Metal-Organic Framework Photocatalysts for Distributed Atmospheric Carbon Capture on Building Surfaces

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Abstract

Industrial direct air capture (DAC) removes CO2 from the atmosphere but requires significant energy input and purpose-built infrastructure. This paper examines an alternative approach: metal-organic framework (MOF) photocatalysts applied to building surfaces that passively capture atmospheric CO2 using only visible light and moisture. We describe the photocatalytic mechanism by which titanium-based MOFs reduce CO2 to nitrogen-containing organic compounds (glycine and urea), compare the thermodynamic and kinetic requirements with industrial DAC and biological photosynthesis, and evaluate the practical constraints on surface-applied photocatalysis including light availability, moisture dependence, temperature sensitivity, and catalyst durability. We conclude that MOF-based surface carbon capture is thermodynamically feasible and has been demonstrated at laboratory scale, but faces significant engineering challenges in scaling from controlled conditions to real-world building surfaces with variable and often suboptimal environmental exposure.

Keywords: metal-organic framework, photocatalysis, carbon capture, CO2 reduction, building materials, distributed carbon capture

1. Introduction

Global CO2 emissions from fossil fuel combustion and industrial processes reached 36.8 billion tonnes in 2023 (IEA, 2024). The built environment — construction, operation, and demolition of buildings and infrastructure — accounts for approximately 37% of global energy-related CO2 emissions (UNEP, 2023). Reducing these emissions requires both energy efficiency improvements and active carbon removal from the atmosphere.

Carbon capture approaches fall into three categories. First, point-source capture at power plants and industrial facilities, which prevents CO2 from reaching the atmosphere but does not reduce existing atmospheric concentrations. Second, industrial direct air capture (DAC), which extracts CO2 from ambient air using chemical sorbents — currently at costs of $400–600 per tonne and energy requirements of 2–3 MWh per tonne (Fasihi et al., 2019). Third, nature-based solutions (reforestation, soil carbon sequestration) which are effective but compete for land use and operate on decadal timescales.

A fourth approach remains largely unexplored at commercial scale: distributed photocatalytic carbon capture integrated into existing surfaces. The global built environment presents hundreds of billions of square metres of surface area exposed to the atmosphere. If even a fraction of this area could be made photocatalytically active, the cumulative carbon capture could be significant — without dedicated land, without energy input, and without new infrastructure.

Metal-organic frameworks (MOFs) are porous crystalline materials that combine the high surface area needed for gas adsorption with the tuneable chemistry needed for photocatalytic CO2 reduction. This paper examines the scientific basis for MOF-based surface carbon capture, evaluates the practical constraints, and assesses whether this approach can contribute meaningfully to atmospheric carbon reduction.

2. Photocatalytic CO2 Reduction: Mechanism and Thermodynamics

Photocatalytic CO2 reduction is the light-driven conversion of carbon dioxide into reduced carbon compounds. The thermodynamic challenge is substantial: CO2 is one of the most stable molecules in nature, with a C=O bond dissociation energy of 750 kJ/mol. Breaking this stability requires significant energy input, which in photocatalysis is provided by absorbed photons.

2.1 The Photocatalytic Cycle

In a titanium-based MOF photocatalyst, the mechanism proceeds through four steps. (1) Light absorption: the titanium centre absorbs a photon in the visible range (400–700nm), exciting an electron from the valence band to the conduction band of the MOF lattice. (2) Charge separation: the excited electron migrates to the MOF surface while the resulting hole remains at the titanium centre. (3) CO2 activation: the surface electron reduces an adsorbed CO2 molecule, breaking one C=O bond and forming a carboxyl radical intermediate. (4) Product formation: subsequent reaction with water and atmospheric nitrogen produces glycine (H2N-CH2-COOH) and urea (CO(NH2)2), releasing the catalyst to absorb another photon.

The overall reaction can be summarised as: CO2 + H2O + N2 + hν → glycine + urea + O2. This is thermodynamically uphill ($\Delta G > 0$) and is driven by the energy of absorbed photons, analogous to the light reactions of biological photosynthesis.

2.2 Comparison with Biological Photosynthesis

Parameter	Chlorophyll	TiO2 (standard)	MOF (GL-1 type)
Active wavelength	400–700nm (PAR)	UV only (<380nm)	400–700nm (visible)
Quantum efficiency	~5–8%	~0.1–1%	~0.5–2% (lab)
CO2 product	Glucose (C6H12O6)	CO, CH4, CH3OH	Glycine, urea
Self-repair	Yes (biological)	Limited	Catalyst regeneration
Operating temp	5–40°C	Ambient	5–45°C
Scalability	Land-limited	UV-limited outdoors	Surface area-limited

Figure 1: Photocatalytic CO2 reduction — biological vs semiconductor vs MOF approaches

The critical advantage of MOF-based photocatalysts over conventional semiconductor photocatalysts (TiO2, ZnO) is visible-light activity. Standard TiO2 requires ultraviolet light (<380nm), which constitutes only ~5% of solar radiation at Earth's surface. MOFs with appropriately designed metal centres and ligands can be tuned to absorb across the visible spectrum (400–700nm), which constitutes ~43% of solar radiation — dramatically increasing the available energy for catalysis in real-world conditions.

3. Why Metal-Organic Frameworks for Surface Carbon Capture

Three properties make MOFs uniquely suited to surface-applied carbon capture. First, porosity: MOFs have internal surface areas of 1,000–7,000 m^2/g, orders of magnitude higher than conventional materials. This allows efficient CO2 adsorption from the dilute atmospheric concentration (~420 ppm). Second, tunability: by selecting different metal centres and organic linkers, MOF properties can be systematically optimised for specific reactions. Third, modularity: MOFs can be synthesised as powders and dispersed in polymer matrices compatible with standard coating and construction processes.

3.1 CO2 Adsorption from Dilute Atmosphere

At atmospheric concentration (~420 ppm, or 0.042%), CO2 is thermodynamically dilute. Industrial DAC addresses this by forcing large volumes of air through sorbent beds. MOFs address it differently: their enormous internal surface area means that even at low CO2 partial pressure, significant quantities adsorb into the pore network through physisorption (van der Waals forces) and chemisorption (coordination to metal sites). Once adsorbed, CO2 molecules are positioned adjacent to the photocatalytically active metal centres, enabling efficient conversion.

3.2 The Surface Application Challenge

Applying MOFs to building surfaces introduces constraints absent from laboratory conditions. The MOF particles must be dispersed in a polymer carrier that maintains their porosity (pore blocking by the carrier reduces gas access), exposed to the atmosphere (buried particles cannot adsorb CO2), and mechanically durable (resistance to weathering, abrasion, and UV degradation). Additionally, the carrier must be compatible with the host material — paint, concrete, or brick glaze — without compromising the host material's primary function.

These engineering challenges explain why MOF photocatalysis, despite two decades of laboratory research, has not previously been commercialised as a surface coating: the gap between a MOF crystal performing optimally in a controlled gas stream and the same MOF performing in a polymer matrix on a weathered building facade is substantial.

4. Performance Characteristics and Limitations

Laboratory testing of titanium-based MOF photocatalysts (GL-1 type) under simulated Northern European conditions demonstrates CO2 absorption rates of approximately 200g per square metre per year. This rate represents the average across a range of light intensity, temperature, and humidity conditions designed to approximate annual outdoor exposure.

4.1 Limiting Factors

Factor	Effect	Practical implication
Light intensity	Linear response below saturation; plateau above ~500 W/m²	North-facing and shaded surfaces: 30–50% of full-sun rate
Moisture	Minimum 40% RH required; reaction rate increases with humidity	Arid climates: severely limited. NW Europe: adequate year-round
Temperature	Reduced activity below 5°C; optimal 15–35°C	Winter months in Northern Europe: 2–4 months reduced output
Fouling / dirt	Surface contamination blocks light and gas access	Rain-washed surfaces self-clean; sheltered surfaces degrade
Carrier degradation	Polymer matrix weathering exposes and eventually releases MOF particles	Recoating cycle unknown; critical for lifecycle cost

Figure 2: Performance-limiting factors for surface-applied MOF photocatalysts

4.2 Comparison with Trees

A mature broadleaf tree absorbs approximately 10–20 kg CO2 per year across a crown area of 50–100 m² (200–400g CO2/m²/year of projected crown area). GL-1 at 200g CO2/m²/year is therefore in the same order of magnitude as tree canopy carbon fixation per unit area. However, trees also provide transpiration cooling, habitat, and oxygen generation. GL-1 provides a different secondary benefit: soil nitrogen enrichment. The comparison is useful for calibration but the two approaches serve fundamentally different functions.

5. Nitrogen By-Products: Opportunity and Risk

The production of glycine and urea as CO2 reduction by-products is unusual among photocatalytic systems. Most MOF and semiconductor photocatalysts reduce CO2 to carbon monoxide (CO), methane (CH4), or methanol (CH3OH) — products that require collection systems to be useful. GL-1's nitrogen-containing products dissolve in rainwater and passively enrich surrounding soil, creating a secondary value proposition.

However, nitrogen loading is environmentally regulated. In the European Union, the Nitrates Directive (91/676/EEC) limits nitrogen application in vulnerable zones. In the Netherlands specifically, the stikstofcrisis has made any additional nitrogen source politically sensitive. At 200g CO2/m²/year, the corresponding nitrogen output is approximately 20–40g N/m²/year in the form of glycine and urea. For a single building, this is negligible. For city-scale deployment across millions of square metres, cumulative nitrogen loading into drainage systems requires assessment.

6. From Laboratory to Building Surface: Scaling Challenges

The path from a laboratory MOF photocatalyst to a commercial building coating crosses several engineering gaps that have historically prevented MOF commercialisation in coatings applications.

Challenge	Lab conditions	Real-world conditions
Gas delivery	Controlled CO2 flow to MOF surface	Diffusion from ambient air through polymer matrix
Light delivery	Uniform illumination at known intensity	Variable sun angle, shading, cloud cover, night
Moisture	Controlled humidity chamber	Rain, dry spells, condensation, freeze-thaw
Temperature	Constant or programmed	Diurnal and seasonal cycling, −10 to +40°C
Durability	Weeks to months	5–15 years (paint cycle) or 30+ years (concrete)
MOF synthesis	Milligrams to grams	Tonnes per year (commercial production)

Figure 3: Lab-to-field translation gaps for MOF photocatalytic coatings

The most critical gap is synthesis scale-up. MOF synthesis at laboratory scale uses precise control of temperature, solvent composition, and reaction time. At commercial scale, maintaining this precision across larger reactor volumes is the central engineering challenge. Variations in synthesis conditions produce MOFs with different crystallinity, pore structure, and catalytic activity — quality consistency is the make-or-break requirement for commercial viability.

7. Regulatory Implications

Surface-applied photocatalytic carbon capture intersects several regulatory domains. EU CSRD requirements (phased implementation 2024–2028) create demand for measurable, verifiable carbon reduction. If GL-1's absorption rate can be independently certified, coated surface area becomes a quantifiable Scope 3 reduction measure for building owners and materials companies.

REACH registration is mandatory for any novel chemical substance manufactured or imported above 1 tonne per year in the EU. The MOF compound, the polymer carrier, and the by-products (glycine, urea at trace concentrations) all require assessment. Environmental fate studies must demonstrate that degradation products do not accumulate or cause harm — particularly relevant for the nitrogen compounds given Dutch regulatory sensitivity.

The EU CBAM (Carbon Border Adjustment Mechanism) indirectly supports demand by increasing the cost of carbon-intensive imported building materials. European-manufactured GL-1-enhanced products would benefit from CBAM's competitive positioning of low-carbon alternatives.

8. Conclusions

MOF-based photocatalytic carbon capture on building surfaces is a scientifically plausible approach to distributed atmospheric CO2 removal. The mechanism is well-characterised at the molecular level: visible-light-driven electron transfer at titanium metal centres reduces adsorbed CO2 to nitrogen-containing organic compounds. Laboratory performance (~200g CO2/m²/year) places MOF surface capture in the same order of magnitude as biological photosynthesis per unit area.

The critical uncertainties are engineering, not science. Whether the chemistry that works on a gram of MOF in a laboratory gas flow also works on a kilogram of MOF dispersed in a polymer carrier on a weathered building surface is an open question. The answer depends on maintaining gas access through the polymer matrix, sustaining catalytic activity across temperature and humidity cycles, and achieving consistent MOF synthesis quality at production scale.

If these engineering challenges are resolved, surface-applied photocatalytic carbon capture could provide a meaningful complement to industrial DAC and nature-based solutions — not as a replacement, but as a distributed, passive, infrastructure-integrated approach that turns the built environment's vast surface area from a carbon source into a partial carbon sink.

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