Photoredox catalysis enabling decarboxylative radical cyclization of γ,γ-dimethylallyltryptophan (DMAT) derivatives: formal synthesis of 6,7-secoagroclavine

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Abstract
An unusual photoredox-catalyzed radical decarboxylative cyclization cascade reaction of γ,γ-dimethylallyltryptophan (DMAT) derivatives containing unactivated alkene moieties has been developed, providing green and efficient access to various six-, seven-, and eight-membered ring 3,4-fused tricyclic indoles. This type of cyclization, which was hitherto very difficult to comprehend in ergot biosynthesis and to accomplish by more conventional procedures, enables the synthesis of ergot alkaloid precursors. In addition, this work describes a mild, environmentally friendly method to activate, reductively and oxidatively, natural carboxylic acids for decarboxylative C–C bond formation by exploiting the same photocatalyst.

Introduction
Visible-light photoredox catalysis is rapidly changing the way organic chemists approach the design and synthesis of molecules by offering new synthetic disconnection opportunities that are usually more convergent, enabling a more diverse chemical space in a rapid fashion [1-15]. Currently, increasing numbers of synthetic chemists are developing photocatalytic processes to make molecules efficiently and in an environmentally friendly manner due to their intrinsic mildness and broad substrate compatibility [16-20]. This transformative synthetic tool often utilizes direct single-electron transfer (SET) between an electronically excited photoredox catalyst and an organic substrate, resulting in oxidation or reduction, to easily generate reactive open-shell radical species and/or intermediates. The substrate is consequently activated for bond cleavage, atom abstraction, or nucleophilic or electrophilic attack. After quenching, the oxidized or reduced photocatalyst regains or loses an electron to return to the starting ground state catalyst [21-26].

While early research has focused on methods for the functionalization of relatively simple hydrocarbons [27-30], develop-
ments in photoredox catalysis have gained traction recently as a viable strategy for the total synthesis of natural products [31-33], modification of biomacromolecules [34], and relatively complex pharmaceutical agents [35-38]. Photocatalysis tremendously enriches the synthetic compound library, providing a precious alternative to directly modify abundant natural substrates, including biomass, which usually requires a multistep process in conventional chemical synthesis [39-41]. Among the various widely available and abundant substrates for photocatalyzed reactions, natural and unnatural \( \alpha \)-amino acids play a very important role, given their paramount importance across several chemistry fields as well as their ability to participate in either redox step of the catalytic cycle [42-45]. For example, the main use of \( \alpha \)-amino acids in syntheses via photoredox catalysis is as readily available precursors of regioselective \( \alpha \)-amino radicals by decarboxylative transformations, by oxidation of the carboxylate anion and/or reduction of the corresponding \( N \)-hydroxyphthalimide- (NHPI)-derived redox-active ester, although it destroys their stereochemical information [46-51]. In addition, the side-chains of aromatic amino acids (mainly electron-rich tryptophan and tyrosine) can be selectively targeted by photoredox catalysis to enable unprecedented modification of the amino acid. In this context, it is worth mentioning that the single-electron oxidation of the indole moiety in tryptophan provides the radical cation, which enables selective C-radical generation at the weaker benzylic position via a sequential electron transfer–proton transfer (ET/PT) [52-59].

With our ongoing interest of establishing new methods for the asymmetric synthesis of nonproteinogenic tryptophan derivatives as well as their associated indole alkaloid natural products [60-67], we became fascinated in exploring whether photoredox catalysis could be applied for the activation of such unnatural amino acids to expedite the development of completely new synthetic pathways. In particular, 4-dimethylallyltryptophan (DMAT) is of interest for the following reasons: 1) it functions as the central intermediate in the biosynthetic pathways leading to numerous prenylated indole alkaloids, such as ergot alkaloids in normal biosynthesis and clavicipitic acid in derailment biosynthesis [68-71]; and 2) the mechanism of the fundamental central C-ring formation of all ergot alkaloids, specifically the decarboxylative cyclization of DMAT, is still a puzzle even though a radical mechanism has been proposed (Figure 1a) [72,73].

**Results and Discussion**

Herein, we propose that visible light irradiation of the cationic iridium photocatalyst \( \text{Ir}\{dF(CF_3)ppy\}_2(dtbbpy)PF_6 \) \( (E_{1/2}^{III/II}=+1.21 \text{ V}, E_{1/2}^{IV/III}=-1.37; E_{1/2}^{IV/III}=-0.89, E_{1/2}^{IV/III}=+1.69 \text{ V}) \) [74] would permit efficient radical generation and

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**Figure 1:** (a) Transformations of DMAT to different classes of ergot alkaloids. (b) and (c) Strategies for the photoredox-catalyzed radical decarboxylative cyclization cascade reaction of DMAT derivatives (this work).
C(sp³)–C(sp³) bond formation either by challenging selective radical–radical cross-coupling or by radical addition to a π-bond, enabling a rare example of intramolecular decarboxylative cyclization with the formation of the 3,4-fused indole carbocycle rings (Figure 1b,c). In detail, the photocatalytic strategy for accessing the two C(sp³) radicals of DMAT derivatives envision the formation of a relatively stabilized allylic-benzylic carbon-centered radical by proton transfer from the oxidized indole radical cation [75], generated by SET from the activated photocatalyst. The α-amino radical generated by reductive decarboxylation of a DMAT derivative with a redox-active ester (−1.26 V to −1.37 V vs a saturated calomel electrode) would enable turnover of the photoredox cycle (Figure 1b). Alternatively, we envisioned a more established approach expecting the direct oxidative photoredox decarboxylation of the carboxylic acid/carboxylate (by SET from the activated photocatalyst) of DMAT to generate the α-aminoalkyl radical that might readily be captured/trapped intramolecularly with the C4-pendant prenyl side-chain previously oxidized [76]. Closure of the photoredox catalytic cycle would then involve SET reduction, and protonation would deliver the desired carbocyclic ring (Figure 1c). If this cyclization reaction could be realized in either way, it would shorten the synthetic route of ergot alkaloids and may offer new opportunities for drug discovery and biochemistry applications.

As natural and unnatural tryptophan-derived redox-active N-hydroxyphthalimide esters have already been used in photoredox catalysis, we decided to use them as the initial substrates [77-85]. To test this concept, we turned our attention to the synthesis of key intermediate 5 (Scheme 1). The synthesis began with protection of the indole nitrogen of the known compound 1, which is readily available from commercially available 4-bromoindole in one step [62]. Regioselective palladium-catalyzed prenylation of 2 with prenylboronic acid pinacol ester and subsequent hydrolysis with LiOH provided the linear prenylated acid 4 in good yield. Coupling acid 4 with N-hydroxyphthalimide using DCC and a catalytic amount of DMAP afforded the key intermediate 5 in 59% yield.

With compound 5 in hand, the required radical–radical coupling was investigated next, and some of the representative results are shown in Table S1 (see Supporting Information File 1). Irradiation from blue light-emitting diodes (LEDs) in the presence of 2 mol % of the photocatalyst [Ir(dF(CF₃)ppy)₂(dtbbpy)]PF₆ in CH₂Cl₂ at room temperature using our integrated photoreactor enabled efficient cyclization to give a decarboxylated compound with the correct mass (m/z 426.2) after 16 h. While we were delighted to find that the proposed radical–radical coupling in the synthesis of extracyclic fused indoles was feasible under these conditions, the observed reaction efficiency was poor (14–33% yield). However, on the ¹H NMR spectrum, some unexpected signals were observed. The appearance of equilibrating species such as rotamers in the ¹H NMR spectrum (see the variable-temperature NMR experiments in Supporting Information File 1, Figure S1) due to the protecting groups complicates the analysis of the reaction products. However, the olefinic signals were a pair of two doublets representing two vicinal vinylic protons [6.48 (d, J = 8.0 Hz, 1H), 6.29 (d, J = 8.0 Hz, 1H), 5.31 (d, J = 8.0 Hz, 1H), and 5.28 (d, J = 8.0 Hz, 1H)], strongly indicating that this product is not the desired structure 6’ but the eight-membered cycloalkene structure 6, shown in Scheme 2. Based on these results and previous reports on the benzylic and allicyclic C–H bond functionalization enabled by metallaphotoredox catalysis [86], we propose a tentative mechanism (Figure 2).

First, the radical cation 1 was generated via the oxidation of indole 5 by the excited Ir-based photocatalyst, followed by sequential regioselective proton transfer on the benzylic
Scheme 2: Photoredox-catalyzed radical decarboxylative cyclization of 5.

**Figure 2:** Proposed reaction mechanism for photoredox-catalyzed radical decarboxylative cyclization.

dimethylallyl unit C–H bond of the C4 side-chain, thereby generating II. Here, the radical is stabilized by both the indole ring and the Δ2-olefin. Next, the resonance-stabilized radical intermediate III was trapped by the active α-aminoalkyl radical, generated by reductive decarboxylation by Ir(II) produced in the photocatalytic cycle (which undergoes oxidation to afford the Ir(III) complex and to close the cycle), thus furnishing compound 6 comprised of an eight-membered ring. The related stabilization effect of the conjugated product 6 might be the thermodynamic driving force for this radical coupling. An alternative route (not shown) would be that, the α-amidoalkyl radical generated by reductive decarboxylation, could add in an 8-endo-trig manner (common in radical chemistry) to the alkene and the resulting radical could be oxidized to the cation by the oxidized form of the photocatalyst to close the photocatalytic cycle, followed by formation of the double bond. Even though no desired cyclized product was observed, an interesting aspect of this reaction was the access of an attractive, unusual, and highly functionalized 3,4-fused eight-membered tricyclic indole, whose ring closure would not have been possible or at least very difficult in the ground state [87-89].

Although not yet completely clarified, some previous studies on the detailed mode of closure of the C ring in ergot alkaloids from DMAT have been shown to involve, before decarboxylative cyclization, oxidation on the C4-prenyl chain to give the stable rearranged allyl alcohol and/or the relatively unstable diene [90,91]. In addition, these results support the hypothesis that the decarboxylative cyclization can occur through subsequent selective 6-exo-trig radical addition. It also has been reported that it is difficult to detect which intermediate is really involved, since they are easily interconvertible to each other by
hydration or dehydration, i.e., a plausible precursor of the allylic alcohol would be the diene, and vice versa [90]. Since both 8 and 10 are easily obtainable from 2 by Mozoroki–Heck coupling with commercially available 2-methyl-3-buten-2-ol, ester hydrolysis (LiOH in THF/H2O), and, finally for 10, dehydration of the tertiary alcohol (mesylation and elimination) (Scheme 3), we decided to test their roles in the photoredox-catalyzed decarboxylative cyclization. With 8 and 10 in hand with the C4-prenyl side-chain already oxidized/functionalized, we recognized that this cyclization event would be triggered using their innate functionality, namely the α-amino carboxylate, through photoredox-mediated oxidative activation and CO2 extrusion, without the need for acid prefunctionalization to the redox-activated ester. Consequently, a technique involving direct generation of α-aminoalkyl radicals from free carboxylic acids of 8 and 10 under mild conditions would make the approach even more efficient and more biosimilar; nevertheless, issues regarding the regioselectivity of the ring formation could be raised, since both the 6-exo-trig and 7-endo-trig cyclization are both favorable, according to the Baldwin rules [92].

We began our investigation of the proposed decarboxylative cyclization by exposing the N-Boc derivative 8, Ir catalyst, and K2HPO4 in DMF to a 34 W blue LED lamp at room temperature (Table 1) [93-97]. To our delight, cyclization was observed under these preliminary conditions, albeit in low yield (35% yield) and low regioselectivity (1:1) (Table 1, entry 1). No regiocontrol was observed; but remarkably, the regioisomers exhibited distinct retention factors on silica gel, allowing 11 and 12 to be isolated separately in good yield as single trans diastereomers [98]. Reducing the substrate concentration increased efficiency while assisting in avoiding the oligomerization pathways (Table 1, entries 2 and 3). Higher photocatalyst loadings resulted in an increased yield (Table 1, entry 4). Control experiments showed that both the photocatalyst and light were essential for product production (Table 1, entries 6 and 7), despite the fact that the removal of base did not result in a significantly reduced efficiency (Table 1, entry 5). The regioselectivity outcome was explained by the relative stability of the intermediate radicals involved, with strong evidence of the importance of steric effects [99]. Indeed, while the addition of the nucleophilic α-amino radical to the α-styrenyl position affords the 6-membered ring (kinetic product via intramolecular 6-exo-trig ring closure) [100] the resulting radical is destabilized, the 7-membered ring (obtained via intramolecular 7-endo-trig ring closure) may well be the thermodynamic product based on the more stabilized benzylic radical that is produced [101].

As largely reported in the literature [102,103], radicals generated next to alcohols do not normally undergo β-elimination to give alkene/carbon–carbon double-bond formation and a hydroxyl radical (·OH). However, it is possible to transform an alcohol into a leaving group, in the radical sense, by converting it into a halide or pseudohalide derivative [104,105]. For alcohol 8, all attempts to make a better leaving group, including phenyl sulfone derivative, to have radical addition–fragmentation on the latter and most likely to shift the regioselectivity towards 6-exo-trig by a favorable interplay of polar effects [99] failed and furnished only the 1,3-diene 10. Unfortunately, when substrate 10 was subjected to the reaction conditions shown above, only tarry compounds were obtained; this result was probably due to the competitive cycloaddition and polymerization.

![Scheme 3: Synthesis of tryptophan derivatives 8 and 10.](image-url)
Table 1: Photoredox-catalyzed radical decarboxylative cyclization of 8.a

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>Concentration of 8</th>
<th>Ir catalyst (mol %)</th>
<th>Ratio of 11/12b</th>
<th>Yield of 11 and 12c</th>
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<tr>
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<tr>
<td>4</td>
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<tr>
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<td>–</td>
<td>N.D.d</td>
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<tr>
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<td>4</td>
<td>–</td>
<td>N.D.d</td>
</tr>
<tr>
<td>8</td>
<td>DMSO instead of DMF</td>
<td>2.5 mM</td>
<td>4</td>
<td>0.7:1</td>
<td>33%</td>
</tr>
<tr>
<td>9</td>
<td>DCE instead of DMF</td>
<td>2.5 mM</td>
<td>4</td>
<td>1:0.7</td>
<td>40%</td>
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</table>

aReaction conditions: 8 (0.1 mmol), K2HPO4 (0.12 mmol), catalyst (x mol %), solvent (4 mL), irradiation with 34 W blue LEDs for 60 h. bRatio of 11/12 was determined by 1H NMR analysis. cIsolated yields. dN.D., not detected.

As shown in Figure 3 and anticipated above, our proposed mechanism begins with visible-light irradiation of the photoredox catalyst [Ir(dF(CF3)ppy)2(dtbpy)]PF6 to access the excited state *[Ir(dF(CF3)ppy)2(dtbpy)]PF6, which can trigger SET oxidation of 8. Rapid decarboxylation leads to α-amino radical V (and the reduced photocatalyst), which is intercepted by the pendant double bond to forge the desired six-membered ring through a key C–C bond formation while furnishing secondary radical VI and the undesired seven-membered-ring compound VII. Closure of the photoredox catalytic cycle would then involve either SET reduction of the radical VI and VII (which upon protonation would deliver the desired product 11 and the undesired product 12), or an hydrogen-atom-transfer...
(HAT) process (which would not place a formal negative charge onto the molecule), where the hydrogen atom required for this possible final HAT step originates from the solvent (DMF) itself [107]. Therefore, we tested the reaction in N,N-dimethylformamide-d$_7$ (DMF-d$_7$), which showed almost quantitative deuterium incorporation. While this result was surprising, further studies into this complex mechanism are ongoing and will be reported in due course.

The synthetic potential and utility of this method was further demonstrated by the formal total synthesis of (±)-6,7-secoagroclavine (Scheme 4) [108-114]. Towards this end, compound 11 was methylated efficiently and selectively at the secondary amide by treatment with methyl iodide in DMF to afford compound 13. In additional two steps, intermediate 13 was transformed to (±)-6,7-secoagroclavine in enantiopure form, as reported previously by the Bisai group in 2018 [115]. All the spectroscopic data of 13 were in agreement with those reported in the literature, confirming that the radical addition reaction provided the trans amino group due to steric hindrance.

Conclusion

In summary, this work illustrates, once more, the synthetic potential of an Ir-polypyridyl complex as a photoredox catalyst that can efficiently convert visible light into chemical energy. In addition, this catalyst was applied to demonstrate the proposed radical mechanism involved in the biosynthetic formation of the central C ring of several DMAT derivatives. The results presented here lend strong credence to decarboxylation and cyclization to form the six-membered ring as well as the nature of the stable oxidized intermediates concerned. Moreover, unprecedented and functionalized 3,4-fused tricyclic indoles with medium-sized rings (seven and eight), which have been largely neglected in previous studies, can be synthesized by this new protocol. Notably, the reaction has been successfully applied in the formal synthesis of (±)-6,7-secoagroclavine, a key intermediate for a common synthetic route to ergot alkaloids, providing an advantageous synthetic method for this class of natural products. Further studies on the utility of the decarboxylative radical cyclization and their applications are currently being investigated in our laboratory.

Supporting Information

Supporting Information File 1
Experimental and copies of spectra. [https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-19-70-S1.pdf]

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References


Scheme 4: Methylation of 11 and the formal total synthesis of (±)-6,7-secoagroclavine.
114. It should be mentioned that racemization was found in products 11 and 12 from the chiral intermediate V, which is common in this radical coupling reaction. See reference [76].

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Abstract

The place of alkyl radicals in organic chemistry has changed markedly over the last several decades, evolving from challenging-to-generate “uncontrollable” species prone to side reactions to versatile reactive intermediates enabling construction of myriad C–C and C–X bonds. This maturation of free radical chemistry has been enabled by several advances, including the proliferation of efficient radical generation methods, such as hydrogen atom transfer (HAT), alkene addition, and decarboxylation. At least as important has been innovation in radical functionalization methods, including radical–polar crossover (RPC), enabling these intermediates to be engaged in productive and efficient bond-forming steps. However, direct engagement of alkyl radicals remains challenging. Among these functionalization approaches, a bio-inspired mechanistic paradigm known as radical ligand transfer (RLT) has emerged as a particularly promising and versatile means of forming new bonds catalytically to alkyl radicals. This development has been driven by several key features of RLT catalysis, including the ability to form diverse bonds (including C–X, C–N, and C–S), the use of simple earth abundant element catalysts, and the intrinsic compatibility of this approach with varied radical generation methods, including HAT, radical addition, and decarboxylation. Here, we provide an overview of the evolution of RLT catalysis from initial studies to recent advances and provide a conceptual framework we hope will inspire and enable future work using this versatile elementary step.

Introduction

The behavior of alkyl radicals has been studied rigorously for decades, though only recently have these come to be widely viewed as selective and useful synthetic intermediates [1-4]. This sea change has been driven by innovations in both the generation and functionalization of alkyl radicals, with successful synthetic reactions requiring efficiency and selectivity in both of these processes and inherent compatibility between each. Radical generation has benefitted from many general mechanistic approaches, including hydrogen atom transfer (HAT) [5], alkene addition [6], and decarboxylation [7], enabling these
intermediates to be easily accessed from diverse starting materials. Functionalization methods have also seen significant development, with elementary steps such as radical–polar crossover (RPC) finding significant purchase [8]; however, these steps are not amenable to all radical generation approaches/substrate classes nor can they form all desired bonds from alkyl radical intermediates, limiting the toolkit of radical reactions.

Recently, radical ligand transfer (RLT) [9-11] has emerged as a radical functionalization paradigm with the potential to overcome the challenges faced by other strategies (Scheme 1). At its core, RLT involves the outer sphere transfer of an anionic, X-type ligand coordinated to a redox-active metal to a radical intermediate, resulting in formation of a new C–ligand bond with concomitant single electron reduction of the metal center. Subsequent reoxidation of the metal with coordination of a new equivalent of anionic ligand allows for the RLT complex to be regenerated, making this strategy inherently compatible with catalysis.

Building on this, one of the most important examples of catalytic RLT can be found in the human body’s own cytochrome P450 enzymes. These catalysts exhibit unique “radical rebound” reactivity at their heme active sites (Scheme 1) [12], a mechanism proposed by Groves and co-workers and heavily explored beginning in the 1970s [13,14]. This two-step functionalization sequence begins with HAT from an alkyl C–H bond to a high valent iron oxo species, resulting in formation of iron hydroxo and alkyl radical intermediates [15]. Subsequent RLT of the hydroxo ligand to the alkyl radical produces a hydroxylated

**Scheme 1:** Overview of the RLT mechanism in nature and in literature. I: The radical rebound mechanism in cytochrome P450 enzymes consists of HAT on a C–H bond, followed by RLT with a hydroxy ligand. II: Kochi reported the oxidation of alkyl radicals through LMCT of copper(II) chloride and subsequent radical chlorine ligand transfer [26]. 1-Cyclohexene was also reported to be oxidized to the vicinal dichlorinated product through a similar mechanism. III: RLT has become more prevalent in reported catalytic cycles involving radical-based transformations including alkene difunctionalization and decarboxylative functionalization. Many of these transformations have also utilized LMCT as a means of generating reactive radical species.
product, allowing for metabolism and excretion of previously diverse bioactive compounds. Similar RLT “rebound” steps have been implicated in non-heme oxygenase and halogenase enzymes as well [16-19], hinting that this strategy might be general; however, enzymatic examples outside of hydroxo and halide ligand transfer are scarce.

Groves’ initial discovery of the radical rebound behavior of P450 oxygenases encouraged early work on site-selective C–H functionalization [20]. Throughout their studies, it was found that manganese could perform the same HAT and RLT steps as iron at heme active sites. Groves developed the manganese tetramesitylporphine catalyst V (Scheme 2), which was found to be capable of functionalizing specific C–H bonds to numerous functionalities, including C–F [21,22], C–N$_3$ [23], and C–Cl bonds [24,25]. Upon these remarkable observations, methodologies involving manganese–porphyrin catalysts have been developed over the years. These methods take advantage of the power of RLT to install a variety of medicinally relevant groups, largely mirroring the selectivity of CYP450s. Intriguingly, studies by Groves have revealed earth abundant iron and manganese to be particularly privileged for this application of RLT, a major advantage for sustainable method development.

Outside of bioinorganic chemistry, the concept of radical ligand transfer was investigated in early work by Jay Kochi in purely synthetic systems (Scheme 1) [26,27]. Studies on the oxidation of alkyl radicals with earth abundant cupric salts uncovered the
ability of simple Cu(II) chloride to form new C–Cl bonds in the presence of transient alkyl radicals, with mechanistic studies implicating homolytic abstraction of a chlorine ligand from the intermediate copper complex. Outside of the substitution products which could be generated from the RLT pathway, alkyl radicals could also undergo an elimination-like pathway to afford unsaturated C–C bonds in the presence of copper(II) sulfate, presumably via competitive RPC to the carbocation followed by E1 olefination.

Kochi also demonstrated that RLT can be combined with other radical generation strategies to enable new, non-biomimetic reactions to be achieved (Scheme 1), showing that photolysis of stoichiometric Cu(II) chloride in the presence of unactivated alkenes allows for direct formation of vicinal dichloride products. The mechanistic study implicated initial formation of a chlorine radical through homolysis of a Cu–Cl bond via ligand-to-metal charge transfer (LMCT) which, following cage escape, could add to the alkene to generate an alkyl radical. This alkyl radical could then be chlorinated via RLT from a second Cu(II) chloride species, furnishing the dichlorinated product. While copper was unable to be used catalytically in this early report, it augured the potential of RLT to be a general strategy in synthetic method development, with modern examples including new alkene addition reactions and decarboxylative functionalizations (Scheme 2).

Recent applications of RLT in catalysis
Upon the discovery and initial exploration of the RLT paradigm by Groves and Kochi, many groups have adopted and characterized new ways of using RLT to form valuable carbon–heteroatom bonds from a diverse pool of simple starting materials. RLT has been especially present in modern catalysis, where complexes of earth abundant iron and manganese have been demonstrated to be particularly privileged in delivery of various ligands to alkyl radicals (Scheme 2). These developments have been supported by discovery of the compatibility of RLT with many different reaction paradigms leading to alkyl radical intermediates under catalytic conditions, including radical addition to alkenes and radical decarboxylation, with many of these being driven by light energy.

RLT in alkene functionalization
Outside of the realm of C–H activation, RLT has been leveraged to afford complex medicinal scaffolds in alkene difunctionalization. A recent example can be found in the merger of RLT with photoredox-catalyzed atom transfer radical addition (ATRA) (Scheme 3). ATRA results in the net addition of a C–X bond across an alkene, forming both valuable C–C and C–X bonds in a single reaction. While ATRA-type reactions were first reported in the 1940s by Kharasch [28], interest in the area was revitalized the early 2010s with the advent of Stephenson’s photoredox catalytic methods which dramatically simplified reaction conditions [29,30], driving ongoing interest in this mechanistic approach [31].

Our group recently devised a dual catalytic method which combines the RLT paradigm with photocatalytic ATRA to enable the modular difunctionalization of alkenes under reagent control (Scheme 3). In Stephenson’s photocatalytic ATRA reports, the C–X bond in the product was proposed to be formed through both direct quenching of a transient alkyl radical by halogen atom transfer (XAT) from the alkyl halide reagent and further oxidation of the transient radical to a carbocation by radical polar crossover (RPC), providing two mechanistic pathways to form the ATRA products [32]. While powerful, this approach is inherently incompatible with introducing alternative functionality instead of the halide included in the alkyl halide reagent, limiting the ability to form different difunctionalization products. Taking inspiration from Groves’ bio-inspired manganese tetradentate manganese catalysts, we found we could instead functionalize the transient alkyl radical via RLT from a simplified manganese salen complex I, allowing for the identity of the carbon–heteroatom bond to be controlled based on added nucleophile and enabling C–Cl, C–N, and C–S bonds to be formed directly while completely suppressing traditional ATRA products [9]. In mechanistic studies, rearrangement products indicative of a carbocationic pathway are not observed, suggesting that RPC does not occur. Further, the inability of ATRA products to undergo S_N2 with the added nucleophiles under our reaction conditions is inconsistent with a tandem ARTA/nucleophilic displacement alternative mechanism. Finally, a functionalization via the canonical organometallic steps of oxidative addition/reductive elimination was ruled out via catalytic reaction of the macrocyclic Groves-type porphyrin catalyst V, a species that is unable to accommodate the mutual cis-orientation of ligands for metal-centered reductive elimination. The system was found to be compatible with unactivated alkenes bearing a wide range of functionalities, including more-substituted alkenes, and a wide range of alkyl halide reagents, permitting a library of difunctionalized products to be prepared from a single alkene.

RLT can also be used to deliver valuable homodifunctionalized products using unactivated alkenes. Vicinal diazides (and to a lesser extent dihalides) have been popular targets for modern method development. Both photochemical [33] and electrochemical [34-36] methods have been effective in delivering products containing these molecular motifs. Intriguingly, several recent alkene diazidation methods have made RLT a key design criterion, with both thermal and photochemical driving forces [37].
Recent interest in alkene diazidation was accelerated by a 2016 report from Xu detailing alkene diazidation using low loadings of a molecular iron catalyst II and stoichiometric hydroxyiodinane as a terminal oxidant [38]. It is proposed that an azidohydroxide is generated in situ and serves as the radical initiator, generating an azido radical which adds to the less substituted position on the alkene. The resultant transient radical is captured via RLT from an in-situ generated iron–azide complex, resulting in net reduction of iron. The competent RLT species can then be regenerated through oxidation by the iodonane species and coordination of another equivalent of azide. This reaction was particularly notable for the wide alkene
scope, including terminal aliphatic alkenes, internal (cyclic) styrenes, and one example of a nonconjugated diene, suggesting RLT to be compatible with many functionalities. The diastereoselectivity of the reaction varies, with high anti-selectivity being achieved with cyclic styrenes and low diastereoselectivity in linear internal alkenes.

Building on this key iron catalysis result, our group and that of Shi contemporaneously reported the photochemical diazidation of alkenes using stoichiometric iron and no external oxidant or ancillary ligand, providing a simple protocol for the preparation of vicinal diamines with excellent functional group compatibility (Scheme 3) [10,39]. In both reports, it is proposed that photoinduced LMCT of an in-situ generated Fe(III) azide species furnishes an azido radical, compatible with unactivated alkene addition. These steps provide the reactive carbon-centered radical intermediate. RLT to this radical from another azide ligand leads to a diazidated product. The overall scope of both reports suggests that the diazidation of simple to complex drugs/natural product-derived alkene substrates is readily achievable, including highly substituted and cyclic aliphatic alkenes. Further, we demonstrated that diazidation could be rendered catalytic using Fe(III) nitrate hydrate III as the iron source and performing the reaction under continuous flow conditions. Interestingly, this mechanism bears some similarity to Lin’s electrocatalytic diazidation, where azido radical generation is proposed via thermal homolysis of a Mn(III) azide species and RLT from a second equivalent of Mn(III) azide furnishes the desired organic diazide, providing a strong demonstration of the applicability of RLT to not only photochemical but electrochemical conditions as well [35].

RLT in decarboxylative functionalization

Aside from its strategic application in alkene difunctionalization methods, RLT has also found synthetic utility in radical decarboxylative reactions. Radical decarboxylative functionalization reactions to form C–X bonds have been demonstrated, with bond construction being proposed to follow one of two pathways: formation of a carbocation through RPC followed by nucelophilic attack or direct RLT from a redox-active metal complex.

Preliminary evidence for a radical decarboxylation/RLT cascade was reported in 1965, when Kochi demonstrated decarboxylative chlorination of various acids with lead(IV) tetraacetate in the presence of lithium chloride (Scheme 4) [40,41]. Nucleophilic lithium chloride was used as the chlorine atom source for this transformation. In the representative scope of this transformation, primary and secondary chlorides could be formed in relatively high yields from their respective acids, a result incompatible with a carbocation RPC mechanism. This Kochi decarboxylative chlorination separated itself from other pioneering methods of decarboxylative functionalization (i.e., Barton and Hunsdiecker) because of its inclusion of RLT as a key element of the mechanism.

In 2015, the Groves group reported their manganese porphin-based catalyst V and related species being capable of participating in decarboxylation reactions (Scheme 4) [42]. The activated Mn(V) species is proposed to perform HAT carboxylic acid O–H bond, directly forming a carboxyl radical and Mn(IV) species which can exchange its hydroxo ligand for a fluoride from triethylamine tris(hydrofluoride) (Scheme 4). Rapid decarboxylation of this intermediate produces the alkyl radical species which could be fluorinated via RLT from the Mn(IV)–F complex, generating a Mn(III) intermediate. To close the cycle and reform the oxo ligand on the Mn(V) species, a stoichiometric amount of iodosylbenzene is used in the reaction.

While initial development of this reaction focused on incorporating the stable 19F, subsequent study expanded the scope to RLT of the unstable 18F radioisotope, an important medical radioisotope used for positron emission tomography (PET) [43]. Optimized conditions of both isotopes included fast reaction times of under two hours; in the case of the 18F radioisotope, reactions were carried out in 10 minutes and resulted in moderate to high yields, demonstrating the potential of RLT reactions to be rapid and efficient. In both cases, benzylic carboxylic acids were most amenable as substrates, with alkyl carboxylic acids such as adamantane and dicyclohexylmethane providing fluorinated aliphatic products in low to moderate yields.

Asymmetric RLT catalysis has also been of recent interest, with exciting preliminary decarboxylative azidation results obtained under thermal conditions by Hongli Bao and co-workers [44]. An asymmetric iron (NON) pincer catalyst IV was employed to decarboxylate benzyl peroxysteresters and form enantiomerically enriched benzyl azides. An Fe(II/III) cycle is proposed, where a single electron transfer from Fe(II) reduces the peroxyster and produces a carboxyl radical and Fe(III), which can coordinate an azide ligand. Rapid decarboxylation produces the transient alkyl radical which can be asymmetrically azidated by RLT from an Fe(III) azide complex, reducing the iron catalyst back to the starting Fe(II) state. Organic azides can be formed in moderate to high enantioselectivity using this approach; however, the scope is largely limited to benzylic products, a result in line with Groves’ finding that benzyl acid substrates perform much more efficiently in decarboxylative RLT reactions than aliphatic acids [42]. Outside of decarboxylation, X. Peter Zhang recently reported the enantioselective synthesis of allylic amines through coupled HAT and RLT on allylic C–H bonds [45].
I. Lead-mediated decarboxylative chlorination

\[
\text{R} \text{–COOH} + \text{Pb(OAc)}_4 + \text{LiCl} \rightarrow \text{R} \text{–Cl}
\]

1.1–2.9 equiv
benzene reflux or light
R = aliphatic acids

Carbonate LMCT and chlorine RLT

\[
\begin{align*}
\text{AcO}^- &\rightarrow \text{AcO}^- + \text{Pb}^{III} + \text{Cl}^- \\
\text{LMCT} &\rightarrow \text{AcO}^- + \text{Pb}^{III} + \text{Cl}^- \\
\text{photo-thermal} &\rightarrow \text{R}^* \\
\text{activation} &\rightarrow \text{R}^* \quad \text{CO}_2
\end{align*}
\]

JACS 1965, 87, 1811–1812
JACS 1965, 87, 2500–2502
refs. [40,41]

II. Decarboxylative fluorination

\[
\text{R} \text{–COOH} \rightarrow \text{R} \text{–F}
\]

cat. V (2.5 mol %)
Et$_3$N–3HF (1.2 equiv)
PhIO (3.3 equiv)

DCE (1 mL, 0.5 mmol scale)
N$_2$, 45 min–1 h, 45 °C

III. Asymmetric decarboxylative azidation

\[
\text{R} \text{–CO}_2\text{–Bu} \rightarrow \text{R} \text{–N}_3
\]

cat. IV (3 mol %, ligand 4.5 mol %)
TMSN$_3$ (1.5 equiv)

THF (1 mL, 0.1 mmol scale)
N$_2$, 12 h, rt

Our group has recently leveraged iron photochemistry to build on these beautiful decarboxylative azidation examples, combining iron-mediated photodecarboxylation via LMCT and azide RLT (Scheme 5) [11]. Irradiating a substoichiometric amount of iron(III) nitrate hydrate III in the presence of carboxylic acid, TMS azide, and sodium carbonate allows for direct synthesis of alkyl azides for a wide range of both activated (benzylic) and unactivated carboxylic acids. Control reactions support the intermediacy of alkyl radicals and the absence of carbocation rearrangements in a variety of probe substrates disfavor the reaction proceeding via RPC.

Intriguingly, no additional oxidant is required for this process, implicating the nitrate counterion functioning as an internal oxidant to regenerate the active Fe(III) species capable of LMCT and RLT. This result is consistent with our finding that using a bulky cobalt porphyrin complex developed and utilized to perform both HAT and RLT. While many challenges remain for achieving general asymmetric induction in RLT catalysis, this advance represents an important step toward this aspirational goal with many lessons to build upon.
Our lab reported decarboxylative azidation of aliphatic and benzylic acids. I: The reaction proceeds via LMCT and RLT catalysis without the addition of terminal oxidant. II: The proposed mechanism includes reoxidation of the iron catalyst through inner-sphere electron transfer by anionic nitrate.

Iron nitrate can catalytically diazidate alkenes in flow with no additional oxidant and literature examples of nitrate oxidation of different transition metals, such as palladium. Control reactions further supported this proposal, including the inability of alternative Fe(III) salts (e.g., FeCl₃) to form more than stoichiometric azide product in the absence of added nitrate. We believe this adventitious discovery of nitrate functioning as a mild and selective oxidant in RLT catalytic systems presents many opportunities for future method development and are avidly pursuing this area of research.

Outlook

After scant exploration following its elucidation in early mechanistic studies of bioinorganic and synthetic systems, radical ligand transfer (RLT) has reemerged as a powerful tool in the design of catalytic radical reactions. This development has been fueled by the unique aspects of RLT, with its ability to functionalize radicals with diverse nucleophilic reagents and inherent compatibility with different elementary steps, including hydrogen atom transfer (HAT) and ligand-to-metal charge transfer (LMCT), enabling new transformations to be unlocked with unprecedented modularity. Further, the privileged position of earth abundant elements such as iron and manganese in RLT has made reactions using this step appealing from a sustainability standpoint. While exciting progress has been made, many opportunities remain using this mechanistic approach. Two key areas that could yield exciting advances are combining RLT with new radical-generating elementary steps and the further development of asymmetric RLT processes. We hope that this perspective provides a useful framework for understanding RLT reactivity and inspires new advances using this versatile and intriguing elementary step.

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References

α-(Aminomethyl)acrylates as acceptors in radical–polar crossover 1,4-additions of dialkylzincs: insights into enolate formation and trapping

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Full Research Paper

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Keywords:
β-amino acids; tandem reactions; radical–polar crossover; tert-butanesulfinamide; zinc radical transfer

Abstract

We demonstrate that α-(aminomethyl)acrylates are suitable acceptors for 1,4-additions of dialkylzincs in aerobic conditions. The air-promoted radical–polar crossover process involves the 1,4-addition of an alkyl radical followed by homolytic substitution at the zinc atom of dialkylzinc. Coordination of the nitrogen atom to zinc enables this Sn2 process which represents a rare example of alkylzinc-group transfer to a tertiary α-carbonyl radical. The zinc enolate thus formed readily undergoes β-fragmentation unless it is trapped by electrophiles in situ. Enolates of substrates having free N–H bonds undergo protodemetalation to provide ultimately the 1,4-addition adduct. In the presence of carbonyl acceptors, aldol condensation occurs providing overall a tandem 1,4-addition–aldol process. When a tert-butanesulfinyl moiety is present on the nitrogen atom, these electrophilic substitution reactions occur with good levels of chiral induction, paving the way to enantioenriched β²-amino acids and β²,²-amino acids.

Introduction

Dialkylzinc reagents react in aerobic medium with a range of α,β-unsaturated carbonyl compounds to provide the corresponding zinc enolates (Scheme 1) [1,2]. While simple, this reaction offers attractive features: 1) it proceeds under mild conditions in the absence of any transition-metal catalyst; 2) the 1,4-addition step can be combined with condensation reactions of the zinc
enolate with electrophiles in protocols wherein all the reactive partners can be introduced from the start, given that dialkylzinc reagents offer a large functional group tolerance; and 3) the radical character of the process allows for the use of alkyl iodides as alkyl source in multicomponent reactions. Trialkylboranes can react in a similar way with enones [3] whereas, distinctively, suitable acceptors for the reaction with dialkylzinc reagents also include \(\alpha,\beta\)-unsaturated carboxylic acid derivatives such as \(\alpha,\beta\)-unsaturated (di)esters [4,5], \(N\)-enoyloxazolidinones [6,7], \(N\)-enoyloxazolidines [8], or alkylidendemalonates [9-11]. These reactions follow a free-radical chain process wherein alkyl radicals (R•) add across the C–C double bond of the 1,4-acceptor, activated by complexation with the dialkylzinc, to deliver an enoxyl radical that undergoes homolytic substitution at zinc (S\(_2\)) to produce a zinc enolate and a new R• that propagates the radical chain (Scheme 1). Initiation occurs upon oxidation of the dialkylzinc reagent by oxygen.

The feasibility of such 1,4-addition reactions is fully reliant on the ease of the intermediate enoxyl radical to undergo alkylzinc-group transfer. Secondary \(\alpha\)-carbonyl radicals (Scheme 1, R\(^1\) \(\neq\) H) undergo readily homolytic substitution. By contrast, tertiary \(\alpha\)-carbonyl radicals (Scheme 1, R\(^1\) \(\neq\) H) are less prone, making additions to \(\alpha\)-substituted 1,4-acceptors more challenging. Typically, ethyl methacrylate does not react with dialkylzinc reagents [12]. Notwithstanding, 1,4-additions of dialkylzinc reagents have been reported with dehydroamino ester derivatives [13,14] and \(\alpha\)-bromoacrylates [15], which both involve an S\(_2\) at zinc of tertiary \(\alpha\)-alkoxycarbonyl radicals (Scheme 2, top). Here, the key to unlock the reactivity is the presence of a Lewis-basic substituent coordinated to the zinc atom: this offers a gain in enthalpy associated to the formation of zinc enolates stabilized by chelation and increases the spin density delocalized at the oxygen atom involved in the chelate. Note that the reported 1,4-additions of dialkylzinc reagents to alkylidendemalonates could benefit from a similar effect, even though in this case, the direct formation of an intermediate enolate remains uncertain [11].

With this context in mind, we surmised that \(\beta\)-aminoenoates I could be suitable 1,4-acceptors (Scheme 2, bottom). We previously reported tandem reactions of such substrates wherein the intermediate enoxyl radical II arising from the addition step evolves via intramolecular addition to tethered alkenes [16,17] or alkynes [18]. We wondered if, in the absence of the pending radical acceptor, the presence of the \(\beta\)-nitrogen atom could nevertheless promote zinc enolate formation. Trapping of this enolate would lead to \(\beta\)-amino acid units, a class of compounds that has attracted a great deal of attention [19-24]. An obvious possible shortcoming that had to be considered was still that the generated zinc enolate III having a \(\beta\)-amino group could undergo \(\beta\)-elimination, thereby precluding its synthetic exploitation.

**Results and Discussion**

**Preparation of \(\alpha\)-(aminomethyl)acrylates**

We commenced our study by preparing a selection of \(\alpha\)-(aminomethyl)acrylates with variations of the nitrogen protecting group and the ester substituent. Towards this end, the direct allylation of primary amines 1–3 with methyl \(\alpha\)-(bromo-
methyl)acrylate was contemplated first under several typical conditions that all afforded non-synthetically useful mixtures of mono- and diallylation, even if excess of the nitrogen nucleophiles was used. An alternative strategy was thus developed relying on the allylation of lithium (trimethylsilyl)amides prepared in situ from the parent amines by a lithiation/silylation/lithiation sequence (Table 1). Using this protocol, α-(aminomethyl)acrylates 5 and 6 derived from benzhydrylamine and aniline were prepared in high yields (Table 1, entries 1 and 2). The procedure was poorly efficient with tosylamine, leading to product 7 in low 20% yield.

With the aim to develop asymmetric variants, we also considered the synthesis of N-(tert-butanesulfonyl) α-(aminomethyl)acrylates 8a–c. For this purpose, the application of the same protocol with (±)-tert-butanesulfinamide (4) and the requisite α-(bromomethyl)acrylates gave satisfactory yields as well. Finally, N-benzyl-N-(tert-butanesulfinyl) α-(aminomethyl)acrylate 10 was prepared by allylation of lithiated N-benzyl tert-butanesulfinamide 9 (Scheme 3).

### 1,4-Addition reactions
Having the requisite α-(aminomethyl)acrylates in hands, we carried out an initial survey of their reaction with Et$_2$Zn in CH$_2$Cl$_2$ at −33 °C on addition of air. In these conditions, acrylate 10 led to the recovery (following aqueous work-up) of sulfinamide 9 without traces of formation of the 1,4-adduct (Scheme 4).

By contrast, 1,4-addition without subsequent fragmentation was observed starting from α-(aminomethyl)acrylates having free N–H bonds (Table 2). The reaction of Et$_2$Zn with acrylates 5–7 afforded the desired 1,4-addition products 11–13 in 42–55% yield. Better results were obtained starting from 8a, which delivered adduct 14a in 79% yield and 70:30 dr. We also noted that in the absence of deliberately added air, these reactions proceeded only with low conversion. For instance, starting from 8a, product 14a was obtained in only 25% yield along with ≈70% of starting material recovery.

These results are relevant in the sense that not only they demonstrate that the oxygen-promoted 1,4-addition of α-(aminomethyl)acrylates with free N–H bonds is a productive process,
Table 2: Air-promoted 1,4-addition of Et₂Zn onto α-(aminomethyl)acrylates having free N–H bonds.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate (R)</th>
<th>Product</th>
<th>Yieldb</th>
<th>drc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 (CH(Ph)₂)</td>
<td>11</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6 (Ph)</td>
<td>12</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7 (Ts)</td>
<td>13</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8a (S(O)(t-Bu))</td>
<td>14a</td>
<td>76</td>
<td>70:30</td>
</tr>
<tr>
<td>5</td>
<td>8a (S(O)(t-Bu))</td>
<td>14a</td>
<td>25d</td>
<td>50:50</td>
</tr>
</tbody>
</table>

General conditions: α-(aminomethyl)acrylate (0.2 mmol), Et₂Zn (1.0 mmol), CH₂Cl₂ (6 mL), air (20 mL introduced via syringe at 0.5 mL·min⁻¹ rate).

Isolated yield. Ratio of diastereomers measured by ¹H NMR spectroscopy prior to purification. No air was added.

but also that the tert-butanesulfinyl moiety is well tolerated and that 1,4-stereoinduction can be achieved. Hence, in order to improve the levels of diastereoselectivity, we investigated further the reaction conditions starting with enoate 8a as model substrate (Table 3).

Carrying out the reaction at −78 °C instead of −33 °C was deleterious both for the yield and the selectivity (Table 3, entry 2). By contrast, we rapidly learned that leaving diethylzinc in contact with the starting acrylate for 1 h prior to the addition of air had a significant impact on the stereoselectivity. When air was

Table 3: Optimization of the air-promoted 1,4-addition of dialkylzinc reagents onto N-(tert-butanesulfinyl) α-(aminomethyl)acrylates.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate (R₂)</th>
<th>Product</th>
<th>Variation of conditions</th>
<th>Yieldd</th>
<th>drc,d</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8a (Me)</td>
<td>14a</td>
<td>none</td>
<td>76</td>
<td>70:30</td>
</tr>
<tr>
<td>2</td>
<td>8a (Me)</td>
<td>14a</td>
<td>−78 °C instead of −33 °C</td>
<td>60</td>
<td>57:43</td>
</tr>
<tr>
<td>3</td>
<td>8a (Me)</td>
<td>14a</td>
<td>oxygen (5 mL) was added at once immediately after Et₂Zn</td>
<td>83</td>
<td>59:41</td>
</tr>
<tr>
<td>4</td>
<td>8a (Me)</td>
<td>14a</td>
<td>toluene instead of CH₂Cl₂</td>
<td>82</td>
<td>75:25</td>
</tr>
<tr>
<td>5</td>
<td>8a (Me)</td>
<td>14a</td>
<td>hexane instead of CH₂Cl₂</td>
<td>82</td>
<td>85:15</td>
</tr>
<tr>
<td>6</td>
<td>8b (t-Bu)</td>
<td>14b</td>
<td>hexane instead of CH₂Cl₂</td>
<td>88</td>
<td>85:15</td>
</tr>
<tr>
<td>7</td>
<td>8c (Bn)</td>
<td>14c</td>
<td>none</td>
<td>76</td>
<td>70:30</td>
</tr>
<tr>
<td>8</td>
<td>8a (Me)</td>
<td>15a</td>
<td>none</td>
<td>71</td>
<td>67:33</td>
</tr>
<tr>
<td>9</td>
<td>8a (Me)</td>
<td>16a</td>
<td>none</td>
<td>n.r.e</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8a (Me)</td>
<td>16a</td>
<td>hexane instead of CH₂Cl₂</td>
<td>n.r.e</td>
<td></td>
</tr>
</tbody>
</table>

All reactions were conducted at a 0.2 mmol scale using 20 mL of air. Isolated yield (mixture of diastereoisomers). Measured by ¹H or ¹³C NMR spectroscopy prior to purification. The relative configuration of the major diastereomer is shown in the scheme; it was determined by chemical correlation for 14b (see below) and inferred by analogy for 14a and 14c. No reaction.
introduced directly after Et$_2$Zn (Table 3, entry 3) a much lower 59:41 dr was observed. This behavior was suggestive of the need for coordination of diethylzinc both to the carbonyl and sulfinyl unit to achieve good levels of selectivity. Hence, to reinforce Lewis pair formation, the reaction was also carried out in apolar solvents such as toluene and hexane (entries 4 and 5 in Table 3). In hexane, an 88% yield with 85:15 dr was obtained, which constituted the best conditions. Importantly, the protocol was found to be similarly applicable with enoates 8b (Table 3, entry 6) and 8c (entry 7) having tert-butyl and benzyl ester groups, which, as the methyl ester unit, are typical in the context of amino acid synthesis. ZnBu$_2$ was also amenable to 1,4-addition (Table 3, entry 8), but not ZnMe$_2$ (entries 9 and 10). This difference can be ascribed to a less favorable homolytic substitution reaction of ZnMe$_2$ in relation to its higher analogues and is in line with previous literature observations [11].

The configuration of the major diastereomer was determined by chemical correlation (Scheme 5). Product (R,S)-14b (85:15 dr), i.e., a mixture of two enantiomerically pure diastereomers, was obtained from (R,S)-tert-butylsulfinamide upon allylation with tert-butyl α-(bromomethyl)acrylate followed by 1,4-addition with Et$_2$Zn. It was then converted into the known β2-amino acid 17 by TFA-promoted concomitant deprotection of the nitrogen and the ester groups. The sample was found to have a negative optical rotation, thereby indicating that the major enantiomer present had S configuration [26]. This allowed to establish that the configuration of the major diastereomer present in (R,S)-14b was (R,S), and thus the sense of chiral induction for the 1,4-addition reactions reported in Table 2.

![Scheme 5: Chemical correlation to determine the configuration of the major diastereomer of (R,S)-14b.](image1)

**Tandem 1,4-addition–aldol condensation reactions**

We then went on to consider tandem 1,4-addition–aldol condensation reactions (Scheme 6), which offer the interesting prospect of generating an all-carbon quaternary stereocenter. α-(Aminomethyl)acrylates 5–7 reacted smoothly at –33 °C within 2 h with Et$_2$Zn in the presence of cyclohexanone to afford amino alcohols 18–20 in quite good yields (63–68%). Even better yields were obtained with enoates 8a and 8b both with cyclohexanone and acetone as carbonyl partners. Starting from 8a and carrying out the reaction in CH$_2$Cl$_2$, product 21a was obtained in 86% yield with 75:25 dr. Alike for the 1,4-addition protocol, better stereinduction was obtained by performing the reaction in hexane: 8b was converted into 21b and 22 in 77–84% yield with higher than 90:10 dr. It is also interesting to note that the levels of induction for the 1,4-addition–aldol condensations are somewhat higher than those obtained for the 1,4-additions. Aldehydes also proved competent terminal electrophiles for the tandem sequence. Illustratively, adducts 23 and 24 were obtained from α-(aminomethyl)acrylates 5 and 8a in 77–88% yields, albeit as poorly selective mixtures of diastereoisomers. This lack of stereocontrol is not surprising, given the well-known difficulty to control the relative configuration between the two adjacent stereocenters created during aldol condensations with zinc enoates.

![Scheme 6: Air-promoted tandem 1,4-addition–aldol condensation reactions of Et$_2$Zn with α-(aminomethyl)acrylates.](image2)
Mechanistic insights

The last part of our work was devoted to gain mechanistic insight for the developed reaction protocols through several diagnostic experiments. Regarding the 1,4-addition process, the lower reactivity noted in the absence of air (Table 2, entry 5) represents already a strong indication for a radical addition mechanism. This is further supported by the result of an I-atom transfer experiment (Scheme 7, top). In the presence of two equivalents of iPrI, the reaction of 8a with Et₂Zn leads to a mixture of product 14a and product 25a, incorporating an iPr moiety, in a 14a/25a 30:70 mixture. Product 25a is formed on addition of an iPr radical generated by I-atom transfer from iPrI to the Et radical, and is diagnostic for the formation of the latter in the reaction medium.

Deuterium labeling experiments were then performed to substantiate the formation of a zinc enolate following radical addition (Scheme 7, bottom). Much to our surprise however, no deuterium incorporation is observed on quenching with ND₄Cl/D₂O the reaction between 8a and Et₂Zn. By contrast, a significant deuterium incorporation is obtained when deuterated starting material (8a-d) is engaged. The combination of these two results is in agreement with the formation of a zinc enolate that undergoes protodemetation with the N–H (or N–D) as proton (or deuterium) source.

To further analyze the influence of the presence of an N–H function, we performed other reactions with N-benzyl enolate 10 which proved highly informative. As discussed previously (Scheme 4), application of the developed protocol for 1,4-addition to 10 only yields N-benzyl-1-tert-butyldiisulfynilamide following β-elimination. By contrast, in the presence of benzaldehyde, 1,4-addition–aldol condensation is predominant, yielding 26 in 56% yield as a 49:25:23:3 diastereomeric mixture (Scheme 8). When 10 is exposed to Et₃B in the presence of iPrI, benzaldehyde, and O₂, which are conditions known to promote radical 1,4-addition, only formation of telomers [7] is noted. This lends clear evidence that the intermediate enol radical does not intervene neither in the β-fragmentation (Scheme 4) nor in the addition across the carbonyl bonds.

Overall, the mechanistic investigations support the scenario depicted in Scheme 9. Oxygen (in air) triggers a free-radical chain reaction between α-(aminomethyl)acrylates and dialkylzinc reagents that entails 1,4-addition and S₂N₂ of the formed enoxyl radical facilitated by coordination of nitrogen to zinc. The zinc enolate thus formed evolves following different pathways according to the type of substrate and reaction conditions. In the absence of a carbonyl electrophile, enolates of substrates with trisubstituted nitrogen groups undergo β-fragmentation. By contrast, those derived from substrates having N–H bonds undergo protodemetalation to provide ultimately the 1,4-addition adduct. In the presence of carbonyl acceptors, these two competitive reactions are sup perseded and the enolate engages in aldol condensation regardless of its nitrogen substitution; the outcome of the reaction is a tandem 1,4-addition–aldol process. When the tert-butanesulfynil moiety is present on the nitrogen atom, electrophilic substitution of the intermediate enolates (protodemetalation or aldol condensation) occurs with decent levels of chiral induction. It should be mentioned here that our attempts to trap the intermediate enolate with a carbon electrophile other than carbonyl acceptors (i.e., iodomethane) were not...
successful and protodemetalation of the enolate outcompeted methylation.

![Scheme 9: Reactivity manifolds for the air-promoted tandem 1,4-addition-electrophilic substitution reaction between dialkylzinc reagents and α-(aminomethyl)acrylates (N-(tert-butanesulfinyl) derivatives shown).](image)

**Conclusion**

In conclusion, we have demonstrated that α-(aminomethyl)acrylates are suitable acceptors for 1,4-additions with dialkylzincs in aerobic conditions. Coordination of the nitrogen atom to zinc is crucial to enable the $S_{12}2$ step of the tertiary α-carbonyl radical that follows radical 1,4-addition in order to deliver a zinc enolate. The latter is poised to undergo β-fragmentation, but this process can be outcompeted by in situ electrophilic substitution reactions which offer synthetically useful procedures: 1,4-addition (for substrates having N–H bonds) or tandem 1,4-addition–aldol reactions (in the presence of carbonyl electrophiles). Asymmetric variants of these transformations are possible using the tert-butanesulfinyl chiral auxiliary on the nitrogen atom. The levels of 1,4-stereoinduction are significant but a convincing model to account for it cannot be put forward at this point. Nonetheless, from a synthetic methodology point of view, the reported protocols are relevant as they offer a new, direct and modular route to enantioenriched α-mono- and α,α-disubstituted β-amino acids (β2-amino acids and β2,2-amino acids), with, for the latter, the noteworthy stereocontrolled construction of an all-carbon quaternary stereocenter. Furthermore, our protocol provides a complement to existing literature, as none of the previously reported methods to convert α-(aminomethyl)acrylates into enantioenriched β-amino acids is applicable for the preparation of β2,2-amino acids [27-31].

**Experimental**

1. **Procedure for the monoallylation of primary amines and tert-butylsulfinamide (preparation of compounds 5–7 and 8a–c).** In a round-bottomed flask under argon, n-BuLi (1.0 equiv, soln. in heptane) was added dropwise to a THF (0.2 mol·L$^{-1}$) solution of the appropriate primary amine or tert-butylsulfinamide (1.0 equiv) at $-55$ °C. The mixture was then stirred at rt for 30 min, cooled to $-55$ °C, and trimethylsilyl chloride (1.0 equiv) was added. The mixture was then stirred at rt for 30 min, cooled to $-55$ °C, and n-BuLi (1.0 equiv, soln. in heptane) was added dropwise. The mixture was stirred at rt for 30 min, cooled to $-78$ °C, and the corresponding α-(bromo-methyl)acrylate (1.0 equiv) was added. The reaction mixture was then stirred for 2 h letting the temperature rise to rt and quenched with aq 1 M NH$_4$Cl. The aqueous layer was extracted with EtOAc (3×) and the combined organic layer was washed (brine), dried (MgSO$_4$), and concentrated under reduced pressure to provide the crude product which was then purified by column chromatography on silica gel.

2. **Procedure for the air-promoted 1,4-addition of dialkylzinc reagents to α-(aminomethyl)acrylates (preparation of compounds 11–13, 14a–c, and 15a).** In a Schlenk-tube under argon, the appropriate α-(aminomethyl)acrylate (0.2 mmol) was dissolved in the indicated reaction solvent (3 mL) and the solution was cooled to $-33$ °C. Then, Et$_2$Zn (1 M in hexanes, 1.0 mL, 1.0 mmol) was added dropwise and the solution was stirred for an additional 80 min at $-33$ °C and then quenched with aq 1 M NH$_4$Cl (5 mL) at 0 °C. The aqueous layer was extracted with CH$_2$Cl$_2$ (2×). The combined organic layer was washed (brine), dried (MgSO$_4$), and concentrated under reduced pressure to provide the crude product which was then purified by column chromatography on silica gel.

3. **Procedure for the air-promoted tandem 1,4-addition–aldol reaction between dialkylzinc reagents, α-(aminomethyl)acrylates and carbonyl derivatives (preparation of compounds 18–20, 21a–b, 22–24).** In a Schlenk-tube under argon, the appropriate α-(aminomethyl)acrylate (0.2 mmol) was dissolved in the indicated reaction solvent (3 mL) and the solution was cooled to $-33$ °C. The carbonyl electrophile (1.0 mmol) and then Et$_2$Zn (1 M in hexanes, 1.0 mL, 1.0 mmol) were added dropwise and the solution was stirred for 1 h. Air (20 mL) was introduced directly into the solution via a syringe fitted with a CaCl$_2$ pad at a 0.5 mL/min rate (syringe pump). After the end of the air addition, the mixture was stirred for an additional 80 min at $-33$ °C and then quenched with aq NH$_4$Cl (5 mL) at 0 °C. The aqueous layer was extracted with CH$_2$Cl$_2$ (2×). The combined organic layer was washed (brine), dried (MgSO$_4$), and concentrated under reduced pressure to provide the crude product which was then purified by column chromatography on silica gel.
(2×). The combined organic layer was washed (brine), dried (MgSO₄), and concentrated under reduced pressure to provide the crude product which was then purified by column chromatography on silica gel.

### Supporting Information

#### Supporting Information File 1
General information, characterization data, chemical correlation, and copies of NMR spectra.

[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-19-103-S1.pdf]

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### References

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Radical chemistry in polymer science: an overview and recent advances

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Abstract
Radical chemistry is one of the most important methods used in modern polymer science and industry. Over the past century, new knowledge on radical chemistry has both promoted and been generated from the emergence of polymer synthesis and modification techniques. In this review, we discuss radical chemistry in polymer science from four interconnected aspects. We begin with radical polymerization, the most employed technique for industrial production of polymeric materials, and other polymer synthesis involving a radical process. Post-polymerization modification, including polymer crosslinking and polymer surface modification, is the key process that introduces functionality and practicality to polymeric materials. Radical depolymerization, an efficient approach to destroy polymers, finds applications in two distinct fields, semiconductor industry and environmental protection. Polymer chemistry has largely diverged from organic chemistry with the fine division of modern science but polymer chemists constantly acquire new inspirations from organic chemists. Dialogues on radical chemistry between the two communities will deepen the understanding of the two fields and benefit the humanity.

Introduction
Early last century, with the groundbreaking macromolecular hypothesis by Hermann Staudinger [1], polymer science was born out of organic chemistry. Since then, polymer science has evolved into an important branch of physical science and a fundament of the modern life. Like many other organic methodologies, radical chemistry was applied to polymer science and nowadays, radical chemistry plays a critical role in both the production of a major portion of industrial polymers and the research on novel materials [2]. In this minireview, we discuss several aspects of radical chemistry found in polymer science.
radical polymerization, reversible deactivation radical polymerization, which emerged late last century. To continue with the discussion on polymer construction, section 2 explores some emergent polymer synthesis techniques via a radical process but other than a chain-growth mechanism by addition of radical species to vinyl monomers. In section 3, we cover radical chemistry approaches used in post-polymerization modification, including chemical crosslinking of polymers and polymer surface modification. Radicals are powerful tools for post-polymerization processes because of their exceptional reactivity. In contrast to the previous sections, we set the topic of section 4 on the radical degradation of polymers, both in nanofabrication and polymer upcycling.

Review

1 Radical polymerization

Radical polymerization has long been an effective and inexpensive method in the synthesis of polymers since it was invented, making it the most important industrial polymerization technique. Polymers produced by radical polymerization represent a major fraction of all industrial polymers.

1.1 Radical polymerization in nature

In addition to well-established processes in modern industry, examples of radical polymerization exist in nature. The principle of the two cases in the following text is based on the radical polymerization of catechol derivatives. Catechols are known as easily oxidizable compounds and are prone to undergo oxidation by losing one or two electrons [3]. This way, either semiquinone radicals or \( o \)-quinones are formed by single or double-electron oxidation, respectively [4]. The semiquinone radicals formed during the oxidation of catechol can undergo a cross-coupling reaction to form polymers (Scheme 1).

One example is the radical polymerization of urushiol. The earliest recorded application of natural radical polymerization can be traced back to the manufacture of lacquerwares several thousand years ago [5]. The surface coating of lacquerwares was made up of a sap from a lacquer tree growing in Asia. The lacquer sap obtained from \( Rhus vernicifera \) lacquer tree mainly consists of urushiol (60–65%), water (20–30%), lacquer polysaccharide (3–7%), water-insoluble glycoprotein (≈1–2%), laccase (≈0.2%), and stellacyanin (≈0.02%) [6,7]. Urushiol is the main active coating-forming ingredient of the resin. A typical urushiol is shown in Scheme 2. In a humid and warm environment, urushiol absorbs oxygen from air and is oxidized to a phenolic oxygen free radical under the action of laccase enzymes [5]. The radical then rearranges to form a semiquinone radical and reacts rapidly with a neighboring urushiol molecule to produce a biphenyl dimer. The dimers further polymerize to form the polymer [8].

Radical processes also occur in oceans. The mussel attachment system consists of a bundle of disc-tipped acellular thread called byssus, which connects the mussel to the surfaces of substrates [10]. A family of proteins called mussel foot proteins (mfp’s) distribute throughout the whole length of byssus while there is an extremely high concentration of mfp’s at the plaque–substrate interface. The mfp’s contain up to 27 mol % of DOPA (\( \text{L-3,4-dihydroxyphenylalanine} \)), which plays a crucial role on mussel adhesion [11]. Although the crucial role of DOPA in mussel adhesion is not fully understood, a prevailing view suggests that DOPA can be oxidized to \( o \)-quinones at an acidic pH and the quinones react with unoxidized catechols to form \( o \)-semiquinone radicals afterwards [12]. The semiquinone radicals can help DOPA adhere onto organic surfaces. At a basic pH, the system is cured and mechanically stabilized through the formation of DOPA-metal coordination bonds.

Scheme 1: Oxidation of catechol and subsequent cross-linking. Scheme 1 redrawn from [3].
cohesion of the DOPA-metal complex helps mussel adhere onto inorganic surfaces (Scheme 3).

1.2 Conventional radical polymerization
Radical polymerization, which IUPAC defines as ‘A chain polymerization in which the kinetic-chain carriers are radicals’ [13], is the most widely used reaction in polymer industry. As far back as the 1950s, the basic theory and comprehension of radical polymerization was established. In the past decades, radical polymerization was introduced to be an efficient industrial synthesis method to produce numerous chemicals such as low-density polyethylene (LDPE), polystyrene (PS), and
poly(vinyl chloride) (PVC) [14]. About half of the industrial polymers manufactured worldwide are produced by radical polymerization [15, 16].

1.2.1 Key features of radical polymerization: Radical polymerization, which has a classical chain reaction process, usually analyzed kinetically on the assumption of a steady state with respect to the concentration of chain carriers (radicals) [17]. Radical polymerization is a complex mechanism. The basic reactions have been known for quite some time now. They can be simply described by 8 equations (Equations 1–8) as follows. In the equations, $I_2$ represents an initiator molecule; $M$ represents a monomer molecule; $P_i$ represents a polymer chain with $i$ repeating units; $S$ represents a solvent molecule; and a dot indicates free radical species. These reactions are classified into four elementary steps: initiation, propagation, termination, and transfer. The initiation step includes Equation 1 and Equation 2, when the thermal initiator decomposes into two small-molecule radical species and the first monomer adds to the growing chain to form the first repeating unit. The propagation step is depicted in Equation 3 when monomers take turns to undergo radical addition. The termination step occurs by either disproportionation (radical β-elimination, Equation 4) or biradical coupling (Equation 5). Chain transfer (Equations 6–8) is usually considered as a type of side effect in radical polymerization [18]. It occurs between the growing chain and a transfer agent, which can be the monomer (Equation 6), the solvent (Equation 7), the polymer itself (Equation 8), or a chain-transfer agent intentionally added to tune the molecular weight or to introduce chain-end functionalities. When chain transfer happens, the originally growing chain halts while a new chain launches from the radical species formed from the chain transfer agent. In the case when a
Table 1: Common ways of radical polymerization in industry.

<table>
<thead>
<tr>
<th>method</th>
<th>contains</th>
<th>where polymerization happens</th>
</tr>
</thead>
<tbody>
<tr>
<td>bulk polymerization</td>
<td>monomer, initiator</td>
<td>in bulk</td>
</tr>
<tr>
<td>solution polymerization</td>
<td>monomer, initiator, solvent</td>
<td>in solution</td>
</tr>
<tr>
<td>suspension polymerization</td>
<td>hydrophobic monomer, hydrophilic initiator, water, suspending agents</td>
<td>in monomer droplet</td>
</tr>
<tr>
<td>emulsion polymerization</td>
<td>hydrophobic monomer, hydrophilic initiator, water, surfactants</td>
<td>in latex/colloid particles</td>
</tr>
</tbody>
</table>

growing chain-end radical transfers to its own backbone, i.e., backbiting occurs, a branching point forms as propagation continues in the middle of the backbone.

$$I_2 \xrightarrow{k_B} 2I^*$$

(1)

$$I^* + M \xrightarrow{k_I} P^*_1$$

(2)

$$P^*_n + M \xrightarrow{k_p} P^*_{n+1}$$

(3)

$$P^*_n + P^*_m \xrightarrow{k_{bd}} P^*_n + P_m$$

(4)

$$P^*_n + P^*_m \xrightarrow{k_{lc}} P^*_{n+m}$$

(5)

$$P^*_n + M \xrightarrow{k_{mon}} P_n + M^*$$

(6)

$$P^*_n + S \xrightarrow{k_{col}} P_n + S^*$$

(7)

$$P^*_n + P_m \xrightarrow{k_{pol}} P_n + P_m^*$$

(8)

Radical polymerization is applicable to a large number of vinylic monomers and is tolerant toward many solvents, functional groups, and impurities common in industrial systems, which makes it an ideal choice for industrial production [19]. Vinylic monomers should be thermodynamically and kinetically polymerizable. The former requires a sufficiently negative free energy of polymerization and the latter an adequate reactivity of the monomer, stability of the derived free radical, and a low proportion of side reactions.

A slow rate of chain initiation, a fast rate of chain propagation, and a rapid rate of chain termination are key features of conventional radical polymerization. Most free radicals have an extremely short lifetime due to a diffusion-controlled termination process between two free radicals. The inevitable termination between radicals makes the synthesis of well-defined polymers and co-polymers very difficult. In addition, polymers obtained from conventional radical polymerization are commonly linear polymers, though transfer to polymer may induce branching.

1.2.2 Radical polymerization in modern industry: In the commercial production of high-molecular-weight polymers, radical polymerization is a widely used method. Its main advantages are (i) the universality to a wide range of monomers such as (meth)acrylates, (meth)acrylamides, dienes, vinyl ethers/esters, etc.; (ii) tolerance to unprotected functionalities in monomers and the solvent including –OH, –COOH, –SO$_3$H, etc.; (iii) different reaction conditions, including bulk, solution, emulsion, and suspension; and (iv) inexpensive and facile setups compared to other polymerization techniques [20].

There are four common industrial methods of radical polymerization [2] as shown in Table 1.

The only components of a bulk polymerization mixture are monomers, the initiator, and optionally, a chain-transfer agent [21]. Products obtained from bulk polymerization have high optical clarity and are usually very pure [2]. The mechanism and equipment are relatively simple for a large-scale production in a short time. However, heat and mass transfer become difficult as the viscosity of the reaction mixture increases. This may lead to autoacceleration, also known as the Trommsdorff–Norrish effect, or even a violent explosive polymerization. At the same time, heat acquisition may cause a broad molecular weight distribution.

Solution polymerization can effectively mitigate problems of bulk polymerization. The use of a solvent can lower the viscosity of the polymerization system, leading to better mass and heat transfer. Good heat transfer can reduce the Trommsdorff–Norrish effect [22]. Meanwhile, the inhibited
termination reactions cause a significant increase in the overall yield.

Polyacrylonitrile (PAN), polyacrylic acid (PAA), and polyacrylamide (PAM), for instance, are obtained by solution polymerization in the polymer industry [23-25]. In addition to the reduced reaction rate due to lower monomer and initiator concentrations, one of the major disadvantages of solution polymerization is that it is difficult to completely rule out chain transfer to the solvent. Therefore, obtaining very high molecular weight product through solution polymerization is tough.

Suspension polymerization is a heterogeneous process and requires the use of a mechanical agitation to mix monomers and dissolved initiators in the liquid phase during the process. A suspending agent, e.g., polyvinyl alcohol (PVA), is added to the system to prevent coalescence. The viscosity in suspension polymerization is low throughout the process which brings good heat transfer and temperature control, and therefore well-defined and high-molecular-weight polymers. PVC, PS, and poly(methyl methacrylate) (PMMA) are industrially produced through suspension polymerization [2]. Nonetheless, the Trommsdorff–Norrish effect exists in suspension polymerization processes, and the residual suspending agent becomes an impurity.

Emulsion polymerization is also a widely-used method in radical polymerization. It is applied to produce several commercially important polymers such as acrylic rubber, nitrile rubber, and polytetrafluoroethylene (PTFE). Polymerization happens in latex or colloid particles that are formed under the action of surfactants, which are also called emulsifiers within the first few minutes [26]. Emulsifiers such as sodium lauryl sulfate, sodium or potassium salts of fatty acids (soaps), salts of alkybenzene sulfonates, and O-polyoxyethyleneated long-chain alcohols are used to change the two incompatible water phase and oil phase into an emulsion phase. The simultaneous presence of a hydrophobic head and a hydrophilic tail on emulsifiers provides the ability to combine water and oil phase into an emulsion. In emulsion polymerization, high molecular weights can be achieved at fast polymerization rates, because both the rate of polymerization and the molecular weight depends on the number of particles. A small latex particle only rooms a single propagating radical at a time. Thus, the chain keeps growing until another radical enters to terminate it. Due to the enormous number of particles, the overall radical concentration in the latex is greatly higher than in a typical bulk polymerization. Meanwhile, the polymerization rate is higher in emulsion polymerization compared to bulk or suspension polymerization. Radicals are divided in different particles also allows for longer lifetimes, which results in a higher degree of polymerization. As the frequency of radical entry decreases with the particle number at a certain initiator concentration, the rate of polymerization and molecular weight can be boosted by raising the number of particles, e.g. by tuning the monomer to surfactant ratio.

The final product can be used as is and does not generally need to be altered or processed. Drawbacks of emulsion polymerization include residual surfactants, significant chain transfer to polymer, and difficulty to dry polymers.

1.3 Reversible deactivation radical polymerization

A key drawback of conventional radical polymerization is that a limited control of molecular weights and architectures can be achieved due to the slow initiation and rapid termination. In 1956, Szwarc coined the term “living polymerization” in an anionic system [27]. Since then, polymer chemists have been in pursuit for a comparable “living radical polymerization”. Despite the fact that radical polymerization is never as “living” as the anionic counterpart, RDRP as per the IUPAC definition, or more commonly named controlled radical polymerization (CRP) has made a booming progress and attracted great attention in the past three decades [28].

1.3.1 Deactivation by reversible coupling: In 1982, Otsu and Yoshida [29] successfully polymerized styrene and MMA using dithiocarbamate compounds, and in 1986, Solomon et al. [30] published a patent entitled “Polymerization Processes and Polymers Produced Thereby”, which led to the successful nitroxide-mediated polymerization (NMP). In 1993, Georges et al. used benzoyl peroxide (BPO) as the initiator and 2,2,6,6-tetramethyl-1-piperidinyloxyl (TEMPO) as the control agent. It was called a bicomponent initiating system containing both stable free nitroxide and a conventional thermal initiator. Polystyrene of different molecular weights was obtained with low $M_w/M_n$ and active chain ends [31].

Although a bicomponent initiating system is economical and practical, the traditional initiators have many problems such as the poor initiation efficiency. It is difficult to control the molecular weight and polymerization rate precisely. In order to solve these problems, Hawker et al. [32-34] proposed the concept of the unimolecular initiation system. In this system, an alkoxyamine compound is used instead of the original nitroxide radical/initiator combination. These unimolecular initiators can decompose to produce a stoichiometric pair of the primary initiating radical and a nitroxide radical, thus combining the roles of a conventional initiator and a control agent. The mechanism is shown in Scheme 4 [35].

Due to the steric effect of TEMPO, the dissociation rate constant, $k_d$, of the corresponding alkoxyamine is very low and it
tends to undergo $\beta$-elimination in acrylic systems. Thus, TEMPO is only suitable for the polymerization of styrenic monomers at a high temperature and for long time [36]. Functionalized TEMPO was therefore developed for the polymerization of other monomers, such as acrylates, under milder conditions [37]. Grimaldi et al. [40] achieved NMP of styrene and $n$-butyl acrylate using SG1-type nitroxide radical (N-tert-butyl-N-(1-diethylphosphono-2,2-dimethylpropyl)nitroxide). Compared with TEMPO, SG1 was considered that it initiated the truly "living"/controlled polymerization at that time and the rate of propagation was much faster than with TEMPO under the same conditions.

1.3.2 Deactivation by atom transfer: Atom transfer radical polymerization (ATRP) was independently reported by the teams of Matyjaszewski [41] and Sawamoto [42] in 1995. The efficient conduct of ATRP relies on the establishment of a reversible activation/deactivation equilibrium reaction between an alkyl halide or halide-like initiator (RX) and a radical species ($R^\cdot$) [43]. During the activation process, the organohalides quickly lose their terminal halogen atoms in the presence of the liganded low-valent metal complex (activator, Mt$^2$/L, typically Cu$^I$/L) to form the active radical species ($R^\cdot$), which in turn initiates polymerization to form the active polymer chain species ($P_n^\cdot$). On the other hand, the termination reactions always present in the system causing the liganded high-valent metal complex (deactivator, $X$–Mt$^{2+}$/L, typically $X$–Cu$^{II}$/L) to accumulate. When the accumulation reaches a certain level, the deactivator interacts with the active radical chain species ($P_n^\cdot$), so that the radical chain species gets into the dormant state ($P_n^X$) via a halogen atom transfer process. This is the deactivation process. Activation and deactivation reactions are always present throughout the process, and the rate of deactivation must be sufficiently high in order to maintain a low radical concentration to effectively inhibit the termination [44]. The mechanism of ATRP is shown in Scheme 5 [14].

Compared with the earlier ATRP techniques (normal ATRP [41], reverse ATRP [45], SR&NI ATRP [46], and AGET ATRP [47]), the recently proposed ATRP techniques (ICAR ATRP [48], ARGET ATRP [49], SARA ATRP [50], eATRP [51, 52], photoATRP [53, 54], and ultrasonic ATRP [55]) require a much...
lower catalyst dosage, even down to 10 ppm [56], which to some extent, solves the problem of metal impurities. Meanwhile, the presence of external stimuli in eATRP, photoATRP, and ultrasonic ATRP, allows spatial and temporal control over the polymerization [57]. Hawker et al. proposed a metal-free ATRP in 2014 using an organic photoredox catalyst mediated by light to overcome the challenge of metal contamination in the precipitated polymers [58]. After the ATRP reaction, a reactive chain end retains as a stable alkyl halide moiety. Therefore, ATRP is particularly suitable for the synthesis of polymers with complex architectures [59,60].

1.3.3 Deactivation by degenerative transfer: Reversible addition-fragmentation chain transfer (RAFT) polymerization is one of the most well-established RDRP technique. It was first proposed in 1998 by Commonwealth Scientific and Industrial Research Organization (CSIRO) researchers Chiefari et al. [61]. Due to the presence of chain-transfer agents (CTAs), such as thiocarbonylthio compounds, in RAFT polymerizations, the chain propagating radical species can add to CTAs to form intermediate radical species. RAFT can rely on reversible chain-transfer reactions between the propagating radical species and the dormant chains to achieve controlled polymerization of the monomers, allowing all polymer chains to grow nearly simultaneously.

The product of RAFT polymerization has a preserved thiocarbonylthio chain end. The polymerization reaction can be continued by adding more monomers. Therefore, RAFT is often used to perform chain expansion reactions or to synthesize functionalized multi-block copolymers [62-64]. Boyer and co-workers developed a photocatalytically mediated RAFT polymerization, PET-RAFT, which removes the requirement for conventional radical initiators. The reaction is oxygen tolerant and can be carried out in a milder environment [65,66]. Pan and co-workers recently further advanced the RAFT techniques by allowing them to be fueled by oxygen [67]. The mechanism of a RAFT polymerization is shown in Scheme 6 [68].

Organometallic-mediated radical polymerization (OMRP) is also a commonly used polymerization method, which uses transition-metal complexes such as titanium and vanadium for coordination polymerization [69]. However, due to the high cost of these complexes and their post-processing, OMRP is not widely

**Scheme 6: Mechanism of RAFT polymerization.** Scheme 6 redrawn from [68].
used. The chain termination reaction of OMRP is considered to have two mechanisms, degenerative transfer and reversible termination, which are comparable to RAFT and NMP, respectively (Scheme 7) [70].

Iodine transfer polymerization (ITP) is also a commonly used degenerate chain-transfer method. Its origin can be traced back to the 1970s [71] and it is mostly used for the polymerization of fluorinated olefins. However, the C–I bond of iodoalkyl compounds used as chain-transfer agents is weak and unstable during storage [21]. Therefore, Lacroix-Desmazes et al. [72] used iodine molecules to synthesize iodine chain transfer agents in situ, a process known as reverse iodine transfer polymerization (RITP), which is similar to reverse ATRP. The mechanism of the RITP is shown in Scheme 8.

RDRP is applicable to a wide range of monomers and the reaction conditions become milder and more versatile with emerging techniques, such as oxygen tolerance or even oxygen initiation [73]. Compared with the conventional radical polymerization, RDRP has shown fascinating advantage in complex polymer polymerization. However, RDRP is currently less applied in industry due to cost and process obstacles. It is expected that future technical innovation will allow RDRP to be more widely employed.

2 Other polymerization techniques involving radical chemistry
As discussed in section 1, chain-growth polymerization via radical addition to vinyl monomers is the most broadly applied polymerization technique. However, radical chemistry is used in other polymerization systems. In this section, we cover these techniques excluded from our previous discussion.

2.1 Oxidative synthesis of conductive polymers
The breaking accomplishments of Shirakawa, MacDiarmid, and Heeger have changed our view of organic polymers, from insulating polymers to electrically (semi)conducting materials [74]. In 2000, they received the Nobel Prize in Chemistry. Typical conductive polymer structures have π-conjugation (Scheme 9A) [75]. They can be synthesized by various methods such as electrochemical and chemical methods. Oxidative polymerization and chain-growth polymerization are also good ways to produce conductive polymers (Scheme 9B) [76].
Nowadays, most conductive polymers are prepared via metal-catalyzed cross-coupling reactions [77]. However, radical polymerization is also an effective way to synthesize conductive polymers at a relatively low cost. Niemi et al. [78] used FeCl$_3$ as catalyst to produce radicals at the 2- and 5-positions of thiophene and synthesized four types of poly(3-alkylthiophene)s (PATs) with different linking ways (Scheme 10).

2.2 Polymerization by thiol–ene chemistry

The thiol–ene reaction (also called alkene hydrothiolation) is the anti-Markovnikov addition of a thiol to a C–C double bond and was first reported in 1905 [80]. It is considered as a click chemistry reaction due to its high yield, stereoselectivity, rate, and thermodynamic driving force.

Generally, the thiol–ene reaction is conducted under radical conditions, often photochemically induced [81]. In a typical thiol–ene system, the polymerization undergoes a free-radical chain mechanism, involving an initiation step from a thiol group via radical transfer or homolysis (Scheme 11, initiation), radical addition of the thiol radical to the ene functionality (propagation 1), transfer from the carbon-centered radical to another thiol group (propagation 2), and biradical termination between either carbon-centered or thiol radicals (termination).

Polymerization by thiol–ene coupling is a step-growth polymerization, which means it can produce polymers with no theoretical upper-limited molecular weight. The simple setup, mild conditions, absence of unfavored byproducts, orthogonality with other reactions, and high yields (nearly full conversion) [82] made thiol–ene polymerizations an ideal way to produce high-molecular-weight cross-linked polymers, optical polymers, biomacromolecules, and materials used in additive manufacturing. It is also compatible to a photopolymerization process. For example, it can be applied to the photo-3D-printing of silicone resin [83]. The refractive index is one of the most impor-
tant optical properties and researchers have invested plenty of effort to develop high refractive-index polymers. A common approach is to incorporate atoms or groups with high polarizability and sulfur is a typical constituent with high molar refractivity and is widely used in optical polymers. For example, Bhagat et al. [84] produced polymers with high cross-linking
density and refractive index from tetravinylsilane, ethanethiol, and benzenedithiol. Polymers made by thiol–ene polymerization usually have well-ordered molecular networks. This character gives thiol–ene polymers highly tunable mechanical response hence it shows great application potential in additive manufacturing. Cook et al. [85] presented the first report of volumetric additive manufacturing-printed thiol–ene resins and showed the potential of the thiol–ene system.

In addition to thiol–ene chemistry, radical hydrosilylation was also used to prepare linear, branched, or cross-linked polymers via a step-growth mechanism (cf. section 3.2) [86].

2.3 Metal-free ring opening metathesis polymerization (MF-ROMP)
ROMP is a powerful and broadly applicable technique for synthesizing polymers. Traditional ROMP systems are initiated by transition-metal complexes and Ru-based alkylidene complexes, which are also known as Grubbs catalysts (Scheme 12A), are the most popular ones [87]. However, Ru-based catalysts are expensive making them less attractive for industrial applications. Living ROMP is commonly terminated by adding a special chemical which can remove the transition metal from the chain end and deactivate it from propagation. However, removing this residue from the product by tradi-

Scheme 12: (a) Three generations of Grubbs catalysts. (b) Proposed mechanism for photo-ROMP via a reductive quenching pathway and (c, d) chemical structures of the (c) initiators and (d) monomers used in photo-ROMP. Scheme 12 redrawn from [89].
nitional chromatographic methods can be a challenging task and limits the application of ROMP-produced polymers in biomedical and microelectronic fields [88]. To avoid such drawbacks, the development of a metal-free (MF) procedures is necessary.

MF-ROMP, also termed photo-ROMP, is a novel technique to polymerize cyclic olefins. It begins with the reductive quenching of an photoexcited photocatalyst (PC) at an enol ether initiator to produce a radical cation carrier [90]. Then, the carrier undergoes cyclic addition with a cyclic olefin monomer to generate a cyclobutene radical cation intermediate. The thermodynamically instable intermediate subsequently forms the propagating radical cation species via a ring-opening process. The reduced PC•− terminates the catalytic loop by reducing the propagating species to provide a polymer chain (Scheme 12B). Boydston and co-workers [91], systematically studied various pyrylium and thiopyrylium PCs (Scheme 13). It is necessary for these PCs having a high excited-state redox potential to oxidize the enol ether initiators. A range of enol ether initiators that has been successfully applied in metal-free ROMP are shown in Scheme 12C.

Meanwhile, metal-free ROMP is applied to monomers like functionalized norbornenes and dicyclopentadienes (DCPD) (Scheme 12D) to synthesize polymers and block copolymers [88,92,93].

3 Post-polymerization radical chemistry

Post-polymerization modification is a chemical process that introduces functionalities to backbones or side-groups of pre-synthesized polymers [94,95]. It typically takes place in polymer solutions. On the other hand, surface modification of polymers is a special case of post-polymerization on polymeric solids. Radical chemistry is overwhelmingly more common in the latter because there are other more selective and efficient solution chemistry methods for post-polymerization modification, such as nucleophilic substitution [94,96]. In this section, we discuss the radical chemistry used in both processes.

3.1 Post-polymerization modification

Radical addition is a popular technique for post-polymerization modification of double-bond-containing polymers (Scheme 14). Thiol–ene and thiol–yne “click chemistry” are highly efficient radical processes well-adopted in synthetic chemistry, material fabrication, and chemical biology (cf. section 2.2) [97,98]. The S’ radical is typically generated using a thermal initiator or a photochemical process [99,100]. 1,3-Diene polymers are most commonly modified via thiol–ene chemistry through the pendant vinyl after the polymerization [101] and this technique can be traced back to 1948 [102]. The excellent temporal and spatial control of the available photochemical approach makes the technique especially viable for non-solution processes [103]. When a multifunctional thiol is used with diene-functionalized polymers, the approach becomes suitable for chemical cross-linking [103,104], vide infra. It has been used to cure a liquid isoprene polymer in precise digital light processing 3D printing [105]. Recently, Kanbayashi et al. reported that thiol–ene chemistry would not cause racemization of an asymmetric center linked to a pendant vinyl group, which can be particularly valuable for functionalization of optically active polymers [106]. Theato and co-workers introduced vinyl/alkyne-bearing poly(vinyl ethers) [107], poly(vinyl cyclopropanes) [108], and poly(ally1 2-yldenecetate) [109] as promising new platforms compatible to thiol–ene chemistry. Atom transfer radical addition (ATRA) is another process that usually qualifies for a definition of “click chemistry” [44]. A similar radical addition to vinyl groups takes place in ATRA despite the halogen atom transfer is mediated by a metal complex. Post-polymerization modification by ATRA was pioneered by Jérôme and co-workers [110,111]. In 2014, Xu et al. demonstrated that it can be extended to a milder photochemical process as well [112].

Radical coupling may also be used to introduce functional groups into polymer backbones. In this context, rapid radical trapping with stable nitroxide radicals is an efficient way [113]. However, this technique requires radical generation on the polymer backbone. A typical approach involves hydrogen abstraction by organic oxidants such as oxygen radicals from peroxide initiators [114], which is similar to the radical cross-
linking process, vide infra. Radicals may also be generated ther-
urally, through photoinduction, or by ATRP initiators incorpo-
rated in the polymer backbones [115-117]. TEMPO and its de-
rivatives have a long history of application as radical trapping
agents. Commercially available HO-TEMPO is a particularly
useful platform for post-polymerization modification via radical
coupling because of the chemical versatility of the hydroxy
moiety (Scheme 15). Site-selective radical C–H activation has
been proven to be a useful tool to functionalize relatively inert
polymer backbones and upcycling of polymer waste (cf. section
4) [118,119]. Radical chain-end modification as a highly specif-
type of post-polymerization modification introduces or
removes functionalities at polymer chain ends [120].

3.2 Chemical crosslinking of polymers

Chemical crosslinking is a suitable approach to increase chemi-
cal resistance [121], mechanical strength [122], and other prop-
erties [123] of polymers. In 1830s, Charles Goodyear invented
vulcanized rubber. By heating natural rubber with lead oxide
and sulfur, the temperature-sensitive rubber became a more
stable material, even at high and low temperatures, while
keeping the elasticity, plasticity, insulation, and other excellent
characteristics [124]. During the vulcanization of natural rubber,
elemental sulfur was heated to form sulfur radicals
which then react with natural rubber crosslinking two indepen-
dent polymer molecules [125]. This is a typical example of
polymer crosslinking by a radical mechanism.

As the traditional vulcanization process, an initiator is needed
to start the radical crosslinking. Besides sulfur, peroxides such as
di-tert-butylicumyl peroxide (BCUP) and dicumyl peroxide
(DCP) are often used in radical crosslinking. Free radicals are
generated at the peroxides’ decomposition temperature and
attack the polymer chains to achieve crosslinking (Scheme 16).
In dry crosslinking processing of crosslinked polyethylene
(XLPE) used in power delivery system, a blend of DCP in low-
density polyethylene (LDPE) is extruded at its melting point. In
comparison to LDPE, the operational temperature and the short-
circuit permissible temperature of XLPE cables are increased
from 70 °C to 90 °C and 150 °C to 230 °C, respectively.
Besides that, XLPE shows a more rubber-like behavior [126].
As the peroxide crosslinking process is industrially important,
multiple kinetic models have been established to understand the
reaction between polymers, peroxides, and monomers [127-
129].

Polysiloxanes are another class of crosslinkable polymers.
Modern silicone industry typically uses Pt-catalyzed hydrosily-
lation to crosslink multi-vinyl polysiloxane with silicon hydride
compounds to manufacture silicone rubbers [130]. However,
hydrosilylation may also be achieved via a radical mechanism
(Scheme 17). In comparison to the Pt-catalyzed system, the
radical-induced hydrosilylation has a lower cost, better toler-
ance to coordinating functionalities, and yields products without metal residues, but its efficiency is inferior to transition-metal catalyzed methods. Silicone rubber was prepared in such a process [131]. Pan and co-workers recently reported a photo-redox hydrosilylation process compatible to both electron-sufficient and -deficient vinyl species [86], and applicable to both post-polymerization modification and crosslinking of polymers bearing pendant vinyl groups [132], demonstrating a promising new orientation of radical hydrosilylation. It is noteworthy, that since the 1940s, polysiloxanes were crosslinked via hydrogen abstraction from Si–CH\textsubscript{3} and a radical coupling mechanism like polyolefins, vide supra [133].

Irradiation can also lead to the crosslinking of polymers. Polymeric materials may become brittle or colored after being exposed to sunlight for a long time, which was called ‘photo-ageing’ [134]. In fact, the light sensitivity of many polymers results from some impurities or additives remaining in polymer materials, which can form radical species through irradiation. This photooxidation process can lead to the generation of some small molecules or chain scissoring. At the same time, the photooxidation process can also result in crosslinking of polymer backbones [135]. Bousquet and Fouassier [135] investigated the photooxidation and crosslinking of photosensitized elastomers. Samples of an EPDM (ethylene-propenebutadiene) terpolymer were prepared with different additives. Observable crosslinking products were obtained through irradiation of different wavelengths. Besides the side reactions induced during photoaging, rational photocrosslinking of polymers is also feasible in the presence of photoinitiators or photoresponsive moieties [136-138]. Sophisticatedly designed photocrosslinking of polymers finds broad applications in modern 3D printing/additive manufacturing [139-142].

Radical chemistry has been demonstrated as a powerful tool for polymer crosslinking and preparation of materials with enhanced properties.

3.3 Polymer surface modification

When modifying the surface of polymers, chemical selectivity typically plays a minor role, while harsh reaction conditions are useful for the modification of chemically inert substrates. Here, radical chemistry comes into play. When polymer surfaces are modified by radical chemistry, radicals are either generated directly on the polymers or on modifiers. In the latter case, a radical addition, substitution, or coupling reaction takes place to complete the modification. Radicals can be generated by a broader selection of homogeneous and heterogeneous approaches, including hydrogen atom abstraction, decomposition of immobilized initiators, electrochemical redox reaction, or irradiation because the reactions only need to take place at the surface.

Small-molecule oxidants, such as organic peroxides, hydrogen peroxide, persulfates undergo homolysis of O–O bonds generating radicals that can break C–H bonds followed by a hydrogen abstraction reaction. Phenolic compounds can be oxidized by molecular oxygen in the presence of laccase, and the resulting phenolic radical reacts with poly(ethersulfone) [143]. Highly reactive gaseous species may also generate radicals on polymer surfaces. For example, atomic oxygen radical anions emitted from 12CaO·7Al\textsubscript{2}O\textsubscript{3} crystals [144] were used to modify PVC and poly styrene [145,146]. Plasma is also a powerful gas-phase tool for polymer surface modification and radical generation [147,148]. It can even generate radicals on otherwise inert fluoropolymer surfaces [149].

Electrochemical reactions are another approach to generate radicals at polymer surfaces. Hydroxyl radicals generated via the electro-Fenton reaction from H\textsubscript{2}O\textsubscript{2} in the presence of the Fe\textsuperscript{3+}\textsuperscript{-} were used to functionalize polypropylene surfaces [150,151]. Using a scanning electrochemical microscope, highly oxidative Ag(II) and NO\textsubscript{3} species were generated at a polymer surface [152], and oxidized the organic surface via a radical process. The homolytic dediazonation of diazonium salts produces highly reactive aryl radicals (Scheme 18) [153]. The chemical conversion can be initiated by electrochemical reduction [154], a reducing agent [155-157], a base [158], heating [159], or photochemically [160]. Aryl radicals may act as a halogen abstractor for alkyl halides and generate alkyl radicals for surface modification [161]. Electrochemical surface modification also works for inert PTFE surfaces in the presence of a 2,2’-dipyridyl redox mediator [162].

Photons and high-energy charged particles can transfer their energy to bound electrons in atoms, exciting the electron to a higher energy level or even the vacuum, generating radical species. The energy of UV photons is comparable to the energy of chemical bonds [163], and therefore photons are particularly
suitable for driving chemical reactions on polymer surfaces. Benzophenone is the best-established source of radicals on polymer surfaces. Its photoexcitation and subsequent reaction with polymers have been studied for decades [164-166]. When irradiated at around 360 nm, benzophenone undergoes excitation to a triplet state with biradical behavior. It then abstracts a hydrogen atom from the polymer resulting in a Ph₂C· species and a radical on the polymer (Scheme 19). This reaction may complete in radical coupling or proceed with radical polymerization from the surface [167-169], resulting in crosslinked polymers, surface-functionalized polymers, or surface-grafted polymers. RDRP was used to graft well-defined polymer brushes from polymer surfaces [170,171]. Photoinduced processes, including photoATRP and PET-RAFT were used [172-175]. Poly(aryl ether ketone)s such as poly(ether ether ketone), bearing a diaryl ketone moiety resembling that of benzophenone, can generate biradicals upon UV irradiation without a photoinitiator [176,177]. Grafted polymers and untethered polymers are generated simultaneously in the presence of a monomer.

Ionizing radiation including high-energy photons (X-rays and γ-rays) and charged α- or β-particles generate charged particles, especially electrons, emitted from the surface of polymers [178]. When a high-energy photon impacts an atomic electron, part of the photon energy is transferred to the electron leading to excitation or ionization and radical formation, and a deflected photon with lower energy is emitted, ready to impact another electron. This process is called Compton scattering [179]. One of the major purposes of radiation modification of polymer surfaces is grafting. The surface grafting can be simply tuned by the dose of radiation [180]. Radiation grafting on polymer surfaces is also compatible with RDRP for high density and well-defined polymer grafts [181-184]. Polymer surfaces can also be modified using electron and ion beams [185,186]. Komatsu et al. reported surface-initiated ATRP from electron-beam irradiated polymer surfaces [187].

The radical chemistry used for post-polymerization modification, crosslinking, and polymer surface modification has many
aspects in common. The key is to activate chemically unreactive polymer backbones with highly reactive radical species to construct new chemical bonds.

4 Radical depolymerization
Radical destruction of polymer chains is an undesirable side reaction sometimes observed in the post-polymerization modification. However, it is also an important chemical process in several circumstances.

Photoresist is one of the bedrocks of the semiconductor industry [188,189]. There are two types of photoresists, positive and negative photoresists, and they become more or less soluble upon radiation, respectively. Some early negative photoresists undergo a photochemical crosslinking process of 1,3-diene cyclic polymers [190] (cf. section 3.2), but such systems are no longer studied due to the poor resolution and sensitivity. On the other hand, positive resists based on decomposition of polymers, especially upon radiation with an electron beam, because of its narrow wavelengths, are still regarded as a promising alternative. Poly(methyl methacrylate) has a long history of being used as a positive resist [191,192]. It undergoes a scission by a Norrish-type I reaction followed by radical unzipping depolymerization under photon or β-irradiation (Scheme 20a). Similarly, poly(olefin sulfone) undergoes depolymerization upon irradiation of light or electron beams [193,194]. It is an alternating copolymer of 1-olefins and SO₂, and therefore the decomposition products are mostly gaseous [195]. While the depolymerization in both systems has a thermodynamic origin [196], the mechanism of poly(olefin sulfone) depolymerization is much more complex. Bowmer et al. proposed a simultaneous radical/cationic process (Scheme 20b) [197]. Meanwhile, an anionic process is also possible in the presence of a photogenerated base [198].

Thanks to their low cost, light weight, and durability, polymeric materials are ubiquitous in modern life. However, over the past decades, people have become aware of the environmental impact of polymeric wastes [199]. One of the approaches to tackle this crisis is upcycling of polymeric wastes, i.e., chemical conversion of polymeric wastes into high-value raw materials [200]. Upcycling of polyesters has been extensively studied in recent years [201]. Nevertheless, upcycling of vinyl polymers, which comprise a major portion of commercial

![Scheme 20: Depolymerization mechanism of common photoresists. (a) A possible mechanism of radiation decomposition of poly(methyl methacrylate). (b) A proposed mechanism of simultaneous radical/cationic decomposition of poly(olefin sulfone) upon radiation [197].](image-url)
polymers, remains a great challenge because of their relatively unreactive backbones. Pyrolysis of such polymers is currently experimented by the industry to recover a variety of small molecules. Researchers have introduced radical depolymerization of vinyl polymers as a promising candidate for this task. Oh and Stach reported the photooxidation of polystyrene in the presence of FeCl$_3$ as a radical source (Scheme 21a) [202]. A molar yield of 23% benzoyl small molecules was achieved. Reissner and co-workers employed a similar approach but using aromatic ketones as photocatalyst (Scheme 21b) [203]. Benzoic acid and other aromatic small molecules were recovered at a yield of ≈40% and ≈20%, respectively. Both processes were carried out under relatively mild conditions, paving a route toward a greener future of vinyl polymer upcycling. However, the yield and value of the small molecules produced in photooxidative depolymerization are still relatively low. Thermodynamics dominates the depolymerization of methacrylates [204,205]. Therefore, pyrolysis of PMMA gives a relatively high conversion to its monomer and the purification is straightforward [206,207].

Polyethylene and polypropylene make up a major fraction of commercial polymers. However, their upcycling is much more challenging. Uncontrolled radical depolymerization of these polymers in thermal processes typically gives low-value fuels and wax [208-210]. Kong et al. recently demonstrated a photothermal radical process for the conversion of polyethylene and polypropylene into blending compatibilizers [211]. Radical depolymerization capability can be incorporated at synthesis. Wang et al. introduced photodegradability to polyolefins by copolymerization of carbon monoxide [212]. Nevertheless, radical depolymerization is an essential tool to tackle the problem of polymer wastes.

**Conclusion**

Radical chemistry has been deeply intertwined with the development of polymer science. Conventional free radical polymerization contributes to a major portion of modern polymer industry while novel polymerization techniques involving radicals emerged in the past decades to enable a rich selection of precisely controlled, high-value polymeric materials. The extremely high reactivity of radical species enabled efficient polymer modifications and depolymerizations with applications in many aspects essential to the advancement of the human society. Since the dawn of polymer science, it has been inextricably linked to organic chemistry. However, the two fields took divergent paths over the past century. Many emergent radical chemistries in the organic chemistry community has not yet found a place in the polymer science. We believe this gap will narrow with a broader use of chemical informatics tools and in-depth dialogs between the organic and polymer communities. Therefore, future opportunities for polymer science evolution lie in the collaboration of radical chemists in both communities.

Used abbreviations in the text and their explanations are collected in Table 2.

**Scheme 21:** Proposed mechanisms of photooxidative depolymerization of polystyrene. (a) Scheme 21a was reprinted with permission from [202]. Copyright 2022 American Chemical Society. This content is not subject to CC BY 4.0. (b) Scheme 21b was adapted from [203] © 2022 T. Li et al., published by American Chemical Society, distributed under the terms of the Creative Commons Attribution 4.0 International License, https://creativecommons.org/licenses/by/4.0/).
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Mechanisms for radical reactions initiating from N-hydroxyphthalimide esters
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Abstract
Due to their ease of preparation, stability, and diverse reactivity, N-hydroxyphthalimide (NHPI) esters have found many applications as radical precursors. Mechanistically, NHPI esters undergo a reductive decarboxylative fragmentation to provide a substrate radical capable of engaging in diverse transformations. Their reduction via single-electron transfer (SET) can occur under thermal, photochemical, or electrochemical conditions and can be influenced by a number of factors, including the nature of the electron donor, the use of Brønsted and Lewis acids, and the possibility of forming charge-transfer complexes. Such versatility creates many opportunities to influence the reaction conditions, providing a number of parameters with which to control reactivity. In this perspective, we provide an overview of the different mechanisms for radical reactions involving NHPI esters, with an emphasis on recent applications in radical additions, cyclizations and decarboxylative cross-coupling reactions. Within these reaction classes, we discuss the utility of the NHPI esters, with an eye towards their continued development in complexity-generating transformations.

Introduction
The historical challenges of using radicals in synthetic chemistry is well documented [1,2]. Traditional approaches for radical generation relied on hazardous reagents and harsh conditions, resulting in low reaction efficiency and undesired byproduct formation [3-6]. As a consequence, the utility of radicals in organic synthesis remained limited for many years and in the past, they were perceived as fleeting reaction intermediates.

Recent progress in photoredox catalysis [6-8], electrochemistry [9,10], and the use of transition-metal (TM) catalysts in radical cross-coupling reactions [11] have dramatically expanded the use of radicals in synthesis, leading to their strategic incorporation as "synthons" in modern organic chemistry, with complementary reactivity to more common polar reaction manifolds [12-15]. The utility of radicals has also been expanded through the recent development of transformations involving radical-
The success of radical reactions is intimately linked to the mechanisms of their initiation and the radical progenitor employed. Amongst the many progenitors that are available, carboxylic acids are one of the most extensively used, owing to their structural diversity and widespread commercial availability [18,19]. Carboxylic acids can generate radicals under oxidative conditions, as in classical decarboxylative halogenation reactions (Hunsdieker reaction) that proceed via a radical mechanism [20,21]. More recent approaches have leveraged photoinduced ligand-to-metal charge transfer to generate radicals from aliphatic [22] and aromatic [23,24] carboxylic acids.

However, more broadly used approaches involve carefully designed activated esters. Barton esters emerged in the early 1980s [25,26] (Scheme 1) and have found applications in a number of functional group interconversions mediated by radical chain decarboxylation [27]. However, their widespread use in synthesis, especially in complex molecular settings, suffers from significant disadvantages. These include thermal and photochemical instability, as evidenced by their low N–O bond dissociation energy (BDE ≈ 42 kcal/mol) [28], the reliance on toxic tin hydrides as reductants and the undesired radical recombination with reactive 2-pyridylthiyl radicals that leads to (alkylthio)pyridine byproducts [26]. More recently, N-hydroxypthalimide (NHPI) esters (3) have emerged as convenient alternatives to Barton esters (Scheme 1) due in part to their ease of synthesis and greater stability (N–O BDE ≈ 75 kcal/mol) [28]. Their use as radical precursors was first described by Okada and colleagues in 1988 [29], who showed that C(sp³)-centered radicals were successfully generated by subjecting NHPI esters to light irradiation in the presence of the photoreductant 1,6-bis(dimethylamino)pyrene (BDMAP). Following their initial discovery, multiple studies have shown their versatility as radical progenitors under thermal, photochemical, and electrochemical conditions [30,31].

Due to their propensity towards single-electron reduction, NHPI esters, and similar derivatives such as N-hydroxytetrachlorophthallimide (TCNHPI) esters, are collectively referred to as "redox-active esters" (RAEs). The versatility of RAEs stems, in part, to the sensitivity of their reduction half peak potentials (E₁/₂) to their environment. For instance, a recent study by Cornella and co-workers, showed that RAEs derived from phenylacetic acid exhibited varying reduction half peak potentials (E₁/₂) ranging from −2.0 V for the NHPI ester to −1.2 V for the corresponding TCNHPI ester (measured in MeCN vs Fc⁰/Fc⁺, see Scheme 2A) [32]. Based solely on their redox potentials, single-electron reduction of RAEs is only possible in the presence of a sufficiently strong reducing agent. However, the reduction of RAEs can also be facilitated through the formation of charge transfer complexes with a donor species or via LUMO lowering activation with Brønsted and Lewis acids (Scheme 2B), collectively offering a number of variables to influence their reactivity.

Upon reduction, RAEs give rise to a radical anion with a weakened N–O bond (BDE < 70 kcal/mol) [33]. While fragmentation of affords a radical species in a constructive step towards initiating the radical reaction, a principal competing step is back-electron transfer (BET) to return the closed shell starting materials (Scheme 2B). A recent study showed comparable rates for fragmentation (8 ± 5 × 10⁻⁵ s⁻¹) and BET (3.15 to 2.06 × 10⁻⁵ s⁻¹) [34] when employing catalytic excited state reductants with moderate reducing potentials (E₁/₂red[Ir⁴⁺/Ir³⁺] ≈ −1.13 V vs Fc⁰/Fc⁺ in MeCN) [35]. This suggests that in the absence of a sufficiently strong driving force, BET and fragmentation compete to influence the resulting concentration of radicals. In such instances, opting for a stronger catalytic reductant or utilizing a stoichiometric electron donor can greatly improve the efficiency of radical generation. On the other hand, additional factors such as the ability of Brønsted and Lewis acid additives to promote the fragmentation step can be considered. Importantly, the diverse mechanisms in which RAEs engage in radical reactions can be exploited to modulate the reactivity of the resulting substrate radicals. For example, under net-reductive conditions, the radical intermediates are typically terminated via hydrogen atom transfer (HAT) or sequential electron transfer and proton transfer (ET/PT) steps. Alternatively, redox-neutral transformations can be envisioned using catalytic reductants, which can enable a complementary scope of downstream functionalizations (Scheme 2B).

In this perspective, we present an overview of the diverse mechanisms that have been proposed for radical based transformat-
ions initiating from NHPI esters. The discussion is organized into four sections: (i) mechanisms under photochemical conditions, (ii) initiation by metal catalysis and stoichiometric reductants, (iii) N-heterocyclic carbene (NHC)-catalyzed radical relay, and (iv) mechanisms under electrochemical activation.

By discussing selected literature examples, we illustrate how the activation mode of NHPI esters, and the reactivity of the resulting radical species, can vary depending upon the choice of catalytic or stoichiometric electron donors, the presence of a TM catalyst, the formation of a charge-transfer complex, and the overall reaction conditions. While we hope that this discussion will spur the continued development of NHPI esters in complexity-generating transformations, it is not comprehensive, and we refer readers to recently published review articles for additional discussion [30,31].

Discussion
Mechanism under photochemical conditions
In this section we provide a summary of the various conditions and activation modes employed in radical reactions of NHPI esters using visible-light irradiation. Upon absorption of light, an excited photocatalyst (*PC) engages in single-electron transfer (SET) with either donor (D) or acceptor (A) molecules (Scheme 3) [8,36]. Accordingly, a reductive quenching mechanism (path a) will operate when an excited photocatalyst effects the one-electron oxidation of a sacrificial donor giving rise to a strongly reducing catalytic species (*PCn−1). On the other hand, in an oxidative quenching mechanism (path b) the excited photocatalyst directly induces the one-electron reduction of an acceptor substrate. Alternatively, the photocatalyst can mediate the formation of an electronically excited substrate (**S) through an energy transfer (EnT) mechanism (path c).

In addition to these mechanistic blueprints, the formation of charge-transfer complexes involving NHPI esters, as well as examples of photoinduced transition metal-catalyzed activation will be discussed. Depending on the specific activation mechanism, both net reductive and redox neutral transformations can be implemented.

Photocatalytic reductive quenching mechanism
Among the most common reactions of NHPI esters are radical additions to electron-deficient olefins under net-reductive conditions, often referred to as Giese type addition reactions
Scheme 3: Common mechanisms in photocatalysis.

(Scheme 4A). In 1991, Okada and co-workers reported the addition of alkyl radicals to α,β-unsaturated ketones, by subjecting NHPI esters to visible-light irradiation in the presence of the photocatalyst [Ru(bpy)$_3$]Cl$_2$ and the reductant 1-benzyl-1,4-dihydropyridine (BNAH) [37]. Two decades later, in 2012 the Overman group demonstrated the utility of this transformation in the total synthesis of (+)-aplyviolene, involving the diastereoselective coupling of a tertiary radical and an enone acceptor [38]. Further developments of this chemistry resulted in the general use of NHPI esters for the construction of quaternary carbons via conjugate addition of 3° radicals [39,40]. In general, this transformation operates under a reductive quenching photocatalytic cycle, requiring a stoichiometric reductant (Scheme 4A). Both TM complexes, and organic dyes such as eosin Y [41-43], have been employed as suitable photocatalysts (Scheme 4B). Under visible light irradiation the photocatalyst (PC) is excited into its corresponding excited state (*PC), where it can be reduced by a suitable electron donor such as DIPEA or Hantzsch ester to generate the reduced form of the photocatalyst (PC$^{–}$) (Scheme 4A). This strong reducing agent mediates the one-electron reduction of the NHPI ester 10, forming radical anion intermediate 11. Fragmentation of 11 via N–O bond homolysis and decarboxylation forms the key tertiary radical 12 with concomitant formation of phthalimidyl anion (“Nphth”) and CO$_2$. Radical 12 undergoes intermolecular addition to the olefin acceptor 13 to form radical intermediate 14. Finally, under reductive conditions radical 14 can undergo hydrogen atom transfer (HAT) or sequential electron transfer and proton transfer (ET/PT) to form the conjugate addition product 15. With this mechanistic blueprint as a backdrop, Phipps and co-workers developed an enantioselective Minisci-type addition, under dual photoredox and chiral Brønsted acid catalysis [44] (Scheme 5A). In their proposed mechanism, the activation of the NHPI ester radical precursor was proposed to occur via a reductive quenching mechanism. However, since the overall transformation is redox-neutral, no stoichiometric reductant was employed. Instead, fluorescence-quenching studies suggested that the reductive quenching of the iridium excited state (*Ir$^{III}$) was taking place "off-cycle" via oxidation of the chiral phosphate co-catalyst (Scheme 5B). This event leads to the generation of a potent Ir$^{III}$ reductant that begins the photocatalytic cycle by reducing 16 into radical anion 17 while regenerating the ground state of the Ir$^{III}$ photocatalyst. After fragmentation, α-amino radical 18 was proposed to undergo addition to the heterocyclic radical acceptor 19 through a ternary transition state 20 involving hydrogen bonding interactions with the chiral phosphate co-catalyst. Notably, a follow-up report revealed that the radical addition is reversible, and that the selectivity determining step involves the deprotonation of 21 to provide radical intermediate 22 [45]. Finally, the iridium excited state (*Ir$^{III}$) formed under blue light irradiation oxidizes 22 to form product 23 and the corresponding reduced Ir$^{III}$ complex, beginning a new photocatalytic cycle.

Photocatalytic oxidative quenching mechanism

The activation of NHPI esters under a photocatalytic oxidative quenching mechanism was reported for the first time by Glorius and co-workers in 2017 [46]. This activation mode was applied
in the functionalization of styrenes using an Ir-photocatalyst and a diverse range of nucleophiles that are H-bond donors (Scheme 6A). Stern–Volmer analysis revealed that quenching of the photocatalyst’s excited state by the NHPI ester occurred only in presence of a hydrogen bond donor such as water (H$_2$O) or methanol (MeOH). This supported the hypothesis that activation of NHPI esters towards photoinduced electron transfer can occur through hydrogen bonding. In the proposed mechanism (Scheme 6B), hydrogen bonded complex 24 undergoes single electron reduction via oxidative quenching of the excited state *Ir$^{III}$, resulting in the formation of radical anion 25 (presumably H-bonded to H$_2$O) and the corresponding Ir$^{IV}$ complex. Radical intermediate 9 formed upon fragmentation of 25, adds to the styrene acceptor forming radical 26. Finally, a radical-polar crossover event between 26 and the Ir$^{IV}$ complex regenerates the Ir$^{III}$ ground state while delivering cation 27 that is then trapped by the oxygen-nucleophile to form the oxyalkylation product 28.

Li and co-workers described the activation of NHPI esters towards SET using a Lewis acid catalyst, allowing for the functionalization of styrene radical acceptors with nucleophiles that do not necessarily engage in hydrogen-bonding interactions, such as electron-rich (hetero)arenes [47] (Scheme 7A). Cyclic voltammetry measurements of a model NHPI ester showed a shift in its reduction potential from –1.79 V to –1.51 V (vs SCE in MeCN) in the presence of In(OTf)$_3$. As such, it was hypothesized that the Lewis acid lowers the LUMO of the NHPI ester via interaction with the oxygen lone pair in the phthalimide moiety (Scheme 7B). Thus, the excited state reductant *Ir$^{III}$
reduces the activated substrate 29 to form the stabilized radical anion 30. Fragmentation into radical 9, followed by radical addition to styrene gives benzyl radical intermediate 26. Turnover of the catalytic cycle through radical-polar crossover affords cation 27 that delivers functionalized product 31 upon nucleophilic addition.

The Doyle and Knowles groups reported the use of NHPI esters as radical precursors in the context of a radical redox annulation method [48] (Scheme 8A). This transformation occurs through an oxidative quenching photocatalytic cycle employing Ir-based photoreductants and a Brønsted acid additive. While the interaction between the RAE 32 and diphenyl phosphoric acid involves hydrogen bonding, in analogy to the Glorius proposal, it is thought that the substrate activation occurs through proton-coupled electron transfer (PCET), forming neutral radical species 33 and the corresponding phosphate conjugate base (Scheme 8B). The hypothesis is supported by an observed increase in the luminescence quenching of *Ir(p-CF3-ppy)3 by 32 in the presence of diphenyl phosphoric acid, as quantified by the Stern–Volmer constant (Ksv = 1146 M$^{-1}$ with acid vs Ksv = 603 M$^{-1}$ without acid). The reaction mechanism continues with the fragmentation of 33 into radical 34. From radical 34 the annulation reaction initiates via intramolecular radical addition, resulting in the formation of intermediate 35. After oxidation of 35 to 36, the photocatalyst is regenerated and product 37 is formed through intramolecular nucleophilic cyclization facilitated by the phosphate base. Importantly, the activation of NHPI esters through PCET may also play a role in transformations mediated by the cyanoarene-based donor–acceptor photocatalyst 4CzIPN, which typically requires the use of strong H$^+$ donors such as trifluoroacetic acid [49-52]. While many reports, including Okada’s original work, have suggested that a proton donor can accelerate the fragmentation rate of RAEs [29,49,53], specific values comparing the fragmentation rate constants or the N–O bond dissociation energies of radical anions and neutral radicals derived from RAEs are not available in the literature.
Scheme 6: Activation of NHPI esters through hydrogen-bonding in an oxidative quenching photocatalytic cycle.

Scheme 7: SET activation of RAE facilitated by a Lewis acid catalyst.
Lumb and co-workers recently published a study on the conversion of biaryl-derived NHPI esters into spirocyclic cyclohexadienones through a photocatalytic radical-mediated dearomatization, with H$_2$O serving as the nucleophile [54] (Scheme 9A). Despite the presence of H$_2$O in the reaction, the reduction of 38 to its corresponding radical anion 39 could occur without the need for hydrogen-bonding (Scheme 9B). Cyclic voltammetry measurements of NHPI ester 38 displayed a reduction half peak potential ($E_{p/2}$) of $-1.17$ V (vs SCE in MeCN) indicating that the single-electron reduction of 38 by a suitably strong reductant, such as *Ir(ppy)$_3$ ($E_{1/2\text{red}}[\text{IrIV/*IrIII}] = -1.73$ V vs SCE in MeCN) would be thermodynamically favorable. Indeed, Stern–Volmer photoquenching experiments confirmed that 38 effectively quenched *Ir(ppy)$_3$ under anhydrous conditions. Consequently, the SET reduction of 38, followed by fragmentation of 39 yielded α-oxo radical intermediate 40. Subsequently, the spirocyclization of 40 induced the dearomatization of the methoxy-substituted aromatic ring, forming intermediate 41, which was then oxidized to cation 42, thereby completing the photocatalytic cycle. The reaction proceeded by regioselective nucleophilic addition of H$_2$O, accompanied by the loss of MeOH to deliver spirocycle 43. Notably, the dearnomatative spirocyclization of biaryl-derived NHPI esters has found application in the total synthesis of natural products, including the plant metabolite denobilone A and the highly oxidized dibenzocyclooctadiene lignans heteroclitin J and kadsulignan E [55].

Activation via charge-transfer complex formation

Under conditions where oxidative quenching is not thermodynamically favorable, the single electron reduction of RAEs can proceed via an alternative mechanism. For example, in the transformation of NHPI ester 44 into spirocycle 45 catalyzed by [Ir(ppy)$_2$(dtbbpy)]PF$_6$, Reiser and co-workers observed that the excited state of this Ir-catalyst ($E_{1/2\text{red}}[\text{IrIV/*IrIII}] = -0.96$ V vs SCE) would not promote the reduction of 44 ($-1.25$ V vs SCE) [56] (Scheme 10). Interestingly, the role of H-bonding in substrate activation was not considered. To explain the observed transformation, it was suggested that the Ir$^{III}$-photocatalyst acted as a photosensitizer in an energy-transfer (EnT) mechanism. This proposal was supported by fluorescence quenching measurements, as well as the direct excitation of 44 by UV irradiation, resulting in the formation of 45 in a 45% yield. According to this hypothesis, NHPI ester 44 would adopt
Scheme 9: Activation enabled by a strong excited-state reductant catalyst and its application in the dearomative spirocyclization of biaryls.

A) 

Scheme 9: Activation enabled by a strong excited-state reductant catalyst and its application in the dearomative spirocyclization of biaryls.

B) 

Scheme 9: Activation enabled by a strong excited-state reductant catalyst and its application in the dearomative spirocyclization of biaryls.

In 2020, the Wang group reported the functionalization of enamides employing radicals derived from NHPI esters in combination with indole nucleophiles [57] (Scheme 11A). This transformation occurred under light irradiation either in the presence or absence of a RuII photoredox catalyst. It was found that the chiral lithium phosphate catalyst (R)-TRIP-Li played a crucial role in accelerating the reaction rate. Following an in-depth analysis of the mechanism, the authors proposed that (R)-TRIP-Li has the capability to engage enamide through H-bonding and NHPI ester through Li-promoted Lewis acid activation, acting as a pocket that facilitates the formation of charge-transfer complex 52 (Scheme 11B). This complex can be excited either by direct irradiation at 390 nm or through RuII-mediated EnT under blue light irradiation (456 nm). Following excitation, SET from the enamide to the active ester forms intermediate 53, which undergoes fragmentation and radical recombination to afford intermediate 54. At this stage, the indole nucleophile substitutes the phthalimidyl anion within the chiral pocket of the phosphate catalyst to form complex 55, before enantioselective addition to the iminium ion affords product 56.

NHPI esters can also engage in π-π interactions with electron-rich species to generate charge-transfer complexes that can absorb light in the visible region. These species are referred to in the literature as electron donor–acceptor (EDA) complexes [58,59] and undergo photoexcitation in the absence of an exogenous photoredox catalyst. When excited by visible light, an intra-complex SET from the donor substrate D to the NHPI ester acceptor takes place, generating radical ion pair 57. Subsequently, this ion pair undergoes fragmentation, forming the corresponding substrate radical 9, which can participate in diverse chemical transformations (Scheme 12).
Different donor molecules are known to form EDA complexes with NHPI esters. For example, the NHPI ester derived from pivalic acid and Hantzsch ester HE form EDA complex which participates in radical mediated hydroalkylation reactions [60, 61] (Scheme 13A). In the presence of electron deficient olefin, classic Giese-type addition takes place under photocatalyst-free conditions, affording product [60]. On the other hand, reaction with 1,7-enyne affords dihydroquinolnone product via a cascade radical addition/cyclization process [61]. In both transformations, HE serves a dual role by activating the NHPI ester through EDA complex formation and providing a hydrogen atom to terminate the radical reaction. The proposed mechanism of the hydroalkylation cascade is depicted in Scheme 13B. Upon excitation of complex with blue light, intra-complex SET takes place from the HE to the NHPI ester, leading to the formation of tert-butyl radical and radical cation following proton transfer to the phthalimidyl anion. Then, addition of 9 to \( \alpha,\beta \)-unsaturated ester yields radical intermediate. At this stage, HAT mediated by another equivalent of BuNAH delivers product, with concomitant formation of radical. Finally, aromatization of via SET to NHPI ester 3, generates pyridinium as a byproduct, while propagating the radical chain reaction.

Aggarwal and co-workers discovered the photoinduced decarboxylative borylation of NHPI esters mediated by bis(catecholato)diboron (B\(_2\)cat\(_2\)) [63] (Scheme 15A). UV–vis absorption measurements showed that a mixture of a model NHPI ester with B\(_2\)cat\(_2\) in dimethylacetamide (DMA) formed a new charge-transfer band in the visible region (>390 nm), which was attributed to the formation of EDA complex (Scheme 15B). Under blue light irradiation, EDA complex triggered a radical chain process initiated by B–B bond cleavage, forming boryl-NHPI ester radical and boryl radical. Subsequent decarboxylation of yields carbon-centered radical and boryl-phthalimide byproduct. Meanwhile DMA-ligated B\(_2\)cat\(_2\) is formed upon dimerization of radical. Reaction between radical and species affords boronic ester while returning boryl radical. Finally, chain propagation proceeds...

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**Scheme 10:** Proposed formation of an intramolecular charge-transfer complex in the synthesis of (spiro)anellated furans.

![Scheme 10](image-url)
Scheme 11: Formation of a charge-transfer complex between enamides and NHPI esters enabled by a chiral phosphate catalyst.

Scheme 12: Activation of NHPI ester through the formation of photoactive EDA-complexes.

gation takes place via reaction of 76 with another equivalent of the NHPI ester 3.

The Baran lab has recently published a complementary electrochemical method, wherein the activation of complex 74 takes place through SET under constant current electrolysis [64]. The Glorius and Y. Fu groups have independently proposed the formation of analogous charge-transfer complexes involving NHPI esters, bis(pinacolato)diboron (B\(_2\)pin\(_2\)), and Lewis bases (pyridine or isonicotinate tert-buty1 ester) in C(sp\(^2\))-borylation methods under photochemical and thermal conditions, respectively [65,66].
The activation of NHPI esters through EDA complex formation is also possible by employing a catalytic donor species, which enables a range of redox neutral transformations. In 2019, Shang and Fu initially demonstrated this approach by utilizing catalytic amounts of triphenylphosphine (PPh\textsubscript{3}) and sodium iodide (NaI) \cite{67}. Upon formation of EDA complex 80, radical addition to silyl enol ether 81 was promoted under blue light irradiation, affording acetophenone product 82 (Scheme 16A). Additionally, Minisci-type additions were carried out in the presence of protonated quinoline radical acceptor 83, affording product 84 (Scheme 16A). Mechanistically, this activation mode involves an intra-complex SET that forms the Ph\textsubscript{3}P–NaI radical cation species 85 and the corresponding radical anion 86. Decarboxylative fragmentation of 86 forms radical 9, which upon radical addition to 84 and deprotonation yields radical 87. Finally, oxidation of 87 mediated by 85 delivers the Minisci addition product 84 while regenerating PPh\textsubscript{3} and NaI (Scheme 16B).

The Ohmiya group has developed a series of light-mediated decarboxylative transformations of NHPI esters using a phenothiazine-based organophotoredox catalyst PTH. This type of catalyst is believed to facilitate SET to NHPI esters through the formation of EDA complexes. Interestingly, upon addition of RAE 58 to a solution of PTH, a noticeable red shift in the UV–vis absorption spectra of PTH was observed, suggesting the formation of a charge transfer complex of the type 88 \cite{68} (Scheme 17A). tert-Butyl radical (64), along with additional 2\textdegree{} and 3\textdegree{} alkyl radicals, resulting from these EDA complexes were harnessed in C(sp\textsuperscript{3})-heteroatom bond forming reactions \cite{69}, and in the difunctionalization of styrenes \cite{68} (Scheme 17B).

The catalytic cycle for the styrene difunctionalization reaction is depicted in Scheme 18. First, EDA complex 88 consisting of RAE 58 and the PTH catalyst is formed. Under blue light irradiation, intra-complex SET leads to the formation of PTH...
radical cation species $\text{89}$ and the radical anion $\text{90}$ with the corresponding charges balanced by the LiBF$_4$ additive. Notably, it was suggested that LiBF$_4$ could also facilitate the reduction of the NHPI ester substrate, potentially by the coordination of Li cation to the phthalimide moiety. Next, fragmentation of $\text{90}$ yields tert-butyl radical $\text{64}$, which then adds to styrene $\text{91}$ affording radical intermediate $\text{92}$. At this stage, recombination of intermediates $\text{89}$ and $\text{92}$ may occur via SET followed by addition or through radical–radical coupling, affording benzylsulfonyl intermediate $\text{93}$. Finally, nucleophilic substitution with alcohol $\text{94}$ in the presence of lithium phthalimide $\text{95}$ leads to product $\text{96}$ and turns over the catalytic cycle. Importantly, species $\text{93}$ can be detected by high resolution mass spectrometry, when the reaction is carried out without nucleophile and using stoichiometric amounts of PTH1.

H. Fu and co-workers reported that the combination of NHPI esters and cesium carbonate (Cs$_2$CO$_3$) gave rise to a new absorption band in the visible region, suggesting the formation of a photoactive charge-transfer complex [70]. This activation mode was initially employed in a decarboxylative coupling reaction with aryl thiols [70]. Further studies showed that 4-((tri-fluoromethyl)thiophenol ($\text{97}$) could act as a catalytic reductant in the aminodecarboxylation reaction of NHPI esters derived from $\alpha$-amino acids [71] (Scheme 19). Accordingly, visible light irradiation of a mixture consisting of N-Boc-alanine NHPI ester $\text{98}$ and Cs$_2$CO$_3$ in DMF resulted in the generation of the excited charge transfer complex $\text{99}$. Subsequent SET mediated by the thiol catalyst followed by fragmentation afforded $\alpha$-amino radical $\text{100}$, which was then oxidized by the resulting thiol-radical species, regenerating the thiol catalyst while forming an iminium intermediate $\text{101}$. Finally, nucleophilic addition of phthalimide anion $\text{102}$ afforded the amination product $\text{103}$.

Bosque and Bach reported the use of 3-acetoxyquinuclidine (q-Ac) as a catalytic donor for the activation of TCNHPI esters derived from $\alpha$-amino acids [72] (Scheme 20). Treatment of N-Boc-proline-derived TCNHPI ester $\text{104}$ with q-OAc in MeCN resulted in the formation of a yellow solution, which upon blue light irradiation provided the aminodecarboxylation product $\text{105}$ in 69% yield. It was hypothesized that the reaction involved the formation of EDA complex $\text{106}$ that led to the formation of $\alpha$-amino radical $\text{107}$ through photoinduced SET followed by fragmentation. Subsequent oxidation of $\text{107}$ by radical cation q-Ac•+ afforded iminium ion $\text{108}$ before nucleophilic addition of the in situ-generated tetrachlorophthalalimyl anion (TCPth) led to the formation of aminal product $\text{105}$. Of note,
the amino-decarboxylation reaction proved unsuccessful when employing alternative photocatalysts such as Ru(bpy)$_3$Cl$_2$ or eosin Y, underscoring the distinctive ability of q-OAc to activate TCNHPI esters via EDA complex formation.

**Photoinduced transition metal-catalyzed mechanisms**

The in situ formation of photoactive catalysts can be achieved by combining simple transition metal (TM) salts with suitable ligands. These TM catalysts are fundamentally distinct from traditional Ru- and Ir-based photoredox catalysts, as they play a dual role, by engaging in photoinduced electron transfer processes with the substrate and participating in the key bond-forming/breaking steps via substrate–TM interactions [73,74]. This paradigm has been employed in the activation of NHPI esters under photoinduced copper (Cu) and palladium (Pd) catalysis.

In 2017, Peters and Fu reported a Cu-catalyzed decarboxylative C(sp$^3$)–N coupling employing NHPI esters as dual reagents [75] (Scheme 21A). The combination of CuCN and the ligands xanthos and neocuproine in a 2:3:1 ratio resulted in the formation of a light absorbing species with an absorption band in the 380–460 nm range. Thus, it was hypothesized that Cu$^+$ catalytic species 109 would give rise to photoexcited complex 110 under blue light irradiation (Scheme 21B). Complex 110 and NHPI
ester 3 would then engage in SET likely through an inner sphere mechanism, providing phthalimide ligated CuII intermediate 111 and carboxyl radical 112. At this stage, the resulting radical species 9 would recombine with 111 to form CuIII complex 113. Alternatively, reaction of 3 with the photoexcited CuI complex through oxidative addition (OA) followed by decarboxylation could directly lead to intermediate 113 (Scheme 21B, blue arrow). However, radical clock experiments support the intermediacy of free radicals, indicating the involvement of the SET pathway (Scheme 21C). Eventually, reductive elimination of 113 afforded product 114 while regenerating the catalytic species 109. It is worth nothing that further transformations of NHPI esters under photoinduced Cu catalysis have been reported in recent years, including decarboxylative alkynylations [76-78] and the C(sp3)-H alkylation of α-amino acids [79].

The ability of NHPI esters to act as dual reagents was also investigated by Glorius and co-workers in the context of a photoinduced Pd-catalyzed aminoalkylation of 1,4-dienes [80] (Scheme 22A). The study showed that a photoexcited Pd0 species formed upon blue-light irradiation of Pd(Ph3)4, was able to promote the activation of NHPI esters via SET (Scheme 22B). The photoinduced electron transfer process between the Pd-photocatalyst and RAE 58 was proposed to form a
Scheme 17: A) Radical generation facilitated by EDA complex formation between PTH1 catalyst and NHPI esters. B) Selected scope of PTH1-catalyzed decarboxylative transformations.

Scheme 18: Proposed catalytic cycle for the difunctionalization of styrenes.
Scheme 19: Formation of a charge-transfer complex between NHPI esters and Cs$_2$CO$_3$ enables decarboxylative amination.

Scheme 20: 3-Acetoxyquinuclidine as catalytic donor in the activation of TCNHPI esters.
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Initiation by metal catalysts and stoichiometric reductants

The activation of NHPI esters under transition metal catalysis without the need of light is also feasible, and generally, two types of coupling reactions can be envisioned. On one hand, the decarboxylative cross-coupling (DCC) of NHPI esters with organometallic reagents, resembling classic Kumada, Negishi, and Suzuki couplings, has been enabled by nickel (Ni), cobalt (Co), iron (Fe), and copper (Cu) catalysts [84-91] (Scheme 23A). The typical mechanism begins by transmetallation of the organometallic coupling partner 120 to the TM catalyst (Scheme 23B). The resulting organometallic intermediate 121 can act as a reducing agent, transferring an electron to RAE 10 to form radical anion 11 and the corresponding oxidized metal complex 122. Following fragmentation, the ensuing alkyl radical 12 is captured by intermediate 122, resulting in the formation of complex 123. At this point, the metal center has undergone a two-electron oxidation, making it well-suited for regenerative elimination yielding the cross-coupling product 124.

Under these catalytic conditions, various TM-catalyzed decarboxylative functionalizations employing RAEs have been established (Scheme 24). Baran and co-workers have reported arylation protocols (Scheme 24A) using arylzinc reagents [84,85], Grignard reagents [85] and arylboronic acids [86], as well as decarboxylative alkenylation [87] (Scheme 24B), alkynylation [88] (Scheme 24C) and C(sp<sup>3</sup>)–C(sp<sup>3</sup>) cross-coupling [89] (Scheme 24D). Finally, similar chemistry has been extended to the decarboxylative borylation of RAEs under Ni [90] and Cu [91] catalysis (Scheme 24E). Importantly, the Wang group has independently studied the decarboxylative Negishi coupling of RAEs with organozinc reagents under Co-catalysis, effecting diverse arylation, alkenylation, and alkynylation reactions [92].

The second type of reaction is referred to as cross-electrophile coupling and involves the Ni-catalyzed reaction of NHPI esters with aryl- and vinyl halides under reducing conditions (Scheme 25A). The general catalytic cycle begins with oxidative addition of an organohalide into a Ni<sup>0</sup> catalyst yielding Ni<sup>II</sup> complex 125 (Scheme 25B). In parallel, the initial SET activation of RAE 10, leading to the formation of radical anion 11, takes place in the presence of a stoichiometric reductant, which can be an organic reductant, such as tetrakis(N,N-dimethylamino)ethylene (TDAE) or Hantzsch ester (HE), or a metal such as zinc (Zn<sup>0</sup>) or manganese (Mn<sup>0</sup>). Upon fragmentation, radical species 12 is captured by the oxidative addition complex 125, giving rise to Ni<sup>III</sup> complex 126. The cross-coupling product 127 is then formed via reductive elimination of 126 which gives Ni<sup>II</sup> intermediate 128. At this stage, it is proposed that the Ni<sup>II</sup> complex 128 can participate in a SET event with another equivalent of substrate 10, generating another equivalent of radical 12, that propagates into the next catalytic cycle. Finally, the corresponding Ni<sup>II</sup> complex 129 is reduced back to
Scheme 22: A) Photoinduced Pd-catalyzed aminoalkylation of 1,4-dienes. B) Proposed catalytic cycle.

Scheme 23: A) TM-catalyzed decarboxylative coupling of NHPI esters and organometallic reagents. B) Representative catalytic cycle.
Weix and co-workers have developed a series of Ni-catalyzed couplings of NHPI esters with different electrophiles, including aryl halides [93,94], bromoalkynes [95], bromoalkanes [96], and pyridyl thioesters [97] (Scheme 26A). Likewise, the Rousseaux group has recently documented the arylation of NHPI esters obtained from cyclopropanecarboxylic acids [98] and malonic acid half amides [99], while the Reisman lab has pioneered an enantioselective cross-electrophile coupling between NHPI esters and alkenyl bromides [100] (Scheme 26A).

In addition, Jolit and Molander disclosed the decarboxylative arylation of NHPI esters derived from bicyclo[1.1.1]pentanes (BCPs) by combining Ni-catalysis and photoinduced EDA complex activation [101] (Scheme 26B).

A novel approach for the activation of redox-active esters was recently reported by Cornella and co-workers [32]. In this study, low valent bismuth (Bi) complex Bi-1 was found to exhibit redox properties similar to those of first row-transition metal catalysts, enabling the activation of tetrachlorophthalimide (TCPht) active esters towards C(sp^3)–N cross-couplings with nitrogen heterocycles (Scheme 27). The catalytic reaction was proposed to begin by oxidative addition of RAE 104 to catalyst Bi-1, forming an in cage radical pair consisting of Bi^{II} species 130 and α-amino radical 107 (Scheme 27B). Importantly, electron paramagnetic resonance (EPR) spectroscopy at
25 °C supported the formation of species 107. However, NMR measurements at ~40 °C showed the accumulation of Bi^{III} complex 131, which can be prepared separately in a stoichiometric experiment. As such, two different pathways may lead to the C(sp^3)–N cross-coupling products. On one hand, in-cage electron transfer from radical 107 to Bi^{II} complex 130 can generate iminium ion 108. Alternatively, intermediate 108 could arise from complex 131 by reductive elimination. Ultimately, the iminium ion can be trapped by the nitrogen nucleophile to form product 132 or by the in-situ-generated tetrachlorophthalimyl anion (–TCPhth) affording product 105.

Stoichiometric reductants can facilitate certain radical-mediated transformations that involve NHPI esters, even without the presence of metal catalysts. Larionov and Sun have independently reported notable examples of these transformations, involving the Zn^{0}-mediated cross-coupling of redox-active esters with chlorophosphines [102] and gem-difluoroalkenes [103], respectively. In the report by Sun and co-workers, it was proposed that the activation of RAE 10 occurs upon reduction with Zn powder to give radical anion 11 (Scheme 28). Following fragmentation, radical intermediate 12 would then attack gem-difluoroalkene 133, affording intermediate 134. Reduction of this radical species by another equivalent of Zn^{0} would then form anionic intermediate 135. Finally, the selective formation of Z-monofluoroalkene product 136 is achieved through anti-coplanar elimination of fluoride.

Shuhua Li and co-workers reported the generation of alkyl radicals from NHPI esters, mediated by a pyridine-boryl radical.
reductant species in the context of alkene hydroalkylation [104] and cross-decarboxylative couplings with 4-cyanopyridines [105] (Scheme 29A). In the mechanism of the latter transformation, pyridine 137 also serves as a catalyst, generating the crucial pyridine-boryl radical 138 via reaction with B$_2$pin$_2$ (Scheme 29B). The proposed species 138 induces the reductive fragmentation of active ester 10, regenerating pyridine 137 while forming alkyl radical 12, CO$_2$ and phthalimide–B(pin) adduct 139. Subsequently, radical–radical coupling between 12 and one equivalent of 138 affords dihydropyridine 140, which upon re-aromatization, facilitated by ZnCl$_2$ acting as a Lewis acid, yields product 141, accompanied by the formation of cyano-B(pin) 142. Importantly, in the absence of ZnCl$_2$, intermediate 140 could be detected by HRMS and $^{11}$B NMR, highlighting the pivotal role of ZnCl$_2$ in promoting rearomatization.

Scheme 26: A) Synthetic applications of decarboxylative cross-electrophile couplings. B) Decarboxylative arylation of BCP-redox active esters enabled by EDA complex activation and Ni catalysis.
Scheme 27: A) Activation of tetrachlorophthalimide redox-active esters enabled by a low-valency Bi complex. B) Proposed mechanism involving two plausible reaction pathways.

Scheme 28: Activation of NHPI esters mediated by Zn\(^0\) applied in a Z-selective alkenylation reaction.
Scheme 29: A) Activation of NHPI esters enabled by a pyridine-boryl radical species applied to the decarboxylative alkylation of pyridines. B) Reaction mechanism.

**N-Heterocyclic carbene (NHC) catalysis**

In 2019, Nagao and Ohmiya reported the decarboxylative coupling of NHPI esters with aldehydes enabled by NHC catalysis [106]. The reaction proceeds with the catalyst NHC-1 at 60 °C and gives rise to ketones (Scheme 30A). The proposed mechanism begins with the reaction of benzaldehyde (143) and the NHC-catalyst 144 to form the neutral Breslow intermediate 145 (Scheme 30B). Then, cesium carbonate deprotonates the enol OH in 145, to provide the enolate form of Breslow’s intermediate 146, which is a suitable reducing agent to trigger the fragmentation of NHPI ester 58 ($E^\circ_{\text{ox}} = -0.97 \text{ V vs SCE in MeCN}$). Hence, it is proposed that enolate 146 induces the single electron reduction of 58, generating the persistent radical 147 and the transient species 148, which fragments into tert-butyl radical (64). Notably, the reduction of NHPI ester 58 could be facilitated by interaction of a cesium cation with the oxygen lone pair of the phthalimide, in analogy to the mechanism discussed in Scheme 7B. Lastly, radical–radical coupling between 64 and 147, accompanied by elimination of the NHC catalyst, yields ketone product 149. In subsequent studies, this NHC-catalyzed radical relay activation mode has been extended to the alkylation of aliphatic aldehydes [107] and to the three-component alkylation of olefins [108].

Alternatively, NHC catalysts can mediate the generation of radical intermediates from NHPI esters via the stabilization of a photoactive EDA complex. In 2020, Wang and Chen reported a photochemical C(sp$_3$)-heteroatom coupling reaction of NHPI esters mediated by NaI and the catalyst NHC-2 [109] (Scheme 31A). Initial investigations showed that the reaction proceeded in the absence of the NHC catalyst, and it was reasoned that substrate 150 and NaI formed EDA complex 151 that would undergo light-mediated decarboxylation (Scheme 31B). However, upon addition of catalyst NHC-2 an improvement of the reaction yield from 36% to 63% was observed. The authors proposed that the addition of the NHC catalyst facilitates the formation of EDA complex 151. In addition, it is thought that the stabilization imparted by the NHC catalyst is crucial in the subsequent radical recombination between C(sp$_3$) radical 152 and the corresponding iodine-centered radical which provides iodination product 153 (Scheme 31B). It is worth noting that the iodination product is formed exclusively when using acetone as the solvent (see compound 154 in Scheme C) whereas in DMF a nucleophilic substitution takes place to afford products of the type 155 (Scheme 31B). Representative examples of the substrate scope are shown in Scheme 31C. The in situ-generated phthalimidyl anion (–Nphth) is a competent nucleophile and gives rise to primary protected amines such as 156. Additionally, sodium phenolate and thiophenolate salts give rise to products 157 and 158, respectively, while the chlorination product 159 was obtained upon the addition of tetrabutylammonium chloride (Scheme 31C).

**Mechanisms under electrochemical activation**

The electrochemical activation of NHPI esters provides significant advantages compared to other methods. It allows for single
electron reduction to be facilitated by cost-effective carbon-based cathodes, eliminating the requirement for precious metal photocatalysts or exogeneous reductants such as Zn\(^0\). In the final section of this perspective, we explore examples where NHPI esters have been utilized as radical precursors under electrochemical conditions.

Giese-type radical additions, which are usually performed under conditions of photoredox-catalysis (see Scheme 4), can also be achieved under constant-potential electrolysis employing graphite electrodes [110] (Scheme 32A). Under these conditions, activation of NHPI ester \(160\) by SET occurs at the cathode’s surface affording the corresponding radical anion \(161\) (Scheme 32B). Subsequent fragmentation leads to the cyclohexyl radical \(162\) which then adds to the terminal carbon of radical acceptor \(163\), leading to radical intermediate \(164\). In the other redox half-reaction, Hantzsch ester (HE) undergoes anodic oxidation to form radical cation \(65\), which then transfers a proton, likely to the phthalimidyl anion ("Nphth"), resulting in the formation of radical species \(165\). Finally, reaction between intermediates \(164\) and \(165\) through sequential electron transfer and proton transfer (ET/PT) leads to the hydroalkylation product \(166\) and the pyridine byproduct \(167\).

In addition, there have been reports of Minisci-type additions where radical intermediates are electrochemically generated from NHPI esters [111-113] (Scheme 33A). The mechanism of this redox neutral reaction involves reductive fragmentation of the radical precursor \(3\) mediated by the cathode under constant-current electrolysis (Scheme 33B). The resulting alkyl radical \(9\) attacks the protonated quinoline \(168\), forming radical cation intermediate \(169\). Finally, single electron oxidation of \(169\) at the

Scheme 32: A) Electrochemical Giese-type radical addition of NHPI esters. B) Reaction mechanism.
anode, followed by rearomatization via proton-transfer forms the alkylated heterocycle 170.

As discussed in Scheme 25, the Ni-catalyzed cross-electrophile coupling between redox-active esters and aryl halides requires the addition of a stoichiometric reductant (typically Zn$^0$ or Mn$^0$) to both activate the NHPI ester and turn-over the catalytic cycle. However, the merger of Ni-catalysis and electrochemistry allows for the implementation of more convenient conditions in which these two crucial reductive steps can be mediated by the cathode (Scheme 34). In this context, Jamison and co-workers developed an electrochemically driven decarboxylative $C(sp^3)$–$C(sp^2)$ cross-coupling protocol that proceeds in a divided electrochemical cell with reticulated vitreous carbon (RVC) electrodes and triethylamine (NEt$_3$) as sacrificial reductant [114] (Scheme 34A). In the proposed mechanism, radical species 9, which is generated upon cathodic reduction of active ester 3, is captured by complex 171 (Scheme 34B). The resulting Ni$^{III}$ complex 172 undergoes facile reductive elimination to form cross-coupling product 173 and Ni$^I$ intermediate 174. Finally, reduction of 174 at the cathode surface restores the Ni$^0$ species 175 giving rise to a new catalytic cycle.

Reductive cross-electrophile couplings that incorporate redox-active esters and aryl halides have the potential to simplify the syntheses of drug-like compounds through $C(sp^3)$–$C(sp^2)$ bond formation. However, their synthetic utility is frequently restricted due to various challenges, such as RAE decomposition and a limited aryl halide scope. In recent years, the Baran lab has made progress in enhancing the practicality and applicability of electrochemically driven decarboxylative couplings involving NHPI esters and aryl-halides [115]. Their optimized reaction conditions required a Ni$^{II}$ precursor, 2,2'-bipyridine (bpy) as ligand, silver nitrate (AgNO$_3$) as an additive and the combination of a magnesium (Mg) sacrificial anode and a RVC cathode (Scheme 35A). A crucial discovery in advancing this methodology was the in situ formation of silver nanoparticles (AgNP) on the cathode's surface [116] (Scheme 35B). The use of this Ag-doped cathode led to slower mass transport and minimized side reactions caused by rapid reduction of RAES, thereby avoiding substrate decomposition and enhancing reaction yields (Scheme 35B). Furthermore, the presence of the AgNP layer on the cathode caused a decrease of the reaction’s overpotential from $-1.66$ V to $-1.15$ V (vs Ag/AgCl), which is thought to prevent catalyst deactivation via successive reduction of the various Ni species, while also avoiding electrode passivation caused by catalyst adsorption (Scheme 35B).

Baran and co-workers have demonstrated that these overall milder reaction conditions greatly improved the functional group compatibility of decarboxylative couplings under reducing conditions. For example, the cross-coupling between NHPI esters and both electron-poor and electron-rich...
Scheme 34: Ni-electrocatalytic cross-electrophile coupling of NHPI esters with aryl iodides.

Scheme 35: A) Decarboxylative arylation of NHPI esters under Ag-Ni electrocatalysis B) Formation of AgNP on the cathode’s surface and its effect on the reaction.
(hetero)aryl halides was equally effective (Scheme 36). In addition, the preparation of unnatural amino acids in multigram scale [115], along with the syntheses of complex terpenes [116] and (+)-calcipotriol [117] have showcased the vast synthetic potential and broad applicability of NHPI esters activated under these electrochemical conditions (Scheme 36).

**Conclusion**

Given their rich history and their continued use in diverse methodologies, N-hydroxyphthalimide esters have been and will remain to be important tools in synthetic organic chemistry. In this perspective, we have surveyed recent advancements in photochemistry, TM catalysis, NHC catalysis, and electrochemistry to show the generality of these RAES in diverse mechanistic paradigms. Their application as radical progenitors continues to broaden the scope of radical-mediated reactions, especially in complex molecular settings, where issues of chemoselectivity can benefit from the multitude of mechanisms for their activation.

Particularly, the use of RAES in natural product total synthesis enables the assembly of strategic C–C bonds through radical coupling reactions that can draw from a wide range of reaction conditions (Scheme 37). Pioneering work by Schnermann and Overman demonstrated the early potential of photocatalytic Giese-type additions, successfully coupling two complex ring fragments and creating adjacent stereocenters, which effectively solved major challenges in the synthesis of (–)-aplyviolene [38] (Scheme 37A). Brown and co-workers devised a diastereoselective Ni-catalyzed decarboxylative arylation as a crucial step in the synthesis of (–)-cajanusine [118] (Scheme 37A). Likewise, the Baran lab employed Ni-catalyzed decarboxylative couplings of RAES to form two strategic C–C bonds in the synthesis of higginsianin A [119] (Scheme 37A). Recently, Lumb and co-workers showcased the use of NHPI esters in key radical cyclizations, allowing the synthesis of diverse dibenzocyclooctadiene lignans [55] (Scheme 37B). A Ru-catalyzed cyclization was employed to construct the quaternary stereocenter in taiwankadsurin A, whereas the corresponding spirocycle in kadsulignan E was formed under Ir photocatalysis. In addition, photoinduced Pd catalysis was applied in the key macrocyclization step to complete the synthesis of kadsuphilin N.

These applications in total synthesis serve as a testament to the synthetic versatility of radical reactions facilitated by the use of

**Scheme 36**: Synthetic applications of decarboxylative couplings of NHPI esters under Ni-electrocatalysis.
RAEs. In the years to come, we anticipate that the continued development of new catalysts and the implementation of increasingly mild reaction conditions will open new possibilities for further applications of NHPI esters in radical reactions. Expanding the mechanisms and reactivity discussed herein will continue to improve our understanding of radical chemistry toward exploring novel chemical space.

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References


36. The cyclic voltammery and spectroscopic data reported by Knowles was used to approximate the $E_{\text{1/2}}$ value, following the procedure reported by Tucker and Stephenson.


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