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Bioinspired Supercharging of Photoredox Catalysis for Applications in Energy and Chemical Manufacturing

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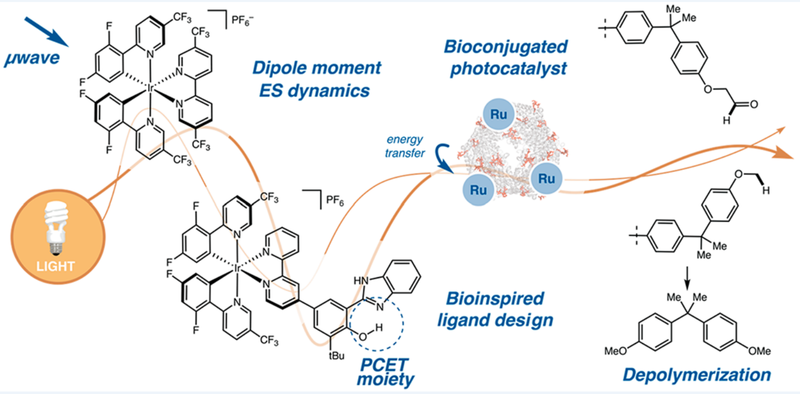

CONSPECTUS: For more than a decade, photoredox catalysis has been demonstrating that when photoactive catalysts are irradiated with visible light, reactions occur under milder, cheaper, and environmentally friendlier conditions. Furthermore, this methodology allows for the activation of abundant chemicals into valuable products through novel mechanisms that are otherwise inaccessible. The photoredox approach, however, has been primarily used for pharmaceutical applications, where its implementation has been highly effective, but typically with a more rudimentary understanding of the mechanisms involved in these transformations. From a global perspective, the manufacture of everyday chemicals by the chemical industry as a whole currently accounts for 10% of total global energy consumption and generates 7% of the world's greenhouse gases annually. In this context, the Bio-Inspired Light-Escalated Chemistry (BioLEC) Energy Frontier Research Center (EFRC) was founded to supercharge the photoredox approach for applications in chemical manufacturing aimed at reducing its energy consumption and emissions burden, by using bioinspired schemes to harvest multiple electrons to drive endothermically uphill chemical reactions. The Center comprises a diverse group of researchers with expertise that includes synthetic chemistry, biophysics, physical chemistry, and engineering. The team works together to gain a deeper understanding of the mechanistic details of photoredox reactions while amplifying the applications of these light-driven methodologies.

In this Account, we review some of the major advances in understanding, approach, and applicability made possible by this collaborative Center. Combining sophisticated spectroscopic tools and photophysics tactics with enhanced photoredox reactions has led to the development of novel techniques and reactivities that greatly expand the field and its capabilities. The Account is intended to highlight how the interplay between disciplines can have a major impact and facilitate the advance of the field. For example, techniques such as time-resolved dielectric loss (TRDL) and pulse radiolysis are providing mechanistic insights not previously available. Hypothesis-driven photocatalyst design thus led to broadening of the scope of several existing transformations. Moreover, bioconjugation approaches and the implementation of triplet−triplet annihilation mechanisms created new avenues for the exploration of reactivities. Lastly, our multidisciplinary approach to tackling real-world problems has inspired the development of efficient methods for the depolymerization of lignin and artificial polymers.

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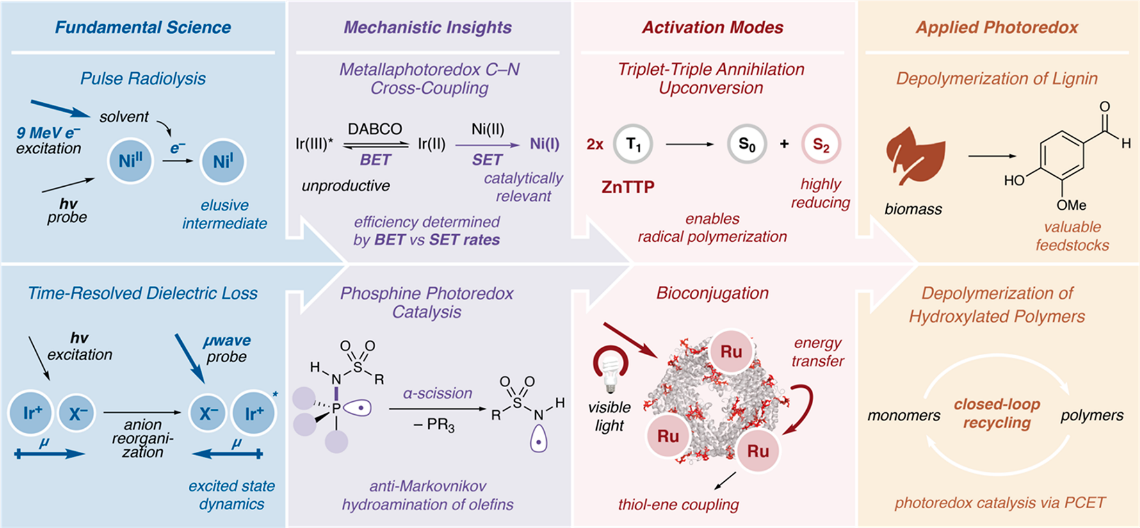

Figure 1. Examples of BioLEC's contributions to the advancement of photoredox catalysis. From left to right: use of spectroscopic techniques as tools to increase fundamental understandings, discovery of new reactivities guided by mechanistic insights, strategies to circumvent nonspecific absorption issues, and depolymerization of native lignin and hydroxylated polymers via photoredox catalysis.

redox Catalysts.. *Nat. Chem.* **2022**, 10.1038/s41557-022-00911-6.[1] *This paper describes the application of time-resolved dielectric loss spectroscopy to probe photoinduced dipole changes in an Ir photocatalyst to characterize the role of its counterion on excited state reactivity.*

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- Nguyen, S. T.; McLoughlin, E. A.; Cox, J. H.; Fors, B. P.; Knowles, R. R. Depolymerization of Hydroxylated Polymers via Light-Driven C-C Bond Cleavage. *J. Am. Chem. Soc.* **2021**, *143*, 12268−12277.[4] *This paper describes a photocatalytic approach for the depolymerization of hydroxylated polymers via a PCET step that leads to C−C bond cleavage and generation of well-defined products that can be functionalized and repolymerized to enter a closed recycling loop.*

1. INTRODUCTION

The search for more efficient, cost-effective, and green manufacturing technologies is of paramount importance as global energy demands continue to increase. Chemical manufacturing alone accounts for 10% of total global energy consumption and is responsible for 7% of the world's greenhouse gas emissions.[5] Fossil fuels remain the most widely employed source of energy to generate the high temperatures and pressures required to manufacture desired products. Therefore, the use of carbon-neutral sources of energy could have a tremendous impact at the global scale in energy-saving strategies and in reducing the chemical manufacturing industry's carbon footprint.[6] Fossil fuels are often also the precursors to starting materials for the production of everyday chemicals. Transformation of abundant biomass to feedstock chemicals could alleviate the need for nonrenewable sources.

Solar energy is an attractive alternative to fossil fuels, as it is carbon-neutral and enough solar energy to power humanity for an entire year reaches the earth every hour.[7] The key setback is not the lack of energy but the means to utilize and convert this power toward useful pathways. Over the last few decades, scientists have been improving the viability and energy conversion efficiency (averaging around 30%)[8] of photovoltaic cells, which can provide electrical power to homes and businesses. Solar energy can similarly be converted to chemical energy when used to excite light-absorbing catalysts and take the place of thermal energy in chemical syntheses in a manner akin to that of photosynthesis.[9,10]

In contrast to traditional synthetic routes, photoredox and metallaphotoredox catalysts utilize light to drive reactivity under very mild conditions that would otherwise be inaccessible or very costly.[11] These methodologies have been mostly employed in the synthesis of small molecules, such as pharmaceuticals and perfumes, but have yet to be translated into mass production of feedstock chemicals or their valorization at large scale.[12] Photocatalytic methods, though highly efficient and mild, proceed via very intricate and meticulously crafted mechanisms that are not easily applicable into broad scope large scale reactions.[9,10] Translating these technologies to a wider range of chemical manufacturing applications therefore requires new approaches that make the reaction steps more robust and more efficient, as well as the underlying mechanistic knowledge to target these steps. Such efforts are intrinsically highly collaborative as tools and techniques from multiple fields must be utilized. In this context, the Bioinspired Light-Escalated Chemistry (BioLEC) Energy Frontier Research Center was founded as an interdisciplinary conglomerate of researchers (physicists, physical chemists, biochemists, organic chemists, and engineers) that synergize to advance photoredox catalysis (Figure 1).

This Account summarizes recent collaborative accomplishments in photoredox catalysis through mechanistic understanding, the development of new reactivities, novel applications of new and existing reactions, and the utilization of photoredox catalysis to tackle industrially relevant problems (Figure 1). We first focus on fundamental studies of photocatalysts and intermediates proposed in traditional photoredox catalytic cycles. Then, we discuss the development of new reactions and the optimization of already existing reactions guided by mechanistic studies. Next, we address the development of unique light-harvesting strategies to drive reactivity. Finally, we show how developed methodologies can transform highly available biomass into chemical feedstocks, and how a light-mediated depolymerization mechanism degraded hydroxylated polymers to yield well-defined monomers that can be later functionalized to enter a much sought-after closed-loop recycling cycle without generating stoichiometric waste.

2. SPECTROSCOPIC TOOLS AS PROBES TO INCREASE FUNDAMENTAL UNDERSTANDINGS OF PHOTOREDOX CATALYSIS

Photocatalytic mechanisms are often proposed based on yield analysis (NMR), Stern−Volmer quenching, and electrochemistry. However, these analytical methods generally do not enable a specific step of a complex mechanism to be interrogated, particularly where short-lived reactive intermediates are invoked. Through collaborations, we employed three time-resolved spectroscopies to probe cutting-edge catalytic mechanisms with greater control over species generation and temporal resolution: pulse radiolysis (PR), time-resolved dielectric loss (TRDL), and photoinduced transient absorption (TA) spectroscopy.

2.1. Pulse Radiolysis

The emerging field of metallaphotoredox[11,13−15] chemistry is exemplified in the Ir/Ni dual photocatalytic system used in cross-coupling reactions to form new C−C and C−heteroatom bonds.[16−18] The first step in many of these reactions is electron transfer from the Ir(III)* photocatalyst to the Ni(II) precatalyst (e.g., (dtbbpy)$NiBr_2$). However, ambiguity remained as to which Ni species is involved in the catalytic cycle, and studying the reduction of (dtbbpy)$NiBr_2$ with electrochemistry shows irreversible behavior due to the two-electron reduction followed by subsequent chemistry.[19] Therefore, a different approach was needed. PR is a powerful technique that has yet to be applied in metallaphotoredox catalysis. PR can be thought of as "electrochemistry without the electrode," enabling rapid (nanosecond) one-electron reduction of Ni(II) in solution to unambiguously generate Ni(I) (see Figure 2A).

A collaboration between the MacMillan group and Brookhaven National Laboratory (BNL) generated Ni(I) with PR and then studied its reactivity with TA spectroscopy.[20] PR initiates by sending a short pulse (~10 ps) of high energy electrons (9 MeV) through a solution, ionizing the solvent.[21] Within nanoseconds, charges or excited states can transfer to solutes to create intermediates present in photocatalytic cycles.[22] By comparing the Ni(I) spectrum to that obtained with spectroelectrochemistry, we discovered that here, Ni(0) must comproportionate to two Ni(I) molecules. Furthermore,

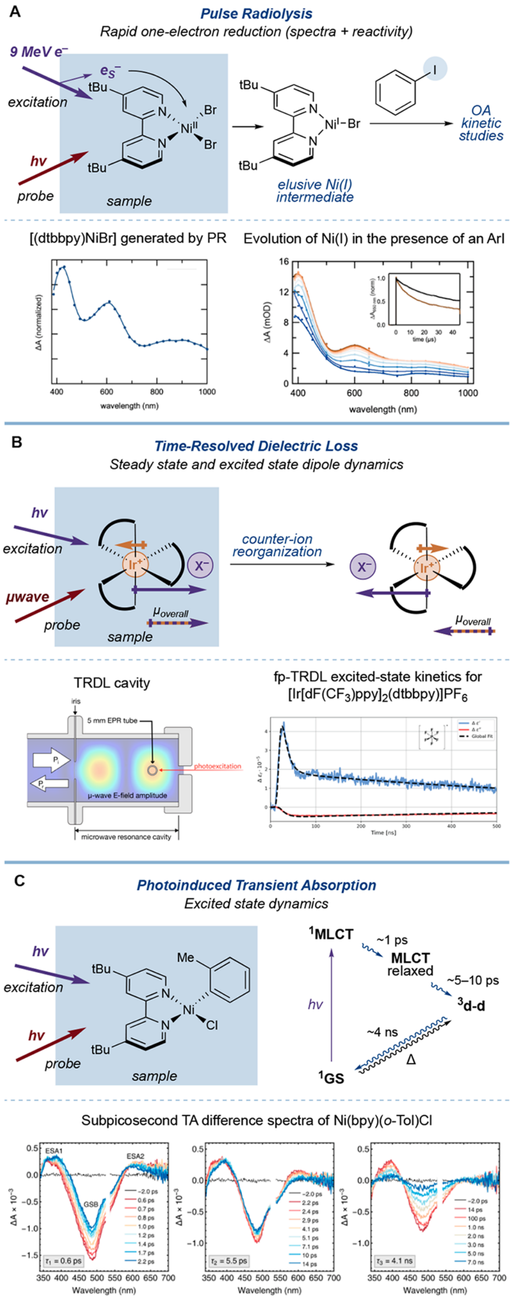

Figure 2. Application of time-resolved spectroscopies to understand fundamental processes in photoredox catalysis. (A) Pulse radiolysis enables the rapid one-electron reduction of Ni(II) in solution to help elucidate the mechanism of oxidative addition in Ir/Ni dual photocatalytic systems. Adapted from ref 20. Copyright 2021 American Chemical Society. (B) Time-resolved dielectric loss spectroscopy measures the dynamics of the dipole of a common Ir photocatalyst during photoexcitation and finds the counterion to play an important role in excited state reactivity. Adapted with permission from ref 1. Copyright 2022 Springer Nature Limited. (C) Photoinduced transient absorption studies the evolution of the excited state of a Ni photocatalyst that is capable of Ni−Ar bond homolysis from direct excitation. Adapted from ref 32. Copyright 2020 American Chemical Society.

we measured rates of reaction of Ni(I) with a series of electronically distinct aryl iodides. Rates for oxidative addition ranged from 1.3×10^4 to 2.4×10^5 M^{-1} s^{-1} depending on the

Hammett value of the para substituent, σ_{para}. Finally, the $[(\text{dtbbpy})\text{NiBr}]_2$ dimer was found to be unreactive with iodobenzene and determined to be mechanistically irrelevant. By generating and characterizing the Ni(I) intermediate, PR helped elucidate this oxidative addition process under synthetically relevant conditions. These studies are of general relevance in Ir/Ni metallaphotoredox catalysis as the formation of elusive Ni(I) species is often postulated as it is also evidenced in the arylation of secondary amines discussed in section 3.

PR is well-suited to such mechanistic studies as it can generate a diverse selection of reactive intermediates such as neutral and charged radicals, H-adducts, triplet excited states, and radical ion pairs. PR can also generate potent redox agents, from the solvated electron to the solvent radical cation, enabling the activation of substrates out of reach to most single-photon photocatalysts. These studies improve fundamental understanding of complex photoredox systems, potentially leading to improved efficiency.

2.2. Time-Resolved Dielectric Loss Spectroscopy

Transition metal complexes are popular for photocatalysis because the formation of their long-lived triplet charge transfer states can drive chemistry. Since many TM complexes are ions, it is likely that the inert counterions can be tuned to enhance photocatalytic reactivity or selectivity. However, the dynamic behavior of counterions following photoexcitation had yet to be studied, as few methods exist to directly characterize ion pairing, let alone response to perturbation.[23] We probed these dynamic counterion effects for the first time and related them to chemical reactivity, providing information about the unique role counterions can play.

TRDL spectroscopy is sensitive to dipoles, whereas other time-resolved spectroscopic methods may probe electronic transitions, bond vibrations, or spin states. Heteroleptic TM complexes exhibit dipole moments in the ground and excited states that can be monitored with TRDL. A collaboration led by the National Renewable Energy Laboratory (NREL) with the Scholes, McCusker, and Knowles groups applied this technique to the popular photocatalyst $[\text{Ir}[\text{dF}(\text{CF}_3)\text{ppy}]_2(\text{dtbpy})]^+\text{X}^-$ and observed the effect of a weakly ($\text{X}^- = \text{BAr}^{\text{F}}{}_4{}^-$) versus tightly ($\text{X}^- = \text{PF}_6{}^-$) bound counterion on the dipole and excited-state chemical reactivity.[1]

Ir complexes were measured in a microwave cavity (Figure 2B) coupled to a waveguide apparatus which can record the time-dependence of dielectric properties of the solution (real and imaginary). Computational modeling of the cavity response gives the ground state dipole and shows its evolution in the excited state. Dipole dynamics show a sub-nanosecond reorganization of the counterion in response to the dipole change within the complex. Substituting the $\text{PF}_6{}^-$ counterion with the weakly associating $\text{BArF}_4{}^-$ prevented this reorganization and reduced the dipole of the MLCT state. Stern−Volmer quenching studies showed a corresponding decrease in the rates of substrate reduction and increase in the rates of oxidation for $\text{PF}_6{}^-$ relative to $\text{BArF}_4{}^-$.

TRDL is a particularly powerful tool to probe the effect of charge distribution on excited-state reactivity, especially in cases where traditional spectroscopy cannot. We now recognize that the identity of the inert counterion can be optimized when developing a new reaction, particularly in low polarity solvents susceptible to ion pairing effects.

2.3. Photoinduced Transient Absorption Spectroscopy

Ni-photoredox catalysis has also been proposed to proceed via direct photoexcitation[24−26] or energy transfer based on product analysis.[27−31] Scholes, Castellano, Doyle, and co-workers investigated a series of photoexcited $\text{Ni}(^{\text{R}}\text{bpy})(\text{Ar})\text{Cl}$ derivatives with TA spectroscopy, which can directly generate and probe excited-state dynamics.[32] Spectral analysis of $\text{Ni}(^{t\text{-Bu}}\text{bpy})(o\text{-Tol})\text{Cl}$ (Figure 2C) revealed an initial MLCT state evolves into a ^{3}d-d excited state over the first 15 ps ($\tau = 5.5$ ps). The excited Ni(II) complexes then undergo Ar−Ni bond homolysis to generate aryl radicals and Ni(I), which offers a novel mechanism to initiate catalysis by Ni(I) in the absence of an exogenous photocatalyst.[33] TA spectroscopy provided vital information that will enable this new mode of reactivity to be exploited. Similar spectroscopic methods have been applied to Ni-photoredox to differentiate energy versus electron transfer in Ni-mediated C−O coupling[29] and dark Ni(I)/Ni(III) cycles in C−N cross-coupling reactions.[34] Overall, we demonstrated that collaborative efforts using unique spectroscopic methodologies provide valuable insight into, and potentially inform future, photocatalytic reactions. More sophisticated techniques, such as multidimensional spectroscopy, could potentially further disentangle the ultrafast mechanisms behind the initial steps of photoredox catalysis.

3. DEVELOPMENT OF NEW REACTIVITIES GUIDED BY MECHANISTIC INSIGHTS

Gaining mechanistic insight into the elementary steps of photoredox catalysis facilitates the advancement and development of new and more efficient reactions in organic synthesis which translates to other fields. The spectroscopic techniques discussed in the previous section enable in-depth mechanistic investigations of elementary steps in photocatalyzed reactions. These mechanistic understandings can be leveraged and translated into the development of new reactivities or an improvement of existing ones through interdisciplinary collaborative efforts.

A notable example of how mechanistic understandings can lead to the improvement of existing reactions is the design of a bioinspired Ir complex with a proton-coupled electron transfer (PCET)-based ligand for the reductive cleavage of *N*-(acyloxy)-phthalimide redox-active esters (Figure 3A).[2] These efforts were carried out by the Knowles, Moore, Scholes, and Rumbles groups in 2021. A number of photocatalytic transformations suffer from limited scopes and/or quantum efficiencies due to charge recombination (CR) issues between the oxidized/reduced photocatalyst and the radical species being formed.[35] In order to increase reaction efficiencies, the rate of the forward reaction must be such that it is competitive with the rate of bimolecular CR processes. Inspired by electron relays present in Photosystem II that can transfer oxidizing/reducing equivalents as a means to suppress CR events,[36] we designed a ligand that contains a BIP (benzimidazole-phenol) moiety that is able to, upon excitation of the photocatalyst, undergo a PCET process to populate an intramolecular charge separated state (CSS) that inhibits the recombination of the subsequent intermolecular CSS (Figure 3B). Utilizing the methyl viologen dication as a substrate surrogate, we were able to demonstrate that the CR process is, in fact, reduced by 24-fold when compared to the parent photocatalyst, $[\text{Ir}(\text{dF}(\text{CF}_3)\text{-ppy})_2(\text{bpy})](\text{PF}_6)$. Excitingly, the CR reduction led to a 2-fold increase in quantum

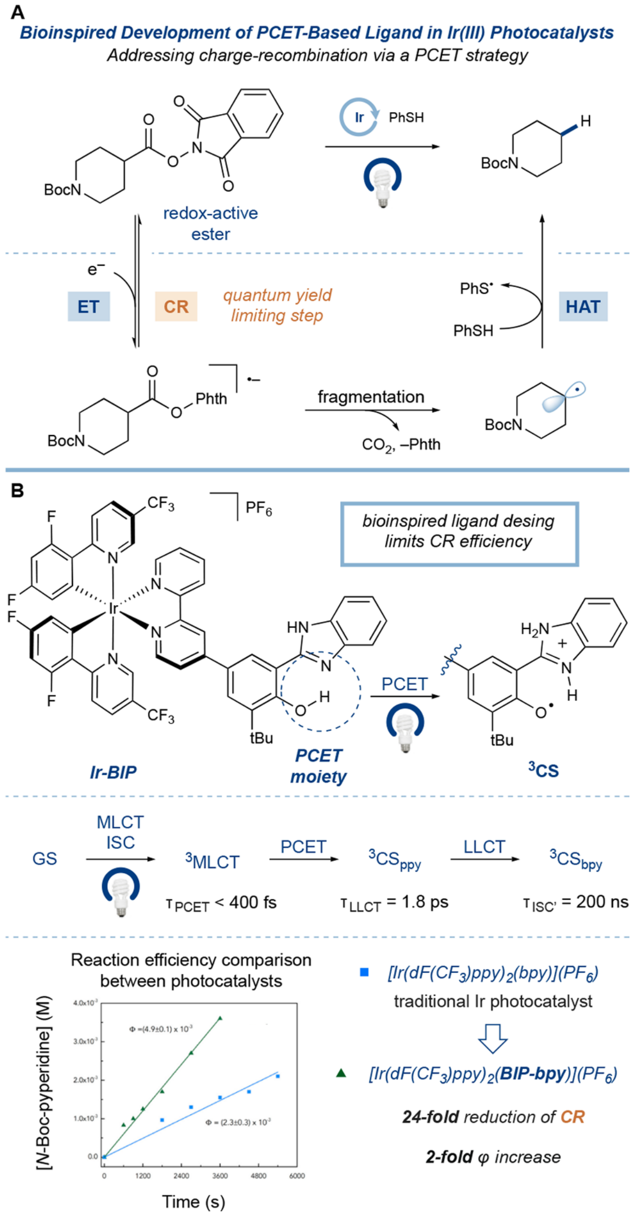

Figure 3. PCET-based ligand to address intramolecular charge recombination. (A) General reaction and mechanism for the reduction of redox-active esters. (B) Ligand design employed to hinder intermolecular charge recombination and comparison of reaction efficiencies of the traditional $[Ir(dF(CF_3)\text{-}ppy)_2(bpy)](PF_6)$ photocatalyst against $[Ir(dF(CF_3)\text{-}ppy)_2(BIP\text{-}bpy)](PF_6)$. Adapted from ref 2. Copyright 2021 American Chemical Society.

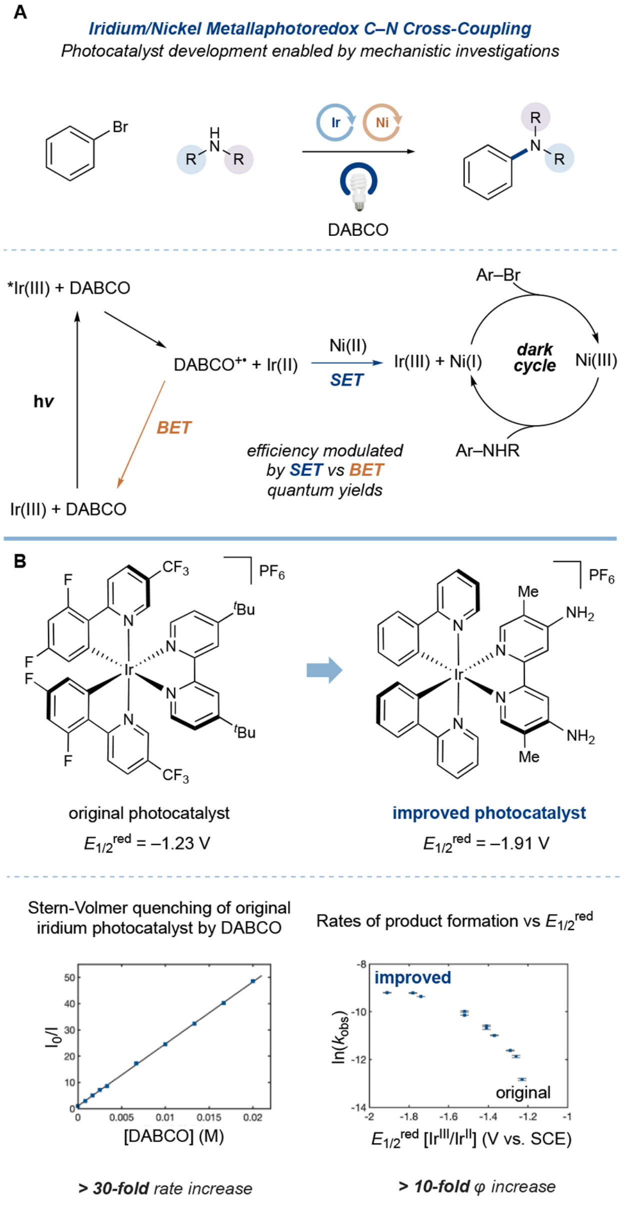

Figure 4. Photocatalyst redesign strategies for C–N cross-coupling. (A) General reaction and mechanism of a C–N coupling reaction. (B) Photocatalyst redesign, Stern–Volmer plot for DABCO quenching of the photocatalyst, and rates of product formation of a series of Ir photocatalyst as a function of their redox potentials. Adapted from ref 34. Copyright 2020 American Chemical Society.

yield efficiency for the photocatalytic reduction of a *N*-(acyloxy)phthalimide redox-active ester.

In 2020, the MacMillan and Scholes groups collaborated to investigate the mechanism and improve upon a metallaphotocatalyzed C–N cross-coupling reaction (Figure 4A).[34] First, Stern–Volmer luminescent quenching experiments of the standard Ir photocatalyst led to the assignment of DABCO as the primary quencher of its excited state. In combination with nanosecond–microsecond pump–probe spectroscopies, alongside with spectroelectrochemistry, we were able to show that, upon quenching, the formation of Ir(II) and $DABCO^{•+}$ species would follow. Moreover, these species were determined to be pertinent as the formation of Ir(II) was shown to reduce Ni(II) to a catalytically relevant and elusive Ni(I) species (as demonstrated in the previous section) that can undergo oxidative addition. Additionally, the efficiency of this step was determined to be crucial for the initiation and perpetuation of the Ni(I)/Ni(III) cycle. Hence, new Ir(III) photocatalysts of increasing electron density on the π^*-localized bipyridine ligands were synthesized and characterized to increase the reductive capability of the intermediate Ir(II) complexes. In particular, the more highly reducing photocatalysts developed in the series led to a 30-fold rate increase and a 10-fold increase in quantum yield. Furthermore, the redesign of the Ir photocatalyst resulted in an expanded scope that includes synthetically useful yields of product formation with challenging drug-like aryl halide substrates previously inaccessible. Overall, the merger of these techniques has demonstrated the chemical advancements that come about from the understanding of the intricacies of the underlying mechanisms of the reactions.

Doyle and co-workers reported a dual phosphine and Ir photocatalytic pathway to construct C(sp^3)−N bonds via an intermolecular anti-Markovnikov hydroamination of unactivated olefins with primary sulfonamides (Figure 5A).[37]

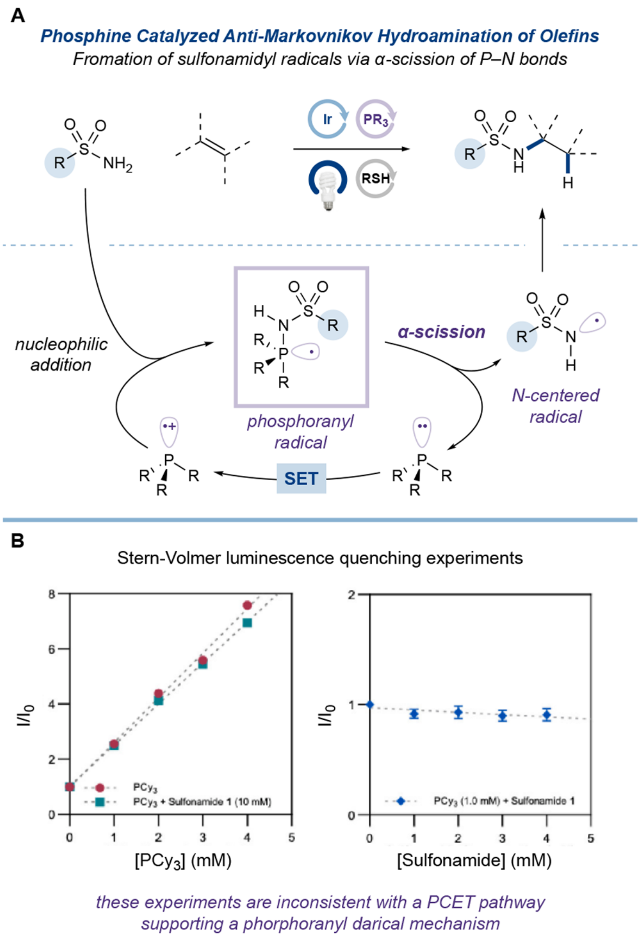

Figure 5. α-Scission of phosphoryl radicals as precursors of N-centered radicals for olefin hydroamination. (A) General reaction and key mechanistic steps. (B) Stern−Volmer experiments consistent with phosphoranyl radical formation. Adapted from ref 37. Copyright 2021 American Chemical Society.

Mechanistic investigations support that an excited photocatalyst oxidizes the phosphine to the corresponding radical cation and forms a phosphoranyl radical intermediate upon nucleophilic addition of the sulfonamide which subsequently generates the sulfonamidyl N-centered radical via α-scission of the P−N bond. This work evaluates multiple mechanistic hypotheses of the transformation and systematically addresses the support and lack thereof for each pathway. One alternative hypothesis considered for the sulfonamide N−H activation was concerted PCET. The results of Stern−Volmer experiments were inconsistent with a PCET mechanism and supported the proposed pathway (Figure 5B). A better understanding of the reactivity was gained by using spectroscopic experiments, and this cocatalytic system is under active investigation for the activation of other challenging substrates.

The examples presented in this section show how elucidating the elementary steps of a mechanism can provide valuable clues for reaction optimizations as well as for the development of reactions that were previously inaccessible. In particular, photocatalyst design can have a tremendous impact on reaction outcomes. Understanding the limitations of the elementary steps of these complex mechanisms can provide clues for the design of more efficient photocatalysts that can increase reaction yields, rates, and even expand the scope to more challenging substrates. In particular, the design of more efficient photocatalysts, as well as the implementation of spectroscopic tools to provide insight into the elementary steps of a transformation, may lead to the development of, for example, more efficient depolymerization strategies such as the ones described in section 5.

4. LOW-ENERGY LIGHT-HARVESTING STRATEGIES FOR CATALYTIC REACTIVITY

Light absorption is the key step needed for photocatalysis to occur.[9] Many catalysts suffer from light-limited operation due to their small absorption bandwidths and low molar absorptivities and are furthermore susceptible to photodamage and nonspecific excitation.[10,38] Previous advancements in widening the absorption bandwidth utilized such tactics as conjugated transition-metal complexes,[39,40] upconverted light to excite a catalyst,[41−43] and direct excitation of the triplet state of a catalyst.[44,45] Particularly, expanding a catalyst's available absorption window to lower energies can avoid nonspecific excitation of optical filters such as substrates and cocatalysts, improve a catalyst's implementation in relevant reactions such as biological cross-linking in vivo, reduce potential damage from irradiation with high-energy light, and improve the scalability of reactions due to increased penetration depths compared to high energy light.[38,46] We designed, investigated, and demonstrated two unique light-harvesting strategies: energy transfer from a dedicated light-harvesting protein to a tethered Ru photocatalyst and triplet−triplet annihilation for direct initiation of free-radical polymerization, in the context of photocatalytic reactions (Figure 6A and C).[3,47]

Schlau-Cohen, MacMillan, Doyle, Castellano, and co-workers utilized a low-energy absorbing photosynthetic light-harvesting protein to excite a photocatalyst through energy transfer and catalyze two radical initiation reactions.[3] Natural organisms partition the light-harvesting and reactive processes of photosynthesis into distinct structural components.[48] This modulation occurs because these processes are contradictory, one requiring harnessing and storing vast amounts of energy and the other quickly dispersing energy toward chemical reactivity. The authors sought to apply this design principle to the development of a photocatalytic bioconjugated system in the context of photoredox catalysis. Due to the intrinsic interdisciplinary nature of the work proposed, a collaboration between several groups was necessary to make the developments required to implement this chemistry. The Schlau-Cohen group conjugated the light-harvesting protein R-phycoerythrin (RPE) to the photocatalyst $[Ru(bpy)_3]^{2+}$ to develop the biohybrid catalyst RPE-$(Ru)_n$ and examined the energy transfer time scale between the components using fluorescence lifetime measurements, transient absorption spectroscopy, and Förster theory (Figure 6A). The Castellano group performed nanosecond transient absorption measurements, which provided concrete evidence that RPE could transfer energy to $[Ru(bpy)_3]^{2+}$; excitation at wavelengths at which only RPE absorbs resulted in spectral

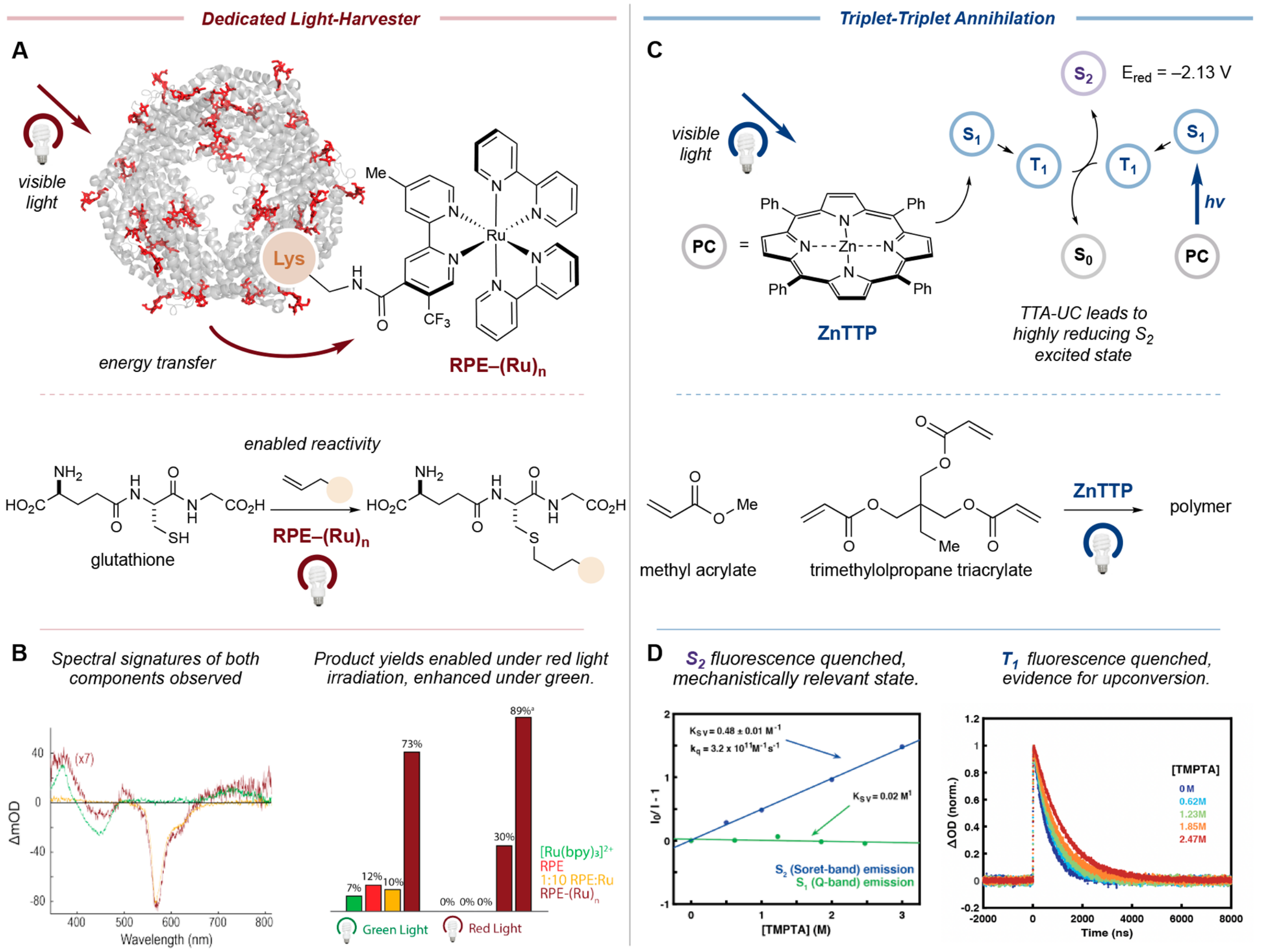

Figure 6. Strategies for advantageous light absorption. (A) Energy transfer from a conjugated broadly absorbing light-harvesting protein enables low-energy light to excite a reactive catalyst. (B) Spectral features of both the light-harvesting protein and catalyst were observed through transient absorption spectroscopy when exciting only the protein, evidencing energy transfer. The biohybrid enabled or enhanced product yields in a photocatalytic thiol–ene test reaction after 2 h. [a]12 h reaction time. Adapted with permission from ref 3. Copyright 2022 Elsevier. (C) Triplet–triplet annihilation enables low-energy light to excite and initiate polymerization between methyl acrylate and trimethylolpropane triacrylate. (D) Transient absorption spectroscopy and Stern–Volmer quenching experiments lend evidence toward triplet–triplet annihilation as the operative mechanism. Adapted with permission from ref 47. Copyright 2020 Elsevier.

signatures of $[Ru(bpy)_3]^{2+}$, indicating energy transfer had occurred (Figure 6B). Finally, the MacMillan and Doyle groups demonstrated the biohybrid for synthetic competency through photocatalytic thiol–ene coupling and cysteinyl desulfurization test reactions. Here, reactivity was enhanced at green wavelengths of common absorption for the components and enabled at red wavelengths where the catalyst alone does not absorb (Figure 6B). This strategy demonstrated the viability of uphill energy transfer from a conjugated light-harvesting structure as a means of enabling the low-energy excitation of a photocatalyst. Similar to the annihilation work described below, these biohybrids offer increased absorption bandwidths, noncompetitive absorption with substrates and cocatalysts, and applications in biological systems.[46,49]

Castellano and co-workers utilized triplet–triplet annihilation to directly catalyze a free-radical polymerization of methyl acrylate (MA) or trimethylolpropane triacrylate (TMPTA) with low-energy light.[47] Triplet–triplet annihilation is a multiphoton excitation mechanism which combines the exciting power of two low-energy photons and allows high-energy light to be emitted or high-energy chemistry to be performed. The authors excited the lower singlet excited states (S_1) of two ZnTPP (zinc(II) meso-tetraphenylporphyrin) molecules, which rapidly intersystem crossed to their respective triplet states (T_1) (Figure 6C). Two of these triplet excited photoinitiators then annihilated to form a ground state (S_0) molecule and a high-energy excited singlet state (S_2) molecule that directly initiates the free-radical polymerization of TMPTA or MA. Using transient absorption spectroscopy and time-resolved and steady-state fluorescence measurements, the authors determined that only the T_1 states and the S_2 state were mechanistically relevant (Figure 6D), as their spectral features were quenched in the presence of TMPTA, lending evidence to triplet–triplet annihilation as the operative mechanism. The S_2 state of ZnTPP directly catalyzes the radical polymerization of TMPTA through electron transfer. The polymerization was monitored by witnessing the decay of the C═C IR band of the monomer over time, and EPR spectroscopic studies supported a mechanism proceeding via radical-initiated upconverted light. This strategy demonstrated the viability of utilizing upconverted light to directly catalyze reactions, offering excitation with low-energy sources, fewer competing side reactions, and less complexity as the upconverter simultaneously acts as the photoinitiator.

As part of our overarching goal to improve photocatalysis, we aim to expand the possibilities for innovative light absorption and confirm viability of developed strategies. By applying triplet−triplet annihilation and dedicated light-harvesting machinery to photocatalytic processes, we demonstrated that low-energy visible light can be used for irradiation and that the possibility of reactions occurring in aqueous and biological environments can one day be realized. In collaboration with the synthetic organic groups, we are currently exploring the generalizability of these strategies including conjugating light-harvesters to the chemically remarkable photoenzymatic mutant, Gluconobacter Ene-Reductase T36A, developed by Hyster and co-workers.[50] We hope to expand these methods to further reactions and systems, such as developing biohybrids containing earth-abundant metal-centered catalysts, expanding the number of reactions which can be directly catalyzed by an upconverting system, and exploiting the potential power of multiphoton excitation and multielectron reactivity.[51]

5. DEPOLYMERIZATION STRATEGIES ENABLED BY PHOTOREDOX CATALYSIS VIA PCET

5.1. Depolymerization of Native Lignin

Due to increasing energy demand and its impact on Earth's climate, moving away from nonrenewable energy sources, such as fossil fuels, is critical. Biomass is an appealing alternative, as it is considered the most abundant renewable source of carbon, biofuels, and chemical feedstocks (Figure 7A).[12] In particular, lignin, a carbon-neutral nonedible polymer, is generated in large quantities by agricultural activity worldwide.[52] The depolymerization of this material into useful monomeric products, however, remains challenging due to the high temperatures and harsh conditions required to break the C−C and C−O linkages that hold the biopolymer together. Light-driven depolymerization of this biomass source is therefore an attractive alternative as it can be achieved under mild conditions without generating stoichiometric waste.[53]

Knowles and co-workers employed photoredox catalysis to depolymerize native lignin via a proton-coupled electron transfer (PCET) activation step.[54] The mechanism for the degradation of this polymer starts with excitation of the Ir(III) photocatalyst into a highly oxidizing Ir(III)* excited state (Figure 7B). In the presence of a base, the hydroxy groups in the polymer can quench this excited state via a PCET step, generating an Ir(II) species and an alkoxy radical.[55,56] This unstable radical undergoes C−C bond β-scission to yield an aldehyde and an alkyl radical that can, through a hydrogen atom transfer (HAT) step, yield depolymerized product. The HAT reagent is regenerated by reoxidation of the Ir(II) species followed by a proton transfer step closing the catalytic cycle. This one-step, redox neutral reaction proceeds at room temperature without the generation of stoichiometric waste. This approach yielded monomers with efficiencies that range from 57 to 98% for model lignin dimeric systems that display β-O-4 linkages. However, the cleavage of plant-derived native lignin is significantly more challenging than these model systems and small molecule lignin fractions, meaning literature examples are scarcely found. Of note, Stephenson and co-workers developed a two-step depolymerization method that consists of the electrocatalytic oxidation of native lignin followed by photocatalytic cleavage promoted by an Ir phocatalyst that

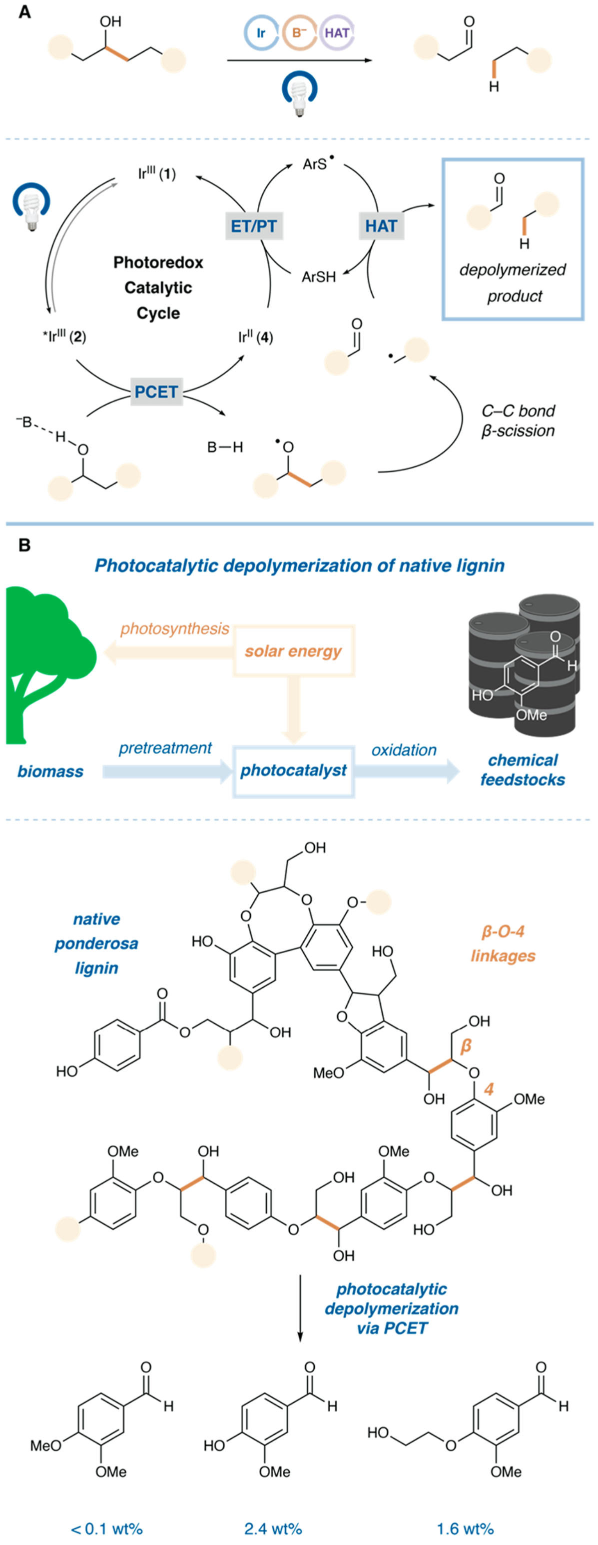

Figure 7. Depolymerization of biomass. (A) Proposed mechanism for the depolymerization of lignin. (B) Top: biomass as a source of chemical feedstock through solar light driven oxidation.[53] Bottom: schematic representation of native lignin and the products obtained through photocatalytic depolymerization via PCET. Adapted from ref 54. Copyright 2020 American Chemical Society.

afforded 2.4 wt % of monomeric material through C−O cleavage of the β-O-4 linkages.[57] In comparison, the photoredox C−C cleavage via PCET method developed by the Knowles group yielded 4 wt % of monomeric material through the preparative scale depolymerization of ponderosa lignin in a manner complementary to Stephenson's two-step approach. Excitingly, native grand fir lignin degraded via PCET was estimated to undergo a minimum of 41% bond cleavage of all β-aryl ether bonds present through derivatization followed by reductive cleavage analysis.

5.2. Depolymerization of Hydroxylated Polymers

The above-described method represents a very promising strategy that could be adapted for the depolymerization of other materials of great societal interest such as plastics. Even though the development and widespread usage of synthetic polymers has had an unarguably positive influence in societal development, the accompanying environmental effects still represent a challenge that needs to be addressed.[58] The recycling strategies of many plastics require multiple C−C bond-breaking steps that are typically hard to access and degrade, often yielding complex mixtures that cannot easily be repolymerized. Hydroxylated polymers, however, are a subclass of plastics that display hydroxyl groups in the backbone which renders them susceptible to depolymerization strategies that proceed via the formation of an alkoxy radical and subsequent C−C bond breaking step. The Knowles group sought to depolymerize these types of polymers via a PCET enabled photoredox catalytic cycle.[4] The degradation of a phenoxy resin yielded the desired monomers in up to 63% yield (Figure 8A). This polymeric resin is typically found in mixtures, and excitingly, degradation of this resin in the presence of added commodity plastics such as poly(vinyl chloride) (M_w ~ 233 000 g/mol), polystyrene (M_w ~ 192 000 g/mol), and poly(methyl methacrylate) (M_w ~ 120 000 g/mol) did not significantly affect the yields of monomer obtained (50−54%) as evidenced by GC analysis. Interestingly, the monomeric product can be easily converted into bisphenol A with a 93% yield, which is a precursor for many other commercial polymers. Gratifyingly, this methodology can be extended to the degradation of hydroxylated homo and copolymers with p-methoxyphenyl (PMP) and silylether (OTBS) substituents at the β-position due to stabilization of the C-centered radical formed upon β-scission. Moreover, the degradation products can be functionalized to afford bifunctional monomers as chemical feedstocks creating a closed-loop of polymerization/depolymerization of recyclable polymers (Figure 8B).

These examples show how photoredox catalysis provides a mild alternative to traditional polymer degradation strategies for the production of chemical feedstocks from abundant biomass as well as creates a closed recycling loop for synthetic polymers containing hydroxyl groups. Implementation of PR and ultrafast spectroscopies described in section 2 may provide further mechanistic insights into the elementary steps involved in the degradation of polymers. Additionally, the development of new activation modes for depolymerization reactions, such as the multi-photo processes described in section 3, might allow us to expand the scope to the degradation of more challenging nonrecyclable plastics.

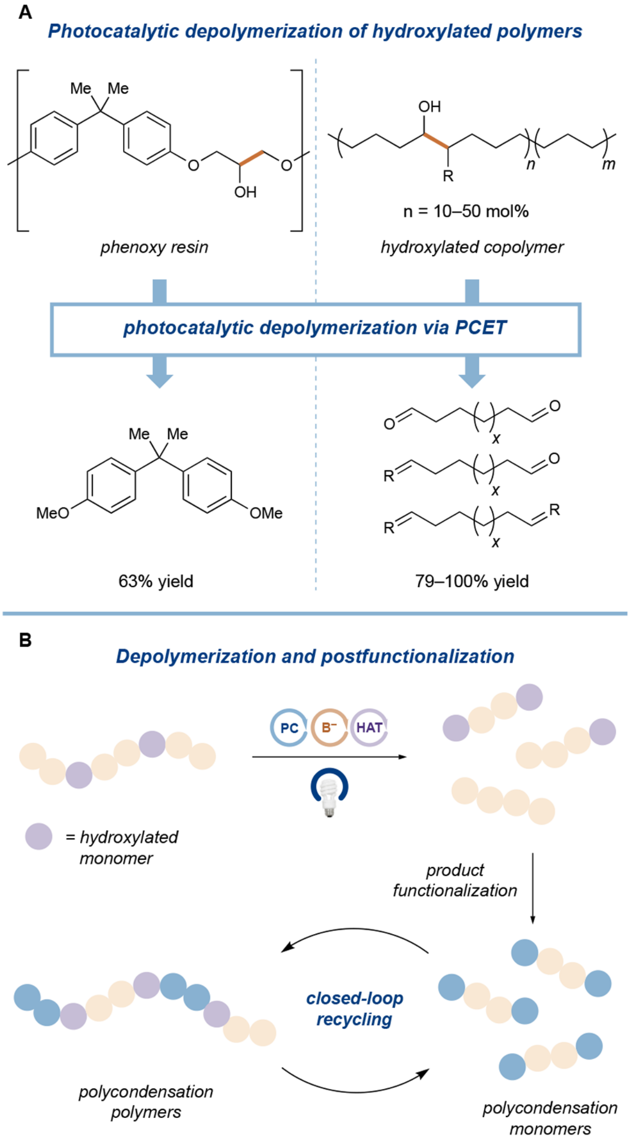

Figure 8. Depolymerization of hydroxylated polymers. (A) Proposed degradation/repolymerization cycle for the recycling of hydroxylated polymers via product functionalization and photocatalytic depolymerization. (B) Monomeric products obtained by photocatalytic depolymerization via PCET of phenoxy resins and hydroxylated copolymers and their product distributions. Adapted with permission from ref 4. Copyright 2021 American Chemical Society.

6. CONCLUSIONS

Light-driven chemistry has the potential to revolutionize the chemical industry as it provides alternative reactivity pathways that lead to the formation of products that are either unattainable through traditional routes or energetically costly due to the high temperatures and pressures required to obtain them. The advancement of this field, however, requires collaborative efforts in order to grow due to the intrinsically interdisciplinary nature of the work required to understand and exploit all aspects of photoredox chemistry. The use of techniques such as PR, TRDL, and TA spectroscopies are not routinely employed by organic chemists, but collaborations across the BioLEC team allowed us to investigate elementary steps in photoredox catalysis that would otherwise remain obscure. These results led us to discover new reactivities and new optimization variables (i.e., the anion of the photocatalyst modulates ES dynamics) of importance to synthetic chemists. Additionally, we developed new photocatalysts that improve the efficiency of C−N coupling reactions guided by spectroscopic techniques as well as C−N cross coupling reactions that proceed through the formation of N-centered radicals generated via a α-scission of a phosphoranyl radical intermediate. Moreover, we successfully employed two light harvesting strategies, triplet−triplet annihilation and bioconjugation, to circumvent non-specific absorption issues in the contexts of polymerization and thiol−ene coupling reactions with enhanced reactivity. These could have a tremendous impact on scaled-up industrial applications as light penetration increases for these low-energy light-induced processes facilitating chemistry in batch reactors. Furthermore, the discovery of the activation of alcohols through a PCET mechanism that results in C−C β-scission of an alkoxy radical led us to the development of a highly efficient method for the challenging depolymerization of native lignin and the depolymerization of industrially relevant hydroxylated polymers. Excitingly, the products of the latter lead to the formation of feedstock chemicals which we leveraged to establish a closed-recycling loop through post-functionalization. These highlighted collaborative efforts developed by BioLEC opened new avenues of exploration in the context of photoredox catalysis that have advanced the field in unprecedented directions.

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Notes

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