Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.36447

Nanofiltration Membrane-Driven Manipulation of Carbonate Chemistry for Marine Carbon Dioxide Removal

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Achieving the targets of the Paris Agreement requires not only rapid reductions in anthropogenic carbon dioxide (CO_2) emissions, but also scalable strategies for durable negative emissions. The oceans have already absorbed roughly one-third to one-half of anthropogenic CO_2, motivating exploration of marine-based carbon dioxide removal (mCDR) approaches.

We investigate whether nanofiltration (NF) membrane-driven ion partitioning can generate chemically distinct aqueous streams with contrasting carbonate equilibria that may be leveraged for CO_2 removal. NF membranes exhibit intrinsic size- and charge-based selectivity, enabling redistribution of major ions and alkalinity without chemical reagents or applied electrochemical polarizations.

Artificial seawater was processed through an NF270 membrane under controlled pressures and flow conditions. Permeate and concentrate streams were analyzed for conductivity, pH, alkalinity, and major ion concentrations. Carbonate system parameters, including pCO_2 and apparent calcium carbonate saturation indices (Ω), were calculated using CO_2SYS and PHREEQC.

Although bulk pH remained similar to the feed solution, selective ion rejection redistributed carbonate alkalinity species across the membrane. The concentrate stream exhibited elevated pCO_2 and increased $CaCO_3$ saturation state relative to the feed, whereas the permeate stream was undersaturated in CO_2. These results demonstrate that membrane-driven ion selectivity alone can modulate carbonate speciation independently of large pH shifts. Ongoing analyses assess potential $CaCO_3$ precipitation via centrifugation and filtration followed by SEM and EDS characterization.

By generating paired CO_2-enriched and CO_2-depleted streams, nanofiltration enables spatial separation of carbon storage and atmospheric uptake within a single process. The enriched stream may be suitable for deep-ocean storage, while the undersaturated stream could enhance atmospheric CO_2 drawdown upon equilibration in surface waters. These findings suggest that membrane-based manipulation of carbonate equilibria offers a chemically tunable and potentially lower-energy pathway for marine carbon dioxide removal.