

Alchemy reimagined: photocatalysis using anthropogenic waste materials

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A fundamental goal of synthetic chemistry is the transformation of lower value molecular feedstocks into more complex substances of greater value. Anthropogenic waste gases are underappreciated and sustainable reagents for reactions and herein we explore the diverse reactivities afforded to these molecules by harnessing the powerful activating ability of photocatalysis.

Re-evaluating the value of anthropogenic waste materials

The idea of converting lower value materials into substances of greater worth has long captivated humanity's imagination. Biblical fables recount the turning of water into wine, while alchemists dreamt of converting base metals into gold. The synthetic organic chemistry community follows a more realizable version of the alchemist's dream: the conversion of small molecule reagents into larger molecular structures, typically of higher value. The discovery of petrochemical-derived small molecules fuelled the exponential explosion of research into a menagerie of methods for synthesising complex molecules for agrochemicals, pharmaceuticals, and a multitude of other industries that positively impact the quality of our lives. However, we must not be limited to petrochemical-based reagents as this is unsustainable. It is time to expand our horizons and find new, sustainable chemical precursors. What more poetic solution

exists than the synthetic conversion of anthropogenic waste gases (harmful human waste released into the atmosphere) into valuable reagents and products. Carbon dioxide (CO₂), sulfur dioxide (SO₂), and methane are produced on colossal scales by our society and their presence in the atmosphere contributes to the inexorable degradation of our planet. These gases are cheap, readily available, and practically inexhaustible reagents for chemical reactions. Unfortunately, the activation of these molecules is far from trivial. Thermally driven, harsh, and energy-intensive conditions would conventionally be necessitated. However, nature provides many examples of how the activation of challenging substrates can be accomplished under much milder conditions; for example, plants convert abundant water and CO₂ into the more valuable products glucose and oxygen via photosynthesis. The analogous process for synthetic chemists involves using light energy to drive photochemical reactions, frequently featuring a photocatalyst (Box 1) [1]. Photocatalysis is a key tool for humanity's 21st century alchemy of anthropogenic waste gases [2,3] and herein the principal methods for the photocatalytic utilisation of CO₂, SO₂, and methane are summarised (Figure 1).

Carbon dioxide

Four distinct photocatalytic approaches are available for using CO₂ as a reagent. The first involves converting CO₂ into other small molecules, such as carbon monoxide (CO), formate, and methanol. Although this approach is primarily focused on the large-scale conversion of CO₂ using heterogeneous photocatalytic systems, it is also possible to directly use the *in situ* generated molecule in subsequent reactions. For instance, carbonylation reactions using CO as a C1 synthon are valuable transformations, but CO is a toxic, challenging to handle gas. Rather than storing dangerous gases such as CO, the desired substrate could instead be generated on demand from more benign CO₂

using photocatalysis. Rhenium(I) carbene complexes, such as [Re(bpy)(CO)₃]Cl, can accomplish this photocatalytic conversion [4,5] and in one such report, CO₂ was transformed into CO over 10 h before being passed through a steel pipe to a connected reactor to take part in a palladium-catalysed carbonylative Suzuki-Miyaura coupling [5].

An alternative methodology involves the direct photoreduction of CO₂ to its reactive radical anion. This extremely challenging process ($E_{\text{red}} = -2.21$ V vs. SCE in DMF) is achievable using strongly reducing photocatalysts such as *p*-terphenyl [$E_{(\text{PC}/\text{PC}\cdot^-)} = -2.63$ V vs. SCE in DMF] [6,7]. The CO₂^{•-} radical anion can then couple with another radical species to yield carboxylated products. As an example, following photoexcitation, the electronically excited *p*-terphenyl (*p*-terphenyl*) can oxidise an amine to generate an α -amino radical and the highly reducing *p*-terphenyl^{•-} species [6]. CO₂ is then reduced and subsequent radical coupling generates the amino acid product.

The third approach exploits the weakly electrophilic carbon centre in CO₂. *In situ* generated carbanions can partake in nucleophilic attack of CO₂ dissolved in solution to form carboxylic acids. The photocatalyst is responsible for reducing the initial substrate or an intermediate radical species to generate the required nucleophilic centre. An example is the addition of CO₂ to imines to generate α -amino acids [8]. Reductive quenching of the photocatalyst by a sacrificial amine electron donor produces the reduced photocatalyst that is then capable of donating an electron to the imine. This generates a nucleophilic α -carbon, which attacks CO₂ to afford the carboxylated target.

Finally, CO₂ has been used in metallaphotoredox catalysis reactions, where the combination of a photocatalyst

Box 1. A brief introduction to photocatalysis

A photocatalyst is a molecule or material that can absorb light to access higher energy electronically excited states. This embedded energy can then drive energy and electron transfer reactions to activate challenging substrates, allowing access to a diverse range of organic transformations. Photocatalysts are typically designed to absorb visible light, meaning they can be selectively photoexcited in reactions. Near-UV-absorbing photocatalysts are also useful, particularly in the context of the direct activation of thermodynamically challenging substrates such as CO₂ and methane. Mechanistically, a photocatalyst in its excited state can transfer energy to an organic substrate to promote it to a more reactive excited state, or it can promote the generation of radicals on the organic substrates via single electron transfer, accessing so-called oxidative or reductive quenching cycles (Figure 1).

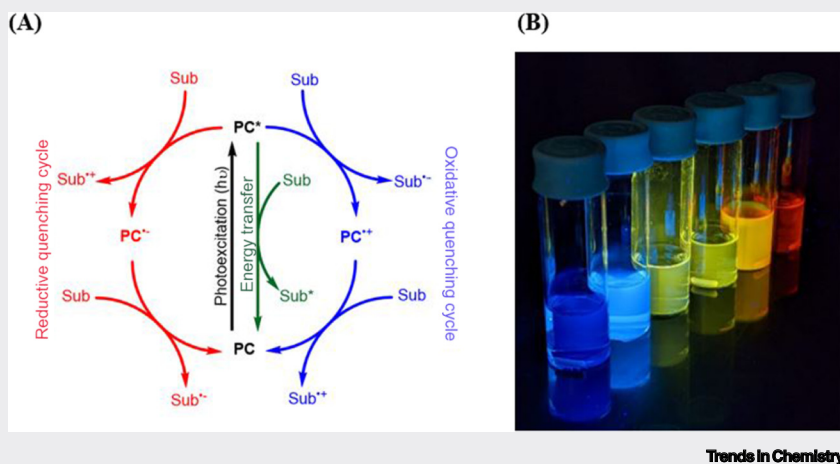


Figure 1. Visualising photocatalysis as a tool for organic synthesis. (A) The three possible prominent reaction pathways operative during photocatalysis reactions: the reductive quenching cycle (red), the oxidative quenching cycle (blue), and energy transfer for substrate sensitisation (green). (B) Six different visible light-absorbing photocatalysts being photoexcited by an external light source. Abbreviations: PC, photocatalyst; Sub, organic substrate.

and a transition metal cocatalyst can enable a diverse range of cross-coupling products [9,10]. Within a generalised framework for these reactions, the cocatalyst is responsible for coordinating an organic substrate and CO₂ to bring them into proximity, while the photocatalyst feeds electrons to the cocatalyst to facilitate dissociation and turn over the catalytic cycle. This is, perhaps, the most flexible and extensively investigated approach for photocatalytic CO₂ utilisation, with a diverse array of reactions reported [10].

Despite the stereotypical poor reactivity of CO₂, photocatalysis has emerged as a flexible tool for using this valuable C1 synthon across a diverse range of approaches. Further innovations, particularly those exploiting metallaphotoredox

catalysis, are expected to emerge, but we would also like to highlight again the methodology involving the conversion of CO₂ to other substrates, such as CO, as this holds potential for expanding the range of functionalities that can be generated beyond carboxylic acids and their derivatives.

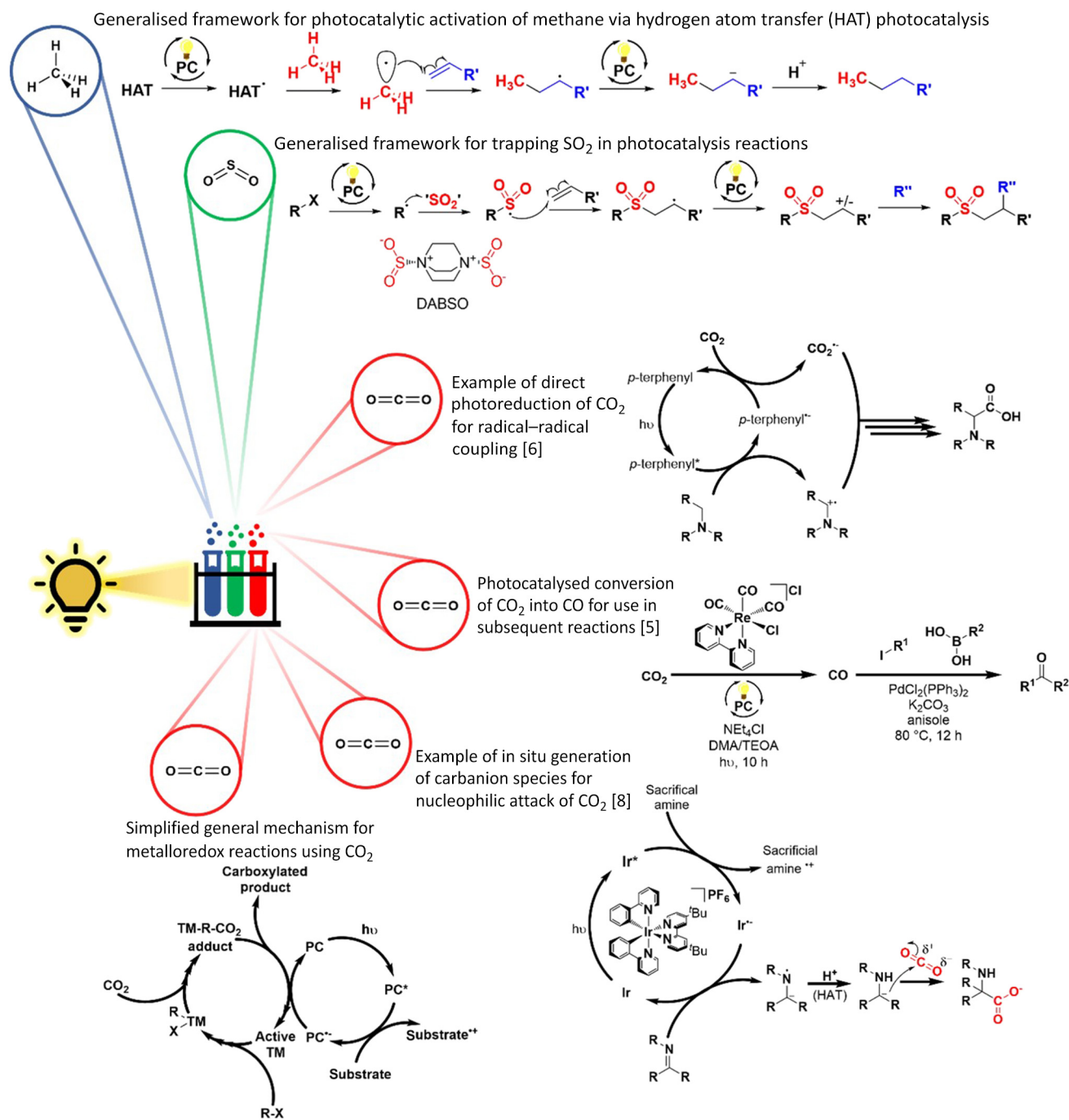
Sulfur dioxide

Synthetic applications of SO₂ have primarily focused on the generation of sulfones, which are valuable motifs in pharmaceutical targets [11]. The principal challenge with SO₂ utilisation is its toxic and gaseous nature, and a solid surrogate synthesisable from gaseous SO₂ would therefore be an appealing alternative synthon that would simplify storage and handling. Fortunately, such a surrogate exists in the form of DABSO, the bench-stable SO₂

adduct of 1,4-diazabicyclo[2.2.2]octane, DABCO•(SO₂)₂. DABSO has been used to trap *in situ* generated radicals in a wide array of photocatalysis reactions. Potassium alkyltrifluoroborate salts, alkyl iodides, Hantzsch esters, diaryliodonium salts, and aryl diazonium salts are just a small selection of substrates that can form carbon-centred radicals for subsequent trapping by SO₂ to generate intermediate sulfonyl radicals. These can then couple to radical acceptors such as alkenes or alkynes [3]. The photocatalyst can play several different mechanistic roles within these reactions, including generating the initial radical and being responsible for reducing or oxidising intermediate radicals to enable the final cyclisation or functionalisation step. This chemistry is versatile in terms of the scope of radical precursors and acceptors that can be employed, but further explorations into new types of radicals that can react with SO₂ would be an exciting expansion of this sulfur synthesis toolbox. For example, nitrogen-centred radicals generated from photocatalysis have seen limited use in this field and could potentially enable the synthesis of other valuable species such as sulfonamides.

Methane

The activation of strong C–H bonds is an infamous problem in organic chemistry due to their stability. Direct photoinduced electron transfer is not currently a viable route for the cleavage of this bond in methane, but photocatalysis can still play a pivotal role in activating this substrate when synergistically combined with hydrogen atom transfer (HAT) catalysts. HAT catalysts can rip a hydrogen atom directly from methane to generate a methyl radical, which can be trapped by organic substrates to yield methylated products. Several catalytic systems have recently been reported for this transformation [12–14]. Cerium-based photocatalysts have been used to generate highly electrophilic alkoxy radicals from 2,2,2-trichloroethanol, which acts as the HAT



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Figure 1. Generalised scheme showing the available approaches for photocatalysis reactions with carbon dioxide, sulfur dioxide, and methane. Abbreviations: HAT, hydrogen atom transfer catalyst; PC, photocatalyst; TM, general transition metal catalyst. See [5,6,8].

catalyst [12]. Alternatively, need for a second additive, as it is a versatile Photoexcitation leads to the liberation of a tetrabutylammonium decatungstate can HAT catalyst in its excited state [13]. Iron(III) chlorine radical, a potent HAT catalyst for generate the methyl radical without the chloride can act in a similar manner [14]. the abstraction of hydrogen from methane,

with the desired carbon-centred radical being trapped by electron-deficient alkenes. Unfortunately, more widespread adoption of methane-derived methylations has so far been limited, primarily as a function of the high pressures necessitated, around 45–50 bar, using specialised photoreactors or continuous flow systems due to the low solubility of methane in suitable organic solvents. Thus, this chemistry is underexplored and limited in terms of the radical acceptor scope, but further exploitation of these technologies should expand the usefulness of this approach.

Concluding remarks

This overview has highlighted examples of photocatalytic activation of three abundant anthropogenic waste gases for the functionalization of larger molecules. We hope this brief account provides an impetus to expand research into the use of these substrates. In particular, the exploration of using *in situ* generated products from CO₂ reduction in subsequent reactions holds potential for using a benign and abundant starting material as a surrogate for more hazardous reagents. In addition, the exploration of new radical precursors and acceptors for trapping by SO₂, as well as the subsequent sulfonyl radical, would expand the versatility of this chemistry even further. Finally, the activation of methane could be expediated by the increased prevalence of continuous flow photoreactors [12]. Perhaps this discussion can also inspire the creative utilisation of other abundant raw materials

as novel reagents. For example, elemental sulfur can easily be reduced by conventional photocatalysts and could be used as an abundant and less hazardous alternative sulfur source for reactions than conventional reagents such as thiols or thioacids [15].

Research within this field illustrates an exciting approach to further expand upon the 21st century alchemist's dream by harnessing the versatile reactivities available to photocatalysis.

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Declaration of interests

The authors have no interests to declare.

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References

1. Bryden, M.A. and Zysman-Colman, E. (2021) Organic thermally activated delayed fluorescence (TADF) compounds used in photocatalysis. *Chem. Soc. Rev.* 50, 7587–7680
2. Cai, B. *et al.* (2021) Light-promoted organic transformations utilizing carbon-based gas molecules as feedstocks. *Angew. Chem. Int. Ed.* 60, 18950–18980
3. Ye, S. *et al.* (2020) Photoinduced sulfonylation reactions through the insertion of sulfur dioxide. *Eur. J. Org. Chem.* 2020, 1274–1287

4. Feng, Y. *et al.* (2021) Study of Re(I) carbene complexes for photocatalytic reduction of carbon dioxide. *Energy Fuel* 35, 19170–19177
5. He, X. *et al.* (2018) Integrative photoreduction of CO₂ with subsequent carbonylation: photocatalysis for reductive functionalization of CO₂. *ChemSusChem* 11, 3382–3387
6. Seo, H. *et al.* (2017) Photoredox activation of carbon dioxide for amino acid synthesis in continuous flow. *Nat. Chem.* 9, 453–456
7. Matsuoka, S. *et al.* (1992) Photocatalysis of oligo (p-phenylenes): photochemical reduction of carbon dioxide with triethylamine. *J. Phys. Chem.* 96, 4437–4442
8. Fan, X. *et al.* (2018) Visible light-promoted CO₂ fixation with imines to synthesize diaryl α -amino acids. *Nat. Commun.* 9, 4936
9. Chan, A.Y. *et al.* (2022) Metallaphotoredox: the merger of photoredox and transition metal catalysis. *Chem. Rev.* 122, 1485–1542
10. Zhang, Z. *et al.* (2020) Visible-light-driven catalytic reductive carboxylation with CO₂. *ACS Catal.* 10, 10871–10885
11. Scott, K.A. and Njardarson, J.T. (2018) Analysis of US FDA-approved drugs containing sulfur atoms. *Top. Curr. Chem.* 376, 1–34
12. Hu, A. *et al.* (2018) Selective functionalization of methane, ethane, and higher alkanes by cerium photocatalysis. *Science* 361, 668–672
13. Laudadio, G. *et al.* (2020) C(sp³)-H functionalizations of light hydrocarbons using decatungstate photocatalysis in flow. *Science* 369, 92–96
14. Zhang, Q. *et al.* (2022) Iron-catalyzed photoredox functionalization of methane and heavier gaseous alkanes: scope, kinetics, and computational studies. *Org. Lett.* 24, 1901–1906
15. Murakami, S. *et al.* (2021) Photocatalytic activation of elemental sulfur enables a chemoselective three-component thioesterification. *Org. Lett.* 23, 7650–7655