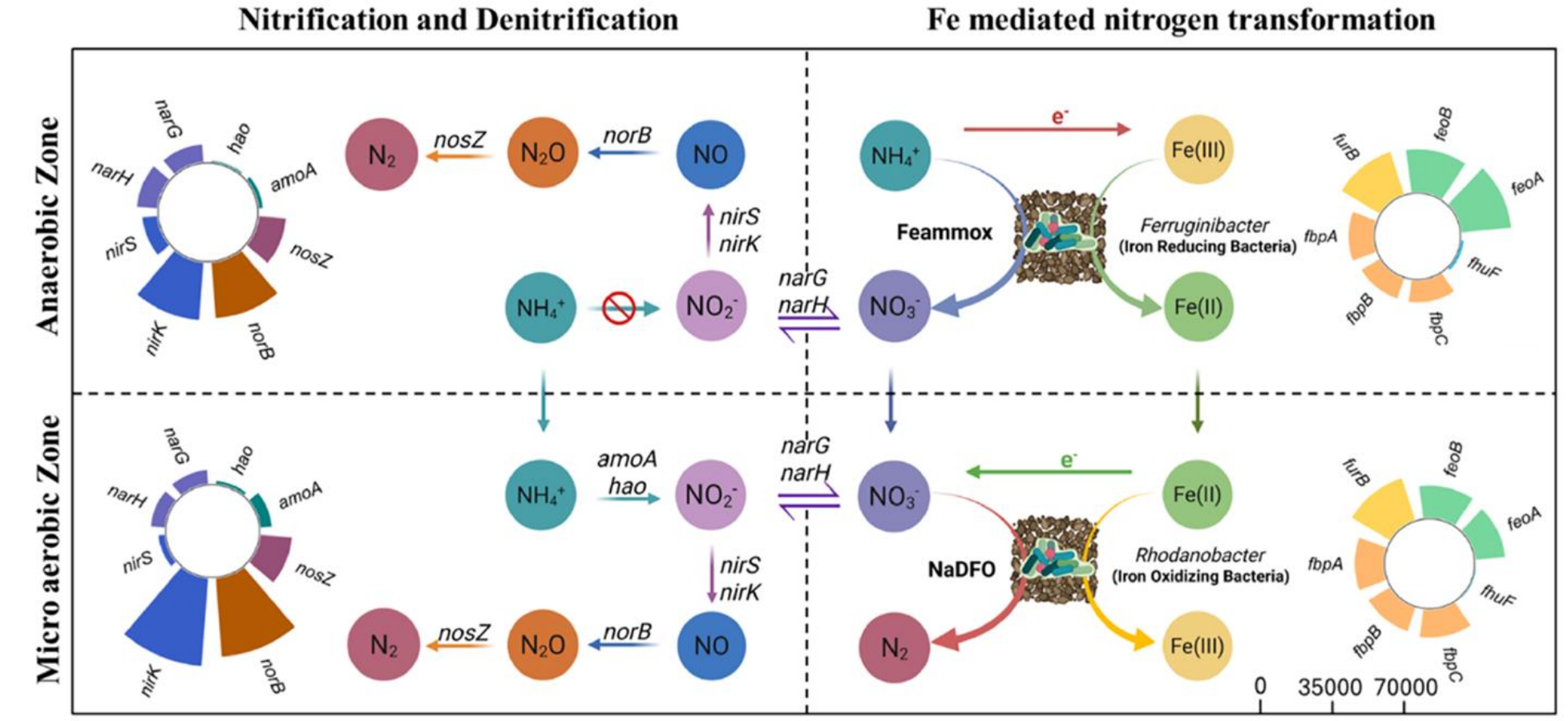


- Fe-reducing bacteria (*Ferruginibacter*) enriched in An zones
- Fe-oxidizing bacteria (*Rhodanobacter*) enriched in MA zones
- Iron cycling creates a two-zone functional diversion



Shukla et al., ES&T Engineering, 2026

Proposed Pathways with Activity Assays



BNR pathways in the basalt biofilter with predicted abundance of functional genes

Shukla et al., ES&T Engineering, 2026

Ongoing Pilot Testing

- ❑ Pathogen removal with IBC
- ❑ Treatment performance with real wastewater



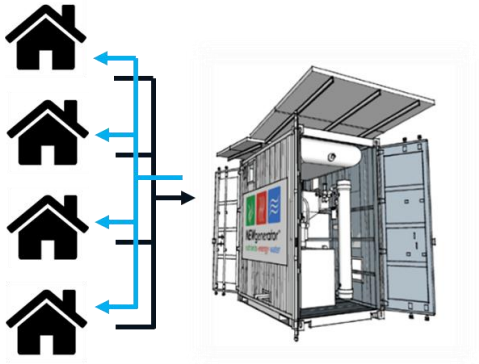
- Three-year program funded by the State of Hawai‘i
- Hawai‘i Onsite Wastewater Technology Evaluation Program (HOWTEP)



Honu Hub

- # Track 13:Honu Hub - An Adaptive Decentralized Wastewater Infrastructure Solution (ADWIS) for Island Communities, by Robert Bair





honuwater.com

Honu
Island wastewater solutions

Conclusions

- Iron in basalt serves as a highly effective auxiliary electron reservoir, overcoming the limitations of imbalanced e- donors and acceptor for N-removal in OWTS.

- The modular two-zone biofilter provides a resilient, low-energy, and sustainable strategy for decentralized nutrient management in rural and island communities.

Acknowledgement

National Science Foundation

Office of Naval Research Science & Technology

Research Group Website

ESWRT 2026

ACS ES&T Eng 2026