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Beyond Amines: A Comparative Analysis of Bio-Sequestration vs. PET-Derived Sorbents in Carbon Capture

Environment * Climate Change * Conservation

The Dual Crisis of Carbon and Plastic Waste

Mitigating anthropogenic climate change requires the rapid deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies to manage over 36 billion metric tons of annual carbon dioxide (CO2) emissions. As atmospheric CO2 surpasses 420 parts per million (ppm) -- straining planetary boundaries and driving ocean acidification -- the Intergovernmental Panel on Climate Change (IPCC) projects that 1.5 to 2.6 billion metric tons of CO2 must be actively removed annually by mid-century.[1][2] For hard-to-abate industrial point sources such as cement, steel, and chemical manufacturing, post-combustion capture remains essential. Simultaneously, global packaging and textile supply chains generate millions of tons of Polyethylene Terephthalate (PET) plastic waste each year, of which only 10% to 15% is mechanically recycled, leaving the remainder to accumulate in landfills, degrade into microplastics, or release gaseous CO2 via incineration.[2][3]

This report evaluates three competing paradigms in carbon management across reaction kinetics, thermodynamic penalties, and lifecycle economics: the industrial benchmark of liquid chemical absorption using Monoethanolamine (MEA); photosynthetic bio-sequestration via Microalgae; and the emerging circular-economy material Bis(2-aminoethyl)terephthalamide (BAETA), a solid chemisorbent synthesized by upcycling waste PET plastic.[2][3]

Liquid Amine Scrubbing: Thermodynamic Penalties and Degradation

Developed in the 1930s for natural gas sweetening, aqueous alkanolamine scrubbing (specifically 30 wt% Monoethanolamine, MEA) is the only post-combustion capture technology operating at full commercial readiness (TRL 9).[1] In the absorber column (40-60 deg C), MEA captures CO2 via a two-step zwitterion mechanism: nucleophilic attack by the primary amine nitrogen on CO2 forms an unstable zwitterion intermediate (RNH2+COO-), which is rapidly deprotonated by a second amine molecule acting as a Br nsted base to yield a stable carbamate (RNHCOO- + RNH3+). Because two moles of amine are required to bind one mole of CO2 (and bicarbonate hydrolysis is kinetically slow), theoretical equilibrium loading is capped at 0.5 mol CO2 per mol amine.[4]

The primary limitation of liquid MEA is the massive thermal penalty required to reverse carbamate formation in the stripper column (100-120 deg C). Reboiler regeneration consumes 3.5 to 4.2 GJ per ton of CO2, reducing host power plant electrical output by 20% to 30%.[5][6] This parasitic load stems from three components: the sensible heat required to raise the 70% water solvent to stripping temperatures, the latent heat of water vaporization needed to generate stripping steam, and the high enthalpy of desorption (~85 kJ/mol) needed to cleave the covalent carbamate bond.[2]

Furthermore, flue gas containing 3% to 15% oxygen triggers free-radical oxidative fragmentation of MEA, releasing volatile ammonia (NH3) and organic acids that bind active solvent into non-regenerable Heat Stable Salts (HSS).[6][7] Above 120 deg C, thermal carbamate polymerization forms 2-oxazolidinone (OZD) and high-viscosity polyamines that foul heat exchangers,[8] while atmospheric reaction of escaped secondary amines with NOx produces carcinogenic nitrosamines and nitramines.[9][10]

Microalgal Bio-Sequestration: The RuBisCO Bottleneck

Microalgal systems reframe CO2 from a waste gas into a biological feedstock, using solar-driven photosynthesis to fix inorganic carbon into lipids, proteins, and carbohydrates for Carbon Capture and Utilization (CCU).[11] However, biological fixation is constrained by the catalytic inefficiency of Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) in the Calvin-Benson-Bassham cycle. Because RuBisCO poorly discriminates between CO2 and O2, competing oxygenation triggers photorespiration -- dissipating ATP and NADPH while releasing fixed carbon and cutting net fixation efficiency by 30% to 50%.[12][13] Moreover, evolutionary trade-offs between CO2 specificity and catalytic turnover rate (kcat) force algae to invest 30% to 50% of their soluble protein into RuBisCO, demanding substantial Nitrogen fertilizer inputs.[14]

At industrial scales, cultivation engineering faces severe spatial and mass-transfer limits. Open raceway ponds offer low capital cost but suffer from rapid CO2 outgassing, extreme evaporative water loss, and biological contamination.[11] Closed photobioreactors (PBRs) improve gas retention and biomass density but incur prohibitive capital costs, parasitic pumping loads, and photosynthetic oxygen inhibition.[11] Capturing the emissions of a single 500 MW coal plant (~3-4 million tons CO2/year) requires 3,500 to 15,000 hectares of pond area, driving standalone sequestration costs to USD 300-1,600 per ton of CO2 unless subsidized by niche nutraceutical co-products.[15]

BAETA: Circular Synthesis and Solid-State Sorption

Developed by chemists at the University of Copenhagen, BAETA (Bis(2-aminoethyl)terephthalamide) transforms waste PET plastic into a high-capacity solid amine chemisorbent via mild catalytic aminolysis.[2][3] Reacting discarded PET bottles or textiles with 1,2-ethylenediamine (EDA) at 60 deg C for 24 hours (or room temperature over longer durations) cleaves the polyester ester linkages via nucleophilic attack, yielding 83% to 90% crystalline white BAETA powder alongside recoverable ethylene glycol (EG) and active oligomeric residues.[2] Crucially, the synthesis tolerates colored, dirty, and food-contaminated post-consumer plastic streams rejected by mechanical recyclers.[2][3]

Structurally, BAETA features a rigid terephthalamide core flanked by two primary amino-ethyl groups that chemisorb CO2 within a solid lattice at capacities of 3.17 to 3.41 mmol/g.[2] Thermogravimetric analysis demonstrates stability up to 250 deg C, enabling BAETA to capture CO2 directly from hot industrial exhaust streams at 150 deg C without pre-cooling.[2][3] Unlike zeolites or Metal-Organic Frameworks (MOFs) poisoned by flue-gas humidity, BAETA thrives across 0-100% relative humidity because water vapor facilitates solid-state zwitterion proton transfer.[2] Eliminating the aqueous solvent carrier avoids the high specific heat capacity (4.18 J/g * K) and

vaporization penalties of water, lowering regeneration energy to 1.8-2.6 GJ/ton CO2 across 150+ validated adsorption-desorption cycles.[2]

| Technical Parameter | | Liquid Amines (MEA) | | Microalgae (PBR / Ponds) | | BAETA (PET-Derived Solid) |

| Capture Mechanism | | Aqueous Chemisorption (Carbamate) | | Biological Photosynthesis (RuBisCO) | | Solid-State Amine Chemisorption |

| Sorption Capacity / Rate | | ~0.5 mol CO2/mol amine (Seconds) | | Growth-rate limited (Hours/Days) | | 3.17-3.41 mmol CO2/g (Minutes)[2] |

| Regeneration Energy | | High (3.5-4.2 GJ/ton CO2)[5] | | Solar-driven (High harvesting energy) | | Low (1.8-2.6 GJ/ton CO2)[2] |

| Operating Temp Window | | Absorber: 40 deg C / Stripper: 120 deg C | | Ambient (20-30 deg C; <40 deg C limit) | | 25 deg C-170 deg C (Stable to 250 deg C)[2] |

| Water & Land Footprint | | High cooling water; compact plant (1-2 ha) | | Extreme evaporation; 3,500-15,000 ha[15] | | Minimal water; compact contactor |

| Ecotoxicity & Feedstock | | Fossil NH3/EO; nitrosamine risk[10] | | Benign biomass; high N/P fertilizer | | Upcycled PET waste + EDA[2] |

| Estimated Capture Cost | | USD 57-80 / ton CO2 (TRL 9)[16] | | USD 300-1,600 / ton CO2 (TRL 5-6)[15] | | USD 40-60 / ton CO2 projected (TRL 4-5) |

Conclusion: Matching Capture Paradigms to Industrial Niches

A rigorous comparative analysis demonstrates that post-combustion carbon management requires aligning material thermodynamics with industrial constraints. Aqueous MEA scrubbing remains the pragmatic near-term incumbent due to existing liquid-handling infrastructure, despite its severe steam regeneration penalty and nitrosamine emissions risk. Microalgal bio-sequestration cannot match chemical sorbents for bulk gigawatt-scale flue gas scrubbing due to RuBisCO kinetics and land intensity, but serves a vital niche in decentralized carbon utilization for sustainable aviation fuels and bioproducts. Conversely, BAETA pioneers a circular-economy breakthrough: by upcycling low-grade PET plastic waste into a moisture-tolerant, thermally resilient (150 deg C+) solid sorbent, it slashes regeneration energy duties while simultaneously addressing global polymer pollution. Scaling fluidized-bed and rotary gas-solid contactors for BAETA should be a primary engineering priority on the path to net-zero industry.

Updates... (Nov 23, 2026): Consolidated prior Nov 23, 2026 CrossRef/PubMed author and date fixes; normalized section heading to "References"; standardized inline currency notation to "USD 300-1,600 per ton"; and corrected second-author initial in Ref. [9] (Azzi, M., & White, S.).

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