

Introduction

Soils serve as the planet's largest natural sink for atmospheric hydrogen, responsible for 80% of global uptake (Fig 1). This process is driven by aerobic soil microbes equipped with high-affinity [Ni-Fe] hydrogenases, which oxidize atmospheric H₂ to meet their metabolic energy needs (Fig 2). By harnessing this natural biogeochemical process, we can engineer biofiltration systems to mitigate concentrated industrial emissions.

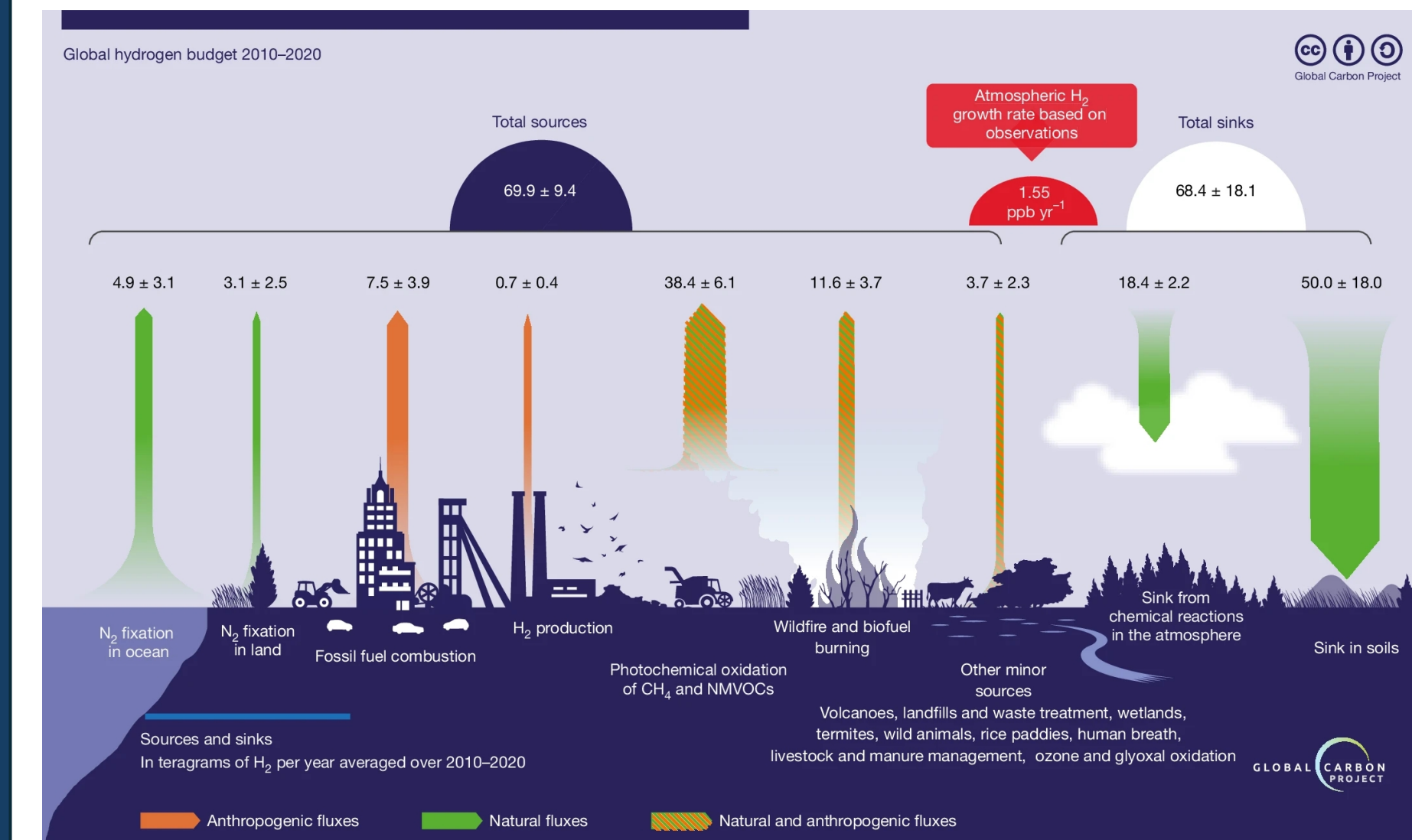
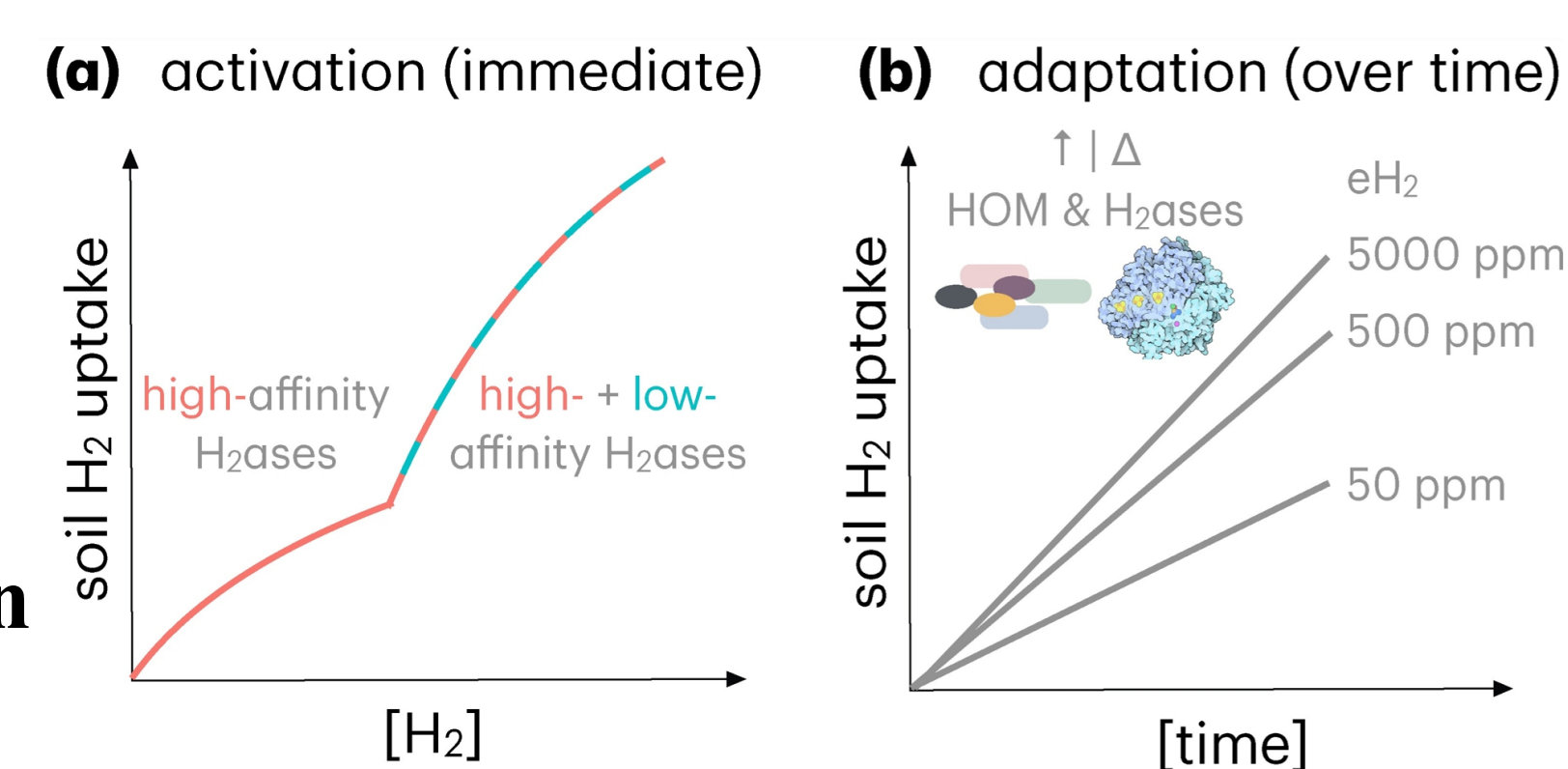


Figure 1. The H₂ budget with sources and sinks, as well as effects on greenhouse gases such as methane, ozone, and water vapor. (Global Carbon Project)

Figure 2. Soil H₂ uptake increases via (a) immediate enzyme activation and (b) long-term microbial growth under elevated H₂ (50–5000 ppm).

Continuous high H₂ exposure creates soil microbiomes highly efficient at H₂ metabolism. Moving beyond observation, this study uses a pre-adapted soil microbiome (500 ppm H₂) to power a prototype biofilter, offering a nature-based solution for capturing industrial leaks.



Methods

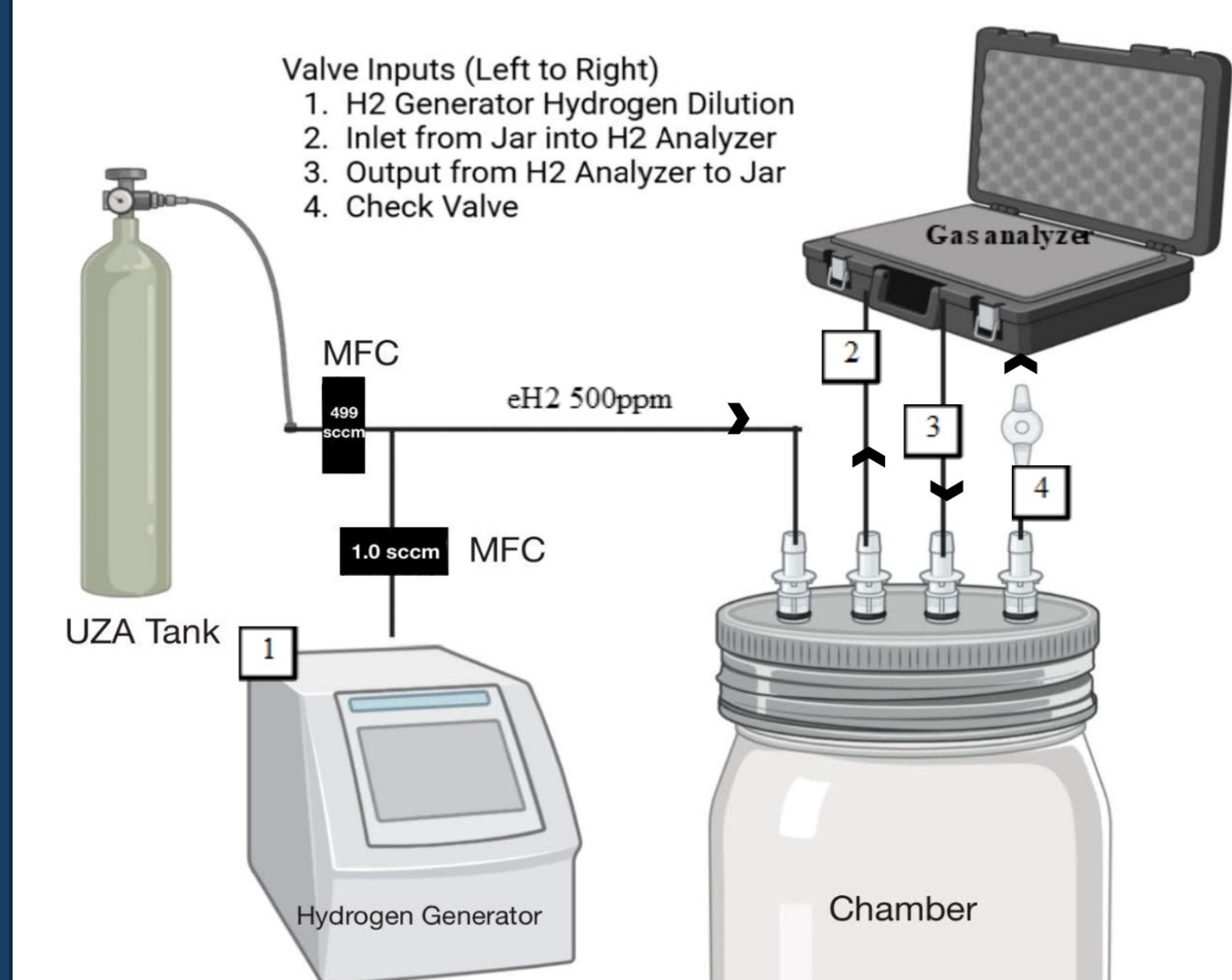
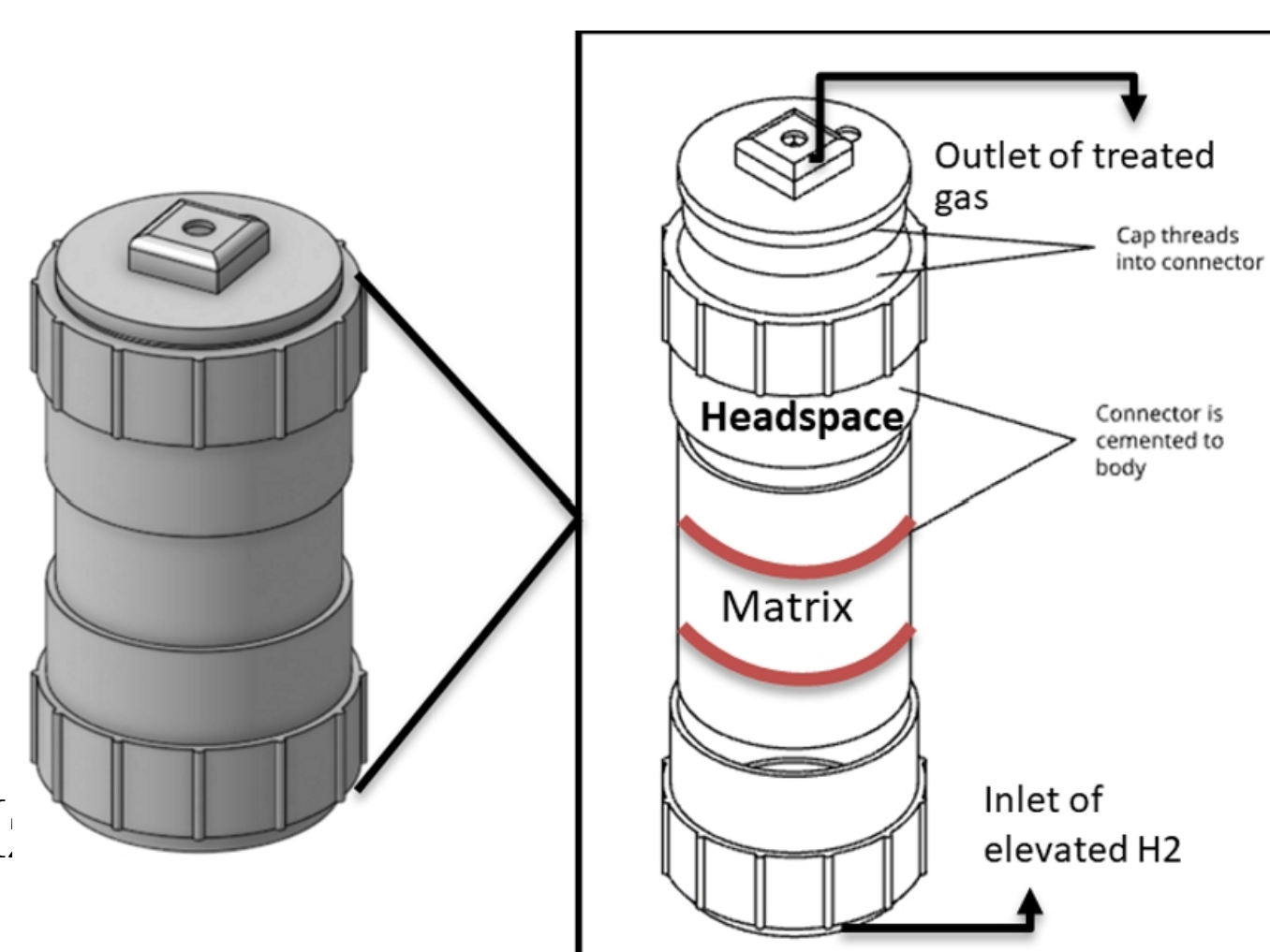


Figure 3. Mass flow controllers mixed ultra zero air gas and generated H₂ to deliver 500 ppm H₂ to the testing chambers. A custom 4-port lid enabled closed-loop recirculation with a LI-COR analyzer for real-time concentration tracking. **Elevated H₂ concentration is 500 ppm compared to atmospheric concentration of 0.53 ppm.**

Individual components and preliminary matrices were evaluated in 1.8L jars, while the fully optimized matrix and control were tested in a 3.98-inch PVC prototype. Chambers were exposed to 500 ppm H₂. A LI-COR 7835 analyzer logged recirculated headspace H₂ at 1 Hz for 20 minutes (Fig 3). H₂ fluxes were calculated in RStudio (gasfluxes), using ANOVA and Tukey HSD for statistical analysis.



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Results

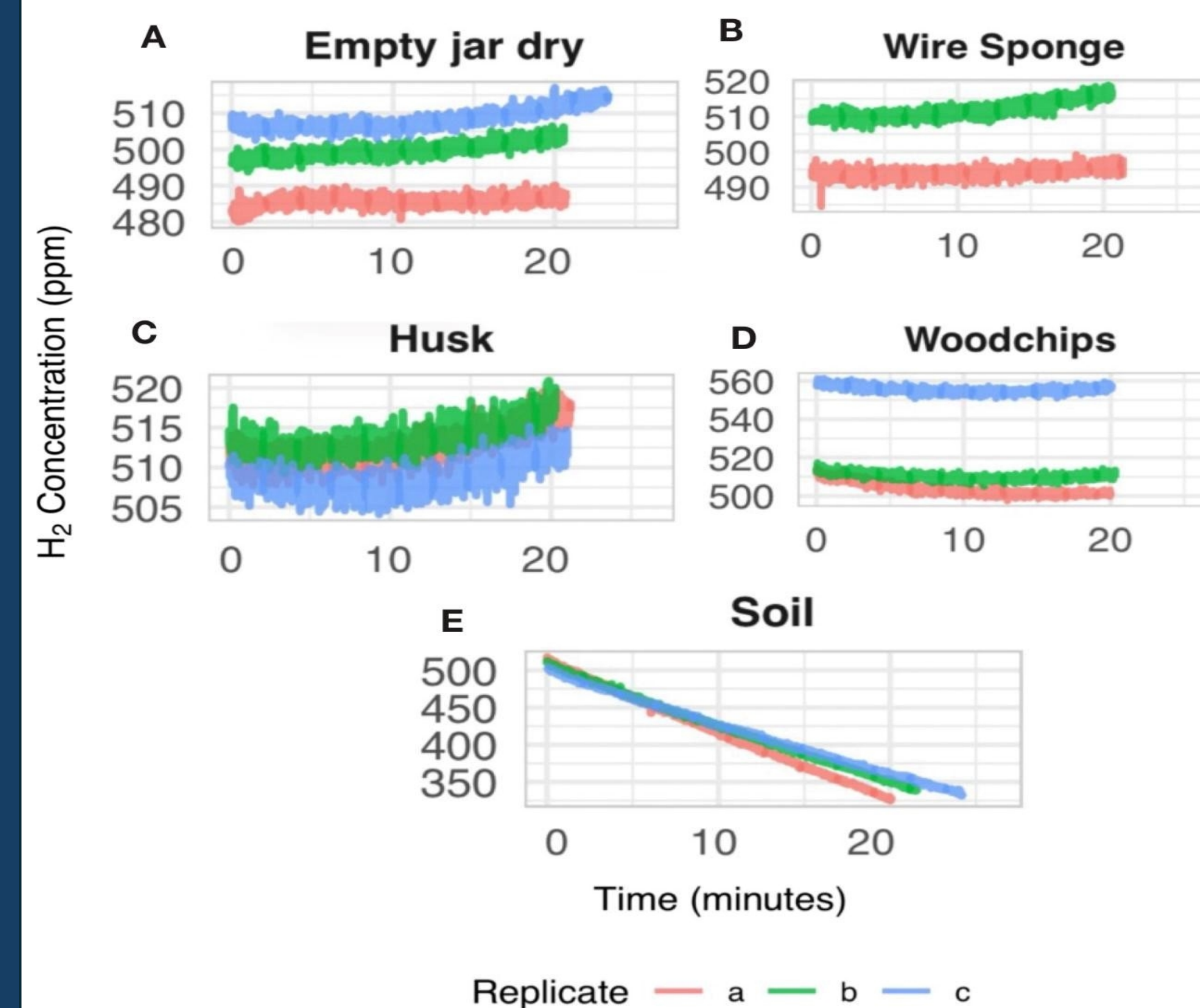


Figure 5. Evaluation of H₂ production / consumption by each matrix component. Continuous plots of H₂ concentration (ppm) over time show each material's interaction with H₂ and provide a baseline for evaluating H₂ emission or consumption before testing matrix combinations. Adapted soil showed the highest H₂ uptake.

Figure 4. Evaluation of matrix combinations for biofilter prototype.

A) and B) show no H₂ consumption, and no strong H₂ production from organic and inorganic materials, suggesting limited interactions of the components. C) and D) show that adapted soil is the main component driving H₂ uptake in these matrix combinations, overriding any potential interactions observed in A and B.

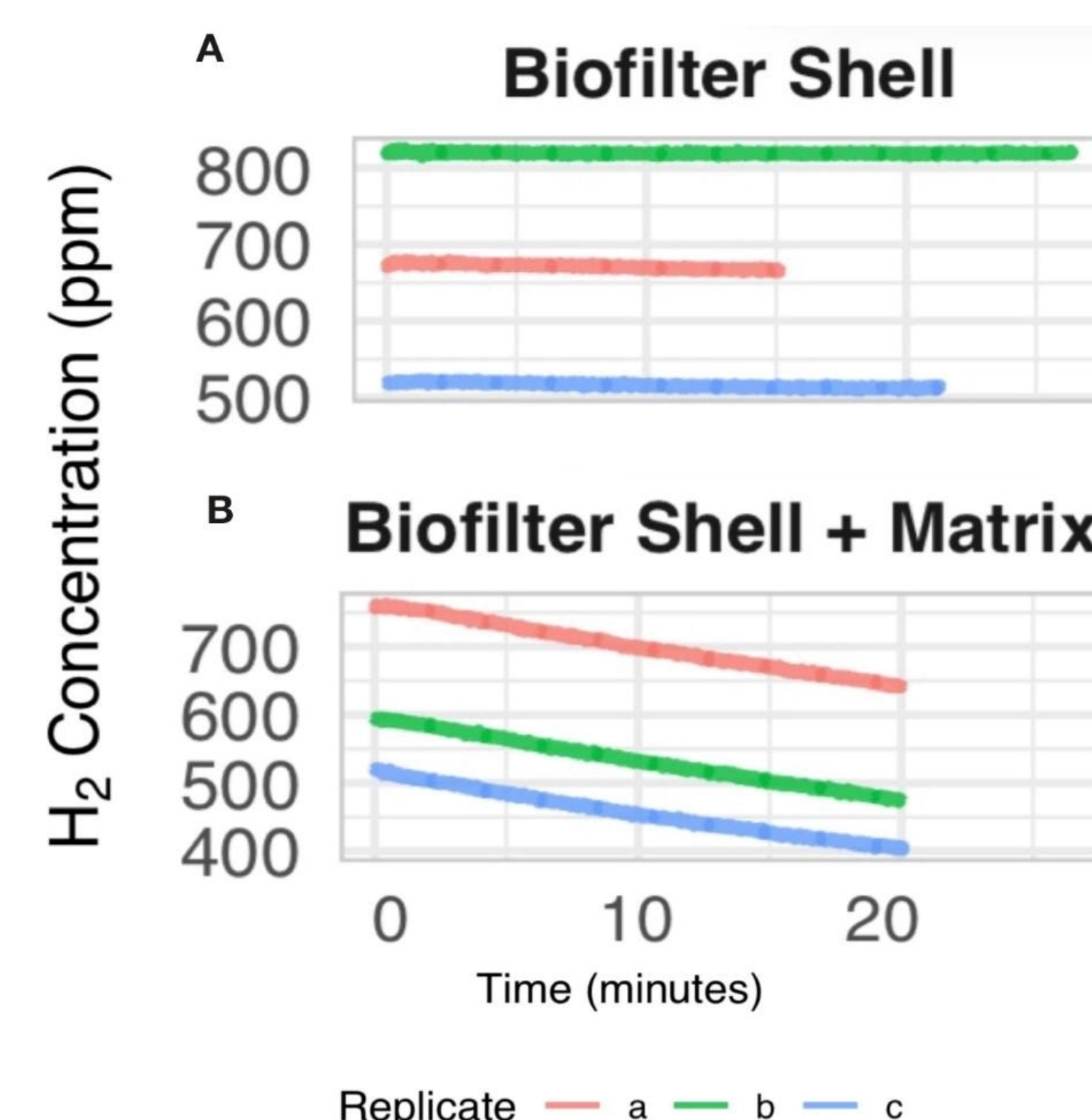
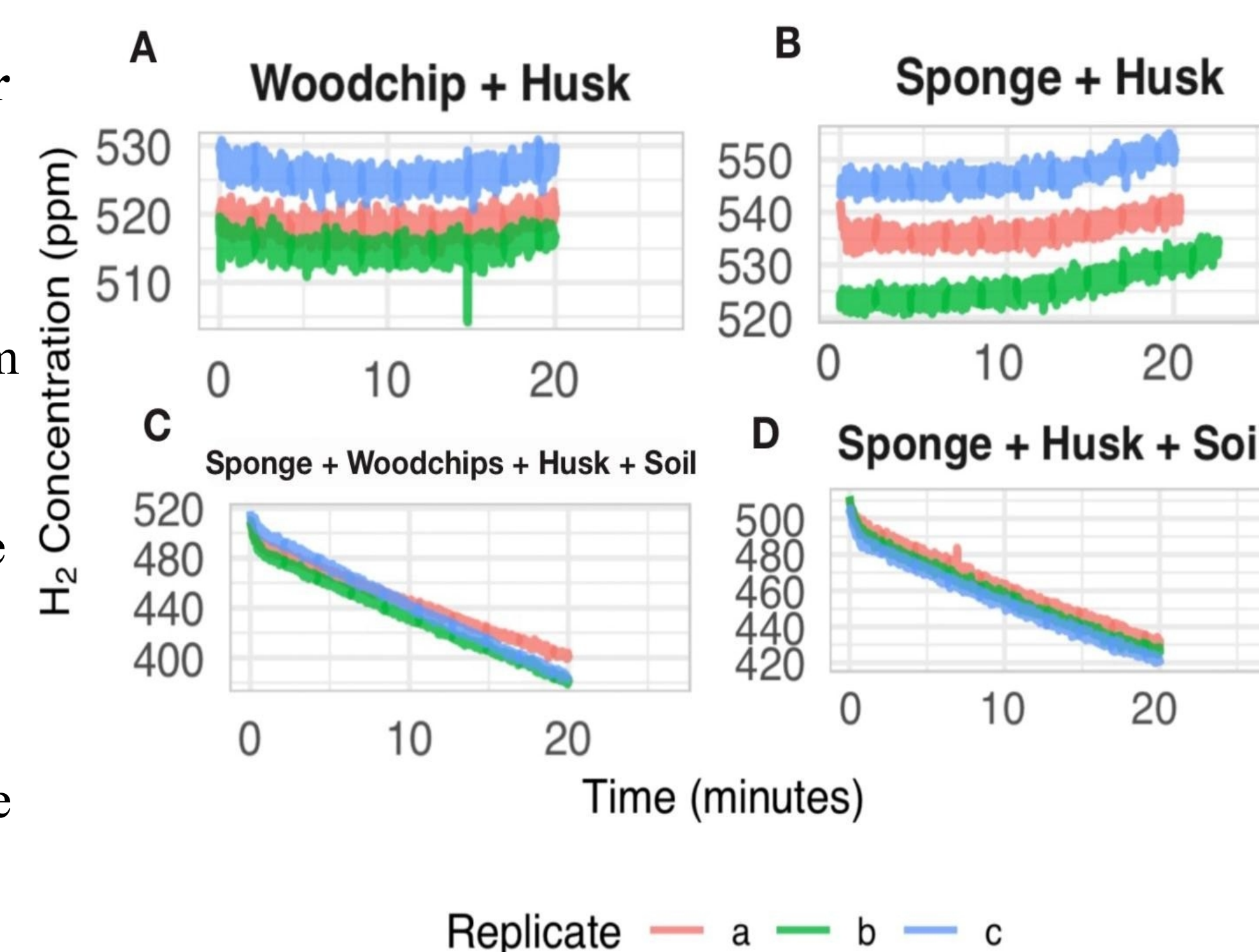


Figure 6. Evaluation of the PVC biofilter shell and optimized matrix combination. Elevated H₂ concentration (ppm) was measured over time.

A) The empty PVC shell shows no significant change in H₂ concentration.

B) The PVC shell with the optimized matrix combination shows active H₂ uptake by the matrix, driven by the adapted soil supported by the Polypropylene sponge and moistened coconut husk consistent with Fig 4.

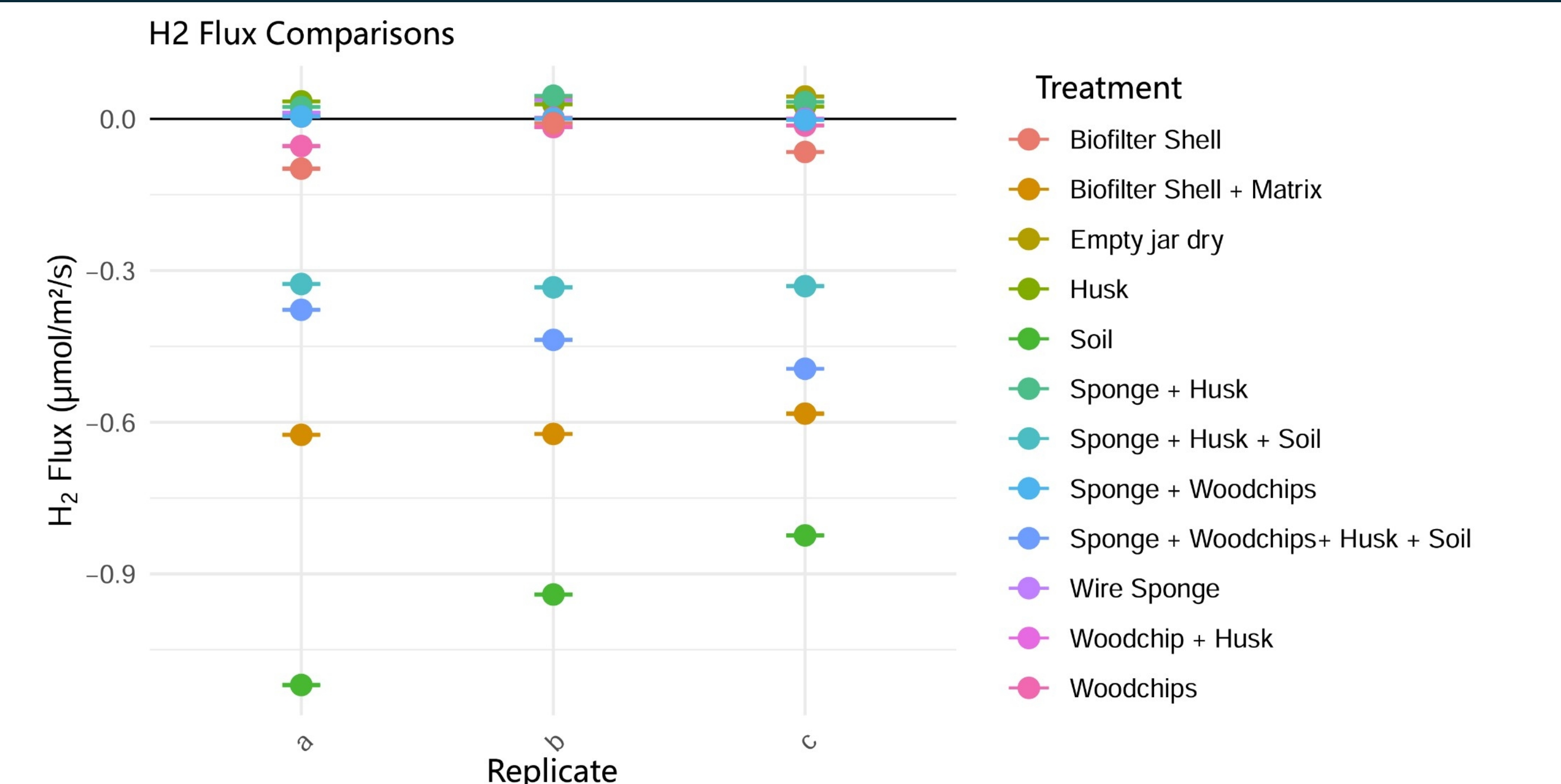


Figure 7. H₂ fluxes (μmol/m²/s) for individual matrix materials, combinations, and the biofilter prototype. Negative fluxes denote H₂ consumption, while positive fluxes indicate H₂ production.

Matrix Composition	Component Type	Mean H ₂ Flux (μmol/m ² /s)	Statistical Significance (p-value)	Overall Effect
Empty Glass Jar	Control	0.00 (Baseline)	-	Inert Baseline
PP Sponge	Inorganic Structural	-0.01	1	Inert
Moistened Coconut Husk	Organic Structural	-0.002	1	Inert
Moistened Woodchips	Organic Structural	-0.06	0.942	Inert
Adapted NY Soil (Isolated)	Active Biological	-0.99	< 0.001	Significant Sink
PP Sponge + Husk	Binary (Structural)	+0.003	1	Inert
Woodchips + Husk	Binary (Structural)	-0.03	1	Inert
NY Soil + PP Sponge + Husk	Complex Mixture	-0.36	< 0.001*	Significant Sink
NY Soil + PP Sponge + Husk + Woodchips	Complex Mixture	-0.47	< 0.001*	Significant Sink
PVC Shell (Empty)	Prototype Control	0	-	Inert Baseline
Final Biofilter Prototype (PVC Shell + PP Sponge + Husk + NY Soil)	Final Assembly	-0.55	< 0.001	Significant Sink

Table 1. Abiotic components (PP sponge, husk, woodchips) showed zero H₂ flux (p ≈ 1.0). Conversely, isolated H₂-adapted soil achieved significant uptake (-0.99 ± 0.15 μmol/m²/s, p < 0.001). Excluding woodchips for structural stability, the final PVC prototype effectively maintained continuous H₂ mitigation (-0.55 ± 0.15 μmol/m²/s, p < 0.001)

Discussion

The adaptation capacity of the soil microbial community pre-exposed to elevated H₂ concentrations plays a critical role in the biofilter matrix's ability to reduce H₂ concentrations by ensuring immediate uptake. The adapted soil in the biofilter may have a greater abundance of microbes with low-affinity hydrogenases, which is consistent with other experiments showing that soils exposed to elevated H₂ significantly increased their H₂ oxidation kinetic parameters compared to native soils. The prototype's lower flux compared to soil alone (-0.55 vs. -0.99 μmol m⁻² s⁻¹) highlights the trade-off between moisture retention and gas diffusion. The husk/sponge matrix optimized this balance, establishing a baseline for future *M. smegmatis* bioaugmentation.

Future Direction

- **Bioaugmented Hydrogel Integration:** Inoculate the matrix with *Mycobacterium smegmatis* immobilized within a synthetic hydrogel to provide a stable moisture reservoir and high-efficiency H₂ oxidation without obstructing gas diffusion
- **Field Application:** Scale the prototype to accommodate higher gas volumes and test its mitigation capacity during real-world venting events at H₂ refueling stations.

Acknowledgements

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