Organic synthetic transformations using organic dyes as photoredox catalysts

Shunichi Fukuzumi* and Kei Ohkubo

The oxidizing ability of organic dyes is enhanced significantly by photoexcitation. Radical cations of weak electron donors can be produced by electron transfer from the donors to the excited states of organic dyes. The radical cations thus produced undergo bond formation reactions with various nucleophiles. For example, the direct oxygenation of benzene to phenol was made possible under visible-light irradiation of 2,3-dichloro-5,6-dicyano-p-benzoquinone (DDQ) in an oxygen-saturated acetonitrile solution of benzene and water via electron transfer from benzene to the triplet excited state of DDQ. 3-Cyano-1-methylquinolinium ion (QuCN+) can also act as an efficient photocatalyst for the selective oxygenation of benzene to phenol using oxygen and water under homogeneous and ambient conditions. Alkoxybenzenes were also obtained when water was replaced by alcohol under otherwise identical experimental conditions. QuCN+ can also be an effective photocatalyst for the fluorination of benzene with \( \text{O}_2 \) and fluoride anion. Photocatalytic selective oxygenation of aromatic compounds was achieved using an electron donor–acceptor-linked dyad, 9-mesityl-10-methylacridinium ion (Acr+–Mes), as a photocatalyst and \( \text{O}_2 \) as the oxidant under visible-light irradiation. The electron-transfer state of Acr+–Mes produced upon photoexcitation can oxidize and reduce substrates and dioxygen, respectively, leading to the selective oxygenation and halogenation of substrates. Acr+–Mes has been utilized as an efficient organic photoredox catalyst for many other synthetic transformations.

Introduction

The rapid consumption of fossil fuels causes not only their depletion but also unacceptable environmental problems such as the greenhouse effect, which can lead potentially to disastrous climatic consequences.\(^1\,^2\) Because fossil fuels are products of photosynthesis, the development of artificial photosynthesis for the production of sustainable and clean energy resources using solar energy has merited increasing attention in order to solve global energy and environmental issues.\(^2\,^\text{--}^\text{10}\) Photosynthesis is initiated by photoinduced electron-transfer reactions in photosynthetic reaction centres. Thus, photoinduced electron-transfer pathways play a pivotal...
role in maintaining life on the planet. A variety of photosynthetic reaction centre models composed of electron donors and acceptors linked by covalent or non-covalent bonding have so far been developed, undergoing efficient charge separation and slow charge recombination.\textsuperscript{11–22} Such photoinduced electron-transfer pathways enable the production of highly reactive radical cations and anions, and have led to the discovery and design of novel organic synthetic transformations.\textsuperscript{23–25}

Inorganic solid photocatalysts such as TiO\textsubscript{2} and ZnO have so far been frequently utilized as photocatalysts.\textsuperscript{26–30} However, the poor absorption of visible light by such inorganic photocatalysts has often limited their utilization for organic synthetic transformations using solar energies although some modified inorganic photocatalysts can absorb visible light.\textsuperscript{26–30} In addition, selective photocatalytic oxygenation reactions with dioxygen have been difficult using inorganic photocatalysts, because substrates are normally overoxidized through to CO\textsubscript{2} due to the extremely high oxidizing ability of the photoexcited state. In contrast to inorganic photocatalysts, organic photocatalysts can absorb visible light and their photoredox properties can be finely tuned by rational design and synthesis.\textsuperscript{31–33} Metal complexes with organic ligands have also been utilized as homogeneous photoredox catalysts for organic synthesis.\textsuperscript{34–38} As compared with inorganic heterogeneous and homogeneous photocatalysts, organic photocatalysts have advantages with regard to lower cost, more synthetic versatility and more fine tuning of the redox properties. Thus, this review focuses on the recent development of various organic synthetic transformations mediated by metal-free organic photoredox catalysis under mild conditions.

**Selective photocatalytic oxidation of benzene to phenol**

Phenol, one of the most important chemicals in industry, is currently produced from benzene by a three-step cumene process.\textsuperscript{39} The cumene process affords very low yields (around 5\%) with byproducts such as acetone and methylstyrene.\textsuperscript{39,40} Thus, extensive efforts have been devoted to achieving the direct synthesis of phenol from benzene and oxygen, which is one of the dream chemical reactions, using heterogeneous inorganic catalysts.\textsuperscript{40–47} However, the synthetic utility with inorganic catalysts has been limited because of low yield, poor selectivity, and the requirement of high temperature. In contrast to inorganic catalysts, the selective oxidation of benzene to phenol has been made possible under visible-light irradiation of 2,3-dichloro-5,6-dicyano-p-benzoquinone (DDQ) in an oxygen-saturated acetonitrile (MeCN) solution of benzene and water (vide infra).\textsuperscript{48}

The photooxidation of benzene occurs with DDQ and water to yield phenol and 2,3-dichloro-5,6-dicyanohydroquinone (DDQH\textsubscript{2}) selectively.\textsuperscript{48} The maximum quantum yield was 45\%, indicating that the photochemical oxidation of benzene by DDQ is quite efficient.\textsuperscript{48} DDQH\textsubscript{2} can be oxidized with tert-butyl nitrite (TBN)\textsuperscript{49} to regenerate DDQ under aerobic conditions.\textsuperscript{48} Catalytic oxygenation occurred to yield phenol (93\%) with 98\% conversion of benzene (30 mM) with DDQ (9.0 mM), TBN (1.5 mM) and water (0.5 M) after photolysis for 30 h.\textsuperscript{48}

The catalytic mechanism is shown in Scheme 1. The photooxidation of benzene to phenol is initiated by intermolecular photoinduced electron transfer from benzene to the triplet excited state of DDQ (\(^3\)DDQ\textsuperscript{*}), because the free energy change for electron transfer determined from the one-electron oxidation potential of benzene (\(E_{\text{ox}} = 2.48\) V versus SCE)\textsuperscript{50,51} and the one-electron reduction potential of \(^3\)DDQ\textsuperscript{*} (\(E_{\text{red}} = 3.18\) V versus SCE)\textsuperscript{52} is largely negative (\(\Delta G_{\text{et}} = -0.70\) eV) and thereby exergonic. The benzene radical cation produced by photoinduced electron transfer from benzene to \(^3\)DDQ\textsuperscript{*} is converted to the benzene \(\pi\)-dimer radical cation (\(\lambda_{\text{max}} = 900\) nm) with benzene,\textsuperscript{53,54} as detected by laser flash photolysis measurements.\textsuperscript{48} The benzene radical cation, which is in equilibrium with the benzene \(\pi\)-dimer radical cation, reacts with water to yield the OH-adduct radical, whereas DDQ\textsuperscript{-} reacts with the OH-adduct radical to yield phenol and DDQH\textsubscript{2}.\textsuperscript{48} DDQH\textsubscript{2} is oxidized by the reaction with tert-butyl nitrite and O\textsubscript{2} via NO\textsubscript{2} to regenerate DDQ.\textsuperscript{48} No further oxidation of phenol occurred.\textsuperscript{48} Such selective oxidation of benzene to phenol results from the much faster back electron transfer from DDQ\textsuperscript{-} to the phenol radical cation as compared with the back electron transfer from DDQ\textsuperscript{-} to the benzene

![Scheme 1](image-url)

Scheme 1  Photocatalytic cycle of selective hydroxylation of benzene to phenol with O\textsubscript{2} and H\textsubscript{2}O using DDQ and TBN as an organic photocatalyst and an oxidation catalyst of DDQH\textsubscript{2} with O\textsubscript{2}, respectively.
radical cation. The driving force of back electron transfer from DDQ$^-$ to the benzene radical cation (1.97 eV) is much larger than that from DDQ$^-$ to the phenol radical cation (1.09 eV). In such a case, the back electron transfer from DDQ$^-$ to the benzene radical cation occurs in the Marcus inverted region, where the back electron transfer in the radical ion pair is much slower than the dissociation of radical ions. In contrast, back electron transfer from DDQ$^-$ to the phenol radical cation occurs at the Marcus top region, where the back electron transfer is much faster than the dissociation of radical ions. This is the reason why the selective photocatalytic oxidation of benzene to phenol occurs without further oxidation of phenol.

The 3-cyano-1-methylquinolinium perchlorate salt (QuCN$^+$ClO$_4^-$) also acts as an efficient organic photocatalyst for the selective hydroxylation of benzene to phenol under homogeneous and ambient conditions, where molecular oxygen and water are the oxidant and oxygen source, respectively (Scheme 2). In this case as well, the benzene radical cation formed by the photoinduced electron-transfer oxidation of benzene with the singlet excited state of QuCN$^+$ reacts with H$_2$O to yield the OH-adduct radical. On the other hand, QuCN$^-$ can reduce O$_2$ with a proton to produce HO$_2^-$. The hydrogen abstraction process of the OH-adduct radical with HO$_2^-$ yields phenol and H$_2$O$_2$ (Scheme 2). The selectivity of formation of phenol was 98% based on the consumption of benzene after 1 h of irradiation. The quantum yield was 16% at the initial stage of the photocatalytic reaction. After 5 h of photoirradiation, the yield of phenol reached 51%. In the case of chlorobenzene with QuCN$^-$, the selective formation of the corresponding phenol was also observed to afford p- and o-chlorophenol in 88 and 11% yield, respectively.

Benzene can also be oxidized using TiO$_2$ as a photocatalyst. In contrast to organic photocatalysts (vide supra), however, the phenol that was produced was overoxidized. When the photocatalytic hydroxylation of benzene to phenol was conducted using TiO$_2$ with a phenolphilic adsorbent derived from a layered silicate under visible-light irradiation, however, phenol was recovered in high yield and purity. The coexisting adsorbent that can promptly and selectively adsorb phenol from a mixture of water, benzene and phenol separated the photocatalytically-formed phenol from TiO$_2$ to prevent its over-oxidation to diphenol, hydroquinone and p-benzoquinone. The selective photocatalytic oxidation of benzene with O$_2$ and H$_2$O to phenol with organic photocatalysts in Schemes 1 and 2 is certainly superior to that with inorganic photocatalysts.

**Selective photocatalytic alkoxylation of benzene**

The selective photocatalytic oxidation of benzene with O$_2$ and H$_2$O with QuCN$^+$ to phenol has been expanded to the photocatalytic alkoxylation of benzene. Alkoxybenzenes are used as an important precursor to pharmaceuticals, insect pheromones and perfumes. The photocatalytic alkoxylation of benzene occurred under photoirradiation of an oxygen-saturated MeCN solution containing QuCN$^-$, benzene and methanol (MeOH) with a xenon lamp (500 W, $\lambda > 290$ nm) to yield methoxybenzene and H$_2$O$_2$. The yield of methoxybenzene after 4 h of photoirradiation was 26%. When methanol was replaced by ethanol, isopropanol and tert-butanol, the photocatalytic alkoxylation of benzene also occurred to yield the corresponding alkoxybenzenes. The benzene radical cation, formed by photoinduced electron transfer from benzene to the singlet excited state of QuCN$^-$ (1QuCN$^+$*), reacts with alcohol to yield the alkoxide-adduct radical (Scheme 3). The radical QuCN$^-$, formed by electron transfer from benzene to 1QuCN$^+$*, can reduce O$_2$ with a proton to produce HO$_2^-$. Hydrogen abstraction by HO$_2^-$ from the OR-adduct radical affords the alkoxybenzene and H$_2$O$_2$ (Scheme 3).

Intramolecular cyclization of 3-phenyl-1-propanol to chroman is known to occur via the nucleophilic capture of organic radical cations by tethered OH functions. Thus, the photocatalytic cyclization of 3-phenyl-1-propanol occurred under the photoirradiation of QuCN$^+$ClO$_4^-$ in an O$_2$-saturated MeCN solution to give the cyclization product, chroman. The yield of chroman was 30% after 15 min of photoirradiation. The photocyclization is also initiated by photoinduced electron transfer from 3-phenyl-1-propanol to 1QuCN$^+$* to produce the
The cationic charge is localized on the aromatic moiety, to which the OH group attacks to yield chroman by hydrogen abstraction with HO₂⁻.

Selective photocatalytic monofluorination of benzene with fluoride and oxygen

Fluorination reactions of aromatic compounds have merited special attention because of their useful application in the fields of material science, the chemical industry and medicine.\(^5\)\(^6\) However, it has been difficult to perform selective monofluorination of aromatic compounds by normal synthetic procedures.\(^6\) Conventional fluorination reactions that afford aryl fluorides, like the Balz–Schiemann reaction where anilines are converted into aryl fluorides and the Halex process where halogen atoms are exchanged for fluorine atoms, generally require harsh conditions and consequently have limited substrate scopes.\(^6\) An organic photocatalyst can provide a new way for the fluorination of benzene with fluoride.\(^6\) The photocatalytic fluorination of benzene occurs under the photoirradiation of an oxygen-saturated MeCN solution of QuCN⁺ containing benzene and tetraethylammonium fluoride tetrahydrofluoride (TEAF·4HF) using a xenon lamp with a UV-light cutting-off filter (500 W; \(\lambda > 290 \text{ nm} \)) attached to yield fluoro-benzene and H₂O₂.

9-Mesityl-10-methylacridinium ion as photoredox catalyst

As described above, the excited states of organic dyes act as strong electron acceptors, which can oxidize substrates by photoinduced electron transfer. However, photoinduced electron-transfer reactions always compete with the decay of the excited states to the ground states. The lifetimes of singlet excited states are the order of nanoseconds and those of triplet excited states are the order of microseconds. In the case of electron donor–acceptor dyad molecules (D–A), photoexcitation affords the charge-separated states (D⁺–A⁻). The lifetimes of the charge-separated states become longer with increasing the driving force of charge recombination in the Marcus inverted region when the energy of the triplet excited state is higher than that of the charge-separated state.\(^1\)\(^6\) It has been reported that the 9-mesityl-10-methylacridinium ion (Acr⁺–Mes) affords the long-lived electron-transfer (ET) state (Acr–Mes⁺), which has a high oxidizing ability (\(E_{\text{red}} = 1.88 \text{ V versus SCE} \)) and reducing ability (\(E_{\text{ox}} = −0.49 \text{ V versus SCE} \)) in benzonitrile.\(^6\) The X-ray crystal structure of Acr⁺–Mes is shown in Fig. 1.\(^6\)

The dihedral angle made by the two aromatic ring planes is approximately perpendicular, indicating that there is no π
conjugation between the donor and acceptor moieties. The ET state of Acr−−Mes in solution decays via intermolecular back electron transfer in fluid solution, because the intramolecular back electron transfer is too slow.64 Such a long lifetime of the ET state was questioned in the case of 9-(1-naphthyl)-10-methyl-acridinium ion (Acr−−NA), because the absorption band at 700 nm due to N− was not observed and the observed transient absorption spectrum in the microsecond time region was assigned to the triplet excited state.65−71 However, the reported phosphorescence of Acr−−Mes with the triplet energy of 1.96 eV70,71 was shown to result from the acridine impurity, because Acr−−Mes, which is now commercially available and synthesized according to the method without the involvement of acridine, exhibits no phosphorescence.72 The ET state (Acr−−N−) initially formed upon femtosecond laser excitation of Acr−−NA was demonstrated to be converted to the π-dimer radical cation [(Acr−−N−)[Acr−−NA]] via an intermolecular reaction with Acr−−NA in the microsecond time region, which exhibited a broad NIR absorption at 1000 nm due to the π−π* transition of the dimer radical cation.73,74 The long lifetime of the ET state of Acr−−Mes has allowed observation of the structural change in the Acr−−Mes(ClO4−) crystal upon photoinduced ET directly by using laser pump and X-ray probe crystallographic analysis, in which the sp2 carbon of the N-methyl group of Acr− is changed to the sp3 carbon in the ET state (Acr1).75 Furthermore, Acr−−Mes has been demonstrated to act as an efficient photoredox catalyst in various organic synthetic transformations because of the high oxidizing and reducing ability of the long-lived ET state (vide infra).

Photocatalytic cycloaddition of dioxygen

The high oxidizing and reducing ability of the ET state of Acr−−Mes (vide supra) provides an efficient way to produce radical cations of electron donors (D−−) and radical anions of the electron acceptor (A−−) at the same time. If the direct coupling between D−− and A−− occurs in competition with back electron transfer from A−− to D−−, Acr−−Mes can act as an organic photoredox catalyst for the coupling between D and A. The best example of this strategy has been reported for the photocatalytic [2 + 2] cycloaddition of dioxygen (O2) to tetraphenylethylene (TPE) via the electron-transfer reactions of TPE and oxygen with the ET state Acr−−Mes (Scheme 6).76 The one-electron oxidation potential of TPE (Eox = 1.56 V versus SCE) is less positive than the value of the one-electron reduction potential of Mes−− (Ered = 1.88 V versus SCE).76 Thus, the electron-transfer oxidation of TPE with the Mes−− moiety of Acr−−Mes−− is thermodynamically favourable, resulting in the formation of TPE−− and Acr−−Mes. The [2 + 2] cycloaddition of TPE−− with O2−−, produced by the electron-transfer oxidation and reduction with Acr−−Mes−−, occurs efficiently in competition with back electron transfer from O2−− to TPE−− to produce the 1,2-dioxetane selectively. The further photocatalytic cleavage of the O−O bond of dioxetane affords benzophenone as the final oxygenated product under photoirradiation for 90 min.76 The second-order rate constant (kcat) of electron transfer from TPE to the Mes−− moiety of Acr−−Mes−− in Scheme 6 was determined to be 2.5 × 109 M−1 s−1 in CHCl3 by laser flash photolysis measurements. This value is close to the diffusion-limited value as expected from the exergonic electron transfer.77 On the other hand, the electron-transfer reduction of O2 with the Acr− moiety of Acr−−Mes−− also occurs efficiently, where the second-order rate constant of electron transfer (kcat) is 3.8 × 108 M−1 s−1. The 1,2-dioxetane was isolated by column chromatography. The isolated yield was 27% after 4 h of photoirradiation.76 The quantum yield of 1,2-dioxetane increases with an increase in the concentration of TPE to approach a limiting value of 0.17 and 0.022 in CHCl3 and MeCN, respectively.77

In general, the most common preparation of 1,2-dioxetanes is through the formal [2 + 2] cycloaddition of singlet oxygen (1O2) to electron-rich alkenes.78 If alkenes are too electron-poor to react with 1O2, however, no oxygenated products are obtained. For example, it has been reported that no products were formed in an oxygen-saturated MeCN solution of TPE in the presence of 1O2 sensitizers such as [60]fullerene and porphyrin derivatives under photoirradiation.79 Thus, the photocatalytic cycloaddition of O2 to alkenes with Acr−−Mes provides a unique pathway to synthesize the dioxetanes of electron-poor alkenes.76

Acr−−Mes also acts as an efficient photoredox catalyst for the cis−trans isomerization of stilbene via the radical cation (Scheme 7).80 It is known that cis−trans isomerization occurs rapidly in the stilbene radical cation.77 The steady-state cis−trans ratio of stilbene has been reported to be 98.8:1.77 The observed yield of trans-stilbene from cis-stilbene was 96% after...
60 min of photoradiation, when the total consumption of cis- and trans-stilbene by the photocatalytic oxidation by O₂ was still 4%.77

When anthracene derivatives are used as substrates, Acrr−Mes acts as an efficient photoredox catalyst for the [4 + 2] cycloaddition of O₂ to the anthracene derivatives to afford the corresponding epidioxyanthracenes via radical coupling between the radical cations of the anthracene derivatives and O₂−, which are produced by the electron-transfer oxidation and reduction of anthracene derivatives and O₂ by the ET state of Acrr−Mes, respectively (Scheme 8).81 In the case of 9,10-dimethylanthracene (DMA), the yield of dimethylepidioxyanthracenes was 99% and no further oxidation occurred.81 In the case of anthracene, however, further photoradiation results in the formation of anthraquinone as the final six-electron oxidation product via 10-hydroxyanthrone, accompanied by the formation of H₂O₂.81

The second-order rate constant (kₑ) of electron transfer from DMA to the Mes− moiety of Acrr−Mes− was determined to be 1.4 × 10¹⁰ M⁻¹ s⁻¹ in MeCN at 298 K, which is close to be the diffusion-limited value as expected from the exergonic electron transfer.82 The rate constant of electron transfer from the Acrr− moiety of Acrr−Mes− to O₂ (kₑ) was also determined to be 6.8 × 10⁸ M⁻¹ s⁻¹ in MeCN at 298 K. The [4 + 2] cycloaddition of O₂ to anthracene is known to occur also by the reaction of anthracene with singlet oxygen (¹O₂),82,83 In order to evaluate the contribution of the singlet oxygen pathway, the rate constant of the reaction of O₂ with DMA was determined through the emission decay rates of ¹O₂ (λₑm = 1270 nm)84,85 in the presence of various concentrations of DMA to be 2.4 × 10⁵ M⁻¹ s⁻¹.81 This value is much smaller than the second-order rate constant (kₑ) of the radical coupling between DM++ and O₂− (1.7 × 10¹⁰ M⁻¹ s⁻¹).81 It was confirmed that no singlet oxygen emission was observed during the photocatalytic oxygenation of DMA with Acrr−Mes− in O₂-saturated CD₂CN.81

Thus, the [4 + 2] cycloaddition of O₂ to anthracene occurs exclusively by the radical coupling between the anthracene radical cation and O₂− rather than the reaction of anthracene and ¹O₂, although both pathways yield the same product.

Selective photocatalytic oxygenation of p-xylene

The photocatalytic oxygenation of p-xylene with O₂ also occurs under the visible-light irradiation of [Acrr−Mes]ClO₄⁻ (λₑm = 430 nm) in oxygen-saturated MeCN containing p-xylene (4.0 mM) to yield the oxygenated product, p-tolualddehyde (34%), p-methylbenzyl alcohol (10%) and the reduced product of O₂, H₂O₂ (30%).81 The photocatalytic reactivity was enhanced by the presence of H₂O (0.9 M) and sulfuric acid (1.0 mM) to yield p-tolualddehyde (75%), p-methylbenzyl alcohol (15%) and H₂O₂ (74%) with a high quantum yield (0.25).86 The 100% yield of p-tolualddehyde and H₂O₂ with a higher quantum yield (0.37) was achieved using 9-mesityl-2,7,10-trimethylacridinium ion (Me₂Acr−Mes), where the hydrogens at the 2- and 7-positions of the acridinium ring are replaced by the methyl groups.86 The Eₚred value of Me₂Acr−Mes (−0.67 V versus SCE) is by 0.1 eV more negative than that of Acrr−Mes (−0.57 V), indicating that the Me₂Acr− moiety acts as a stronger electron donor. The rate constants of the electron-transfer reduction of O₂ were determined from the quenching of the transient absorption due to the ET state by O₂ to be 6.8 × 10⁸ M⁻¹ s⁻¹ for Acrr−Mes+ and 2.0 × 10¹⁰ M⁻¹ s⁻¹ for Me₂Acr−Mes+ in MeCN at 298 K.86 Thus, the reducing ability of Me₂Acr−Mes− was significantly enhanced by the electron-donating methyl substitution of the acridinium ring of Acrr−Mes. This may be the reason why the 100% yield of tolualdehyde and H₂O₂ with a higher quantum yield (0.37) was achieved when using Me₂Acr−Mes (vide infra). No further oxygenated product, p-toluic acid or p-phthalaldehyde, was produced during the photocatalytic reaction.

Photocatalytic oxygenation also occurred using durene and mesitylene as substrates.83 The Eₚox values of toluene derivatives are lower than the one-electron reduction potential (Eₚred) of the ET state of R₂Acr−Mes (R₂Acr−Mes+: R = H and Me: 2.06 V versus SCE in MeCN).86 Thus, electron transfer from toluene derivatives such as p-xylene to the Mes− moiety of R₂Acr−Mes+ is energetically feasible, whereas electron transfer from toluene (Eₚox = 2.20 V)51 to the Mes− moiety is energetically unfavourable when no photocatalytic oxidation of toluene by O₂ occurred with Acrr−Mes under the same experimental conditions.86 The Eₚox values of the oxygenated products of the corresponding benzaldehydes are also higher than the Eₚred value of R₂Acr−Mes−.86 This is the reason why the selective oxygenation of p-xylene to p-tolualdehyde was achieved without further oxygenation of p-toluic acid.

The photocatalytic reaction is also initiated by electron transfer from p-xylene to the Mes− moiety of R₂Acr−Mes− to produce the p-xylene radical cation, which undergoes fast deprotonation to afford the deprotonated radical. This is followed by rapid O₂ addition to afford the peroxy radical. The disproportionation of the peroxy radical affords p-tolualdehyde, p-methylbenzyl alcohol and O₂. p-Methylbenzyl alcohol is readily oxidized to yield p-tolualddehyde with Acrr−Mes−.86 On the other hand, O₂− undergoes disproportionation with a proton to yield H₂O₂ and O₂ (Scheme 9). The radical intermediates involved in Scheme 9 were detected by EPR.
The addition of aqueous sulfuric acid enhanced the deprotonation of the p-xylene radical cation and the disproportionation process of O$_2^-$, respectively, leading to a remarkable enhancement in photocatalytic reactivity as mentioned above. The photocatalytic reactivity and stability of Acr$^+$–Mes were further improved by incorporating Acr$^+$–Mes into mesoporous silica-alumina with a copper complex [[(tmpa)Cu]$_2$]$^+$ (tmpa = tris(2-pyridylmethyl)amine) for the selective oxygenation of p-xylene by O$_2$ to produce p-tolualdehyde because the [[(tmpa)Cu]$_2$]$^+$ complex acts as an efficient catalyst for the O$_2$ reduction.

Methyl-substituted naphthalenes were also oxidized with O$_2$ using Acr$^+$–Mes as a photoredox catalyst. It should be noted that 2-methylnaphthalene does not react with O$_2$ to produce oxygenated products. This underscores the utility of Acr$^+$–Mes in the photocatalytic oxygenation of substrates as compared with O$_2$ photosensitizers. The photocatalytic oxidation of triphenylphosphine (Ph$_3$P) and benzylamine (PhCH$_2$NH$_2$) with O$_2$ also occurs efficiently using Acr$^+$–Mes as a photoredox catalyst to yield Ph$_3$P=O and PhCH$_2$N=CHPh, respectively.

### Photocatalytic oxidative bromination of aromatic hydrocarbons with hydrogen bromide and oxygen

The bromination of aromatic compounds has been one of the most important and fundamental reactions in organic synthesis, providing key precursors for various transformations such as Grignard reactions and Suzuki–Miyaura coupling. Electrophilic bromination in nature mainly occurs by oxidative bromination through the catalyzed oxidation of the halide ion to form a brominating reagent, whereas bromination is usually carried out with hazardous, toxic, and corrosive molecular bromine, which is better to be avoided from an ecological point of view. The best candidate for oxidants would be oxygen since hydrogen peroxide or water would be the only side-products. In this context, Acr$^+$–Mes was reported to act as an efficient organic photocatalyst for the oxidative bromination of aromatic hydrocarbons by O$_2$ with hydrogen bromide to produce the monobrominated products selectively. Both the product yield and selectivity for the bromination of 1,3,5-trimethoxybenzene (TMB) were 100% with a quantum yield of 4.8%. The photocatalytic turnover number was 90 based on the initial concentration of Acr$^+$–Mes. When methoxy-substituted aromatic compounds were replaced by toluene derivatives, the consumption of substrate occurred efficiently under the same experimental conditions. However, the yield of the brominated product and its selectivity were significantly lower compared with methoxy-substituted benzenes, because the photobromination competes with photooxygenation with oxygen to yield the corresponding aromatic aldehyde (Scheme 9).

The photocatalytic reaction is also initiated by intramolecular photoinduced electron transfer from the Mes moiety to the singlet excited state of the Acr$^+$ moiety of Acr$^+$–Mes to generate the ET state (Acr$^+$–Mes$^*$) as shown in Scheme 10, where the Mes$^*$ moiety can oxidize TMB to produce TMB$^*$ whereas the Acr$^+$ moiety can reduce O$_2$ with proton to HO$_2^*$. The TMB$^*$ reacts with Br$^-$ to form the Br-adduct radical, which undergoes dehydrogenation with HO$_2^*$ to afford the corresponding monobrominated product and hydrogen peroxide. Hydrogen peroxide further reacts with HBr and the substrate to produce another monobrominated product and H$_2$O. The selectivity of monobromination results from the lower reactivity of the radical cations of brominated benzenes with Br$^-$.

Although the substrates that can be brominated are limited by their one-electron oxidation potentials, which should be less positive than the E$_{ox}$ value of Acr$^+$–Mes (2.06 V versus SCE), this limitation is compensated for by the high selectivity for the bromination to avoid over-bromination. When HBr was replaced by HCl, photocatalytic chlorination of aromatic substrates with Acr$^+$–Mes also occurred under otherwise identical experimental conditions.

### Photocatalytic intramolecular anti-Markovnikov hydroetherification of alkenols

Nicewicz and co-workers recently utilized the high oxidizing ability of the ET state of Acr$^+$–Mes for the anti-Markovnikov...
hydroetherification of alkenols with 2-phenylmalononitrile as a redox-cycling source of a H-atom, with complete regioselectivity without any trace of the undesired Markovnikov regioisomer.97,98 The utility of Acr+–Mes as an organic photoredox catalyst is underscored when compared directly with the frequently employed [Ru(bpy)]32+,97 which failed to give any of the desired product.97 The high oxidizing ability of the ET state of Acr+–Mes allowed for greater latitude in potential substrates with alkenes possessing the one-electron oxidation potentials ranging up to +2.0 V versus SCE.97

The photocatalytic cycle is shown in Scheme 11.97 The ET state of Acr+–Mes oxidizes the alkenol via electron transfer from the alkenol to the Mes+ moiety of the ET state to produce the corresponding radical cation, which is cyclized followed by H-atom transfer from 2-phenylmalononitrile. The resulting radical could serve as an oxidant for the Acr+ radical to produce the carbanion, regenerating the ground state Acr+–Mes. Proton transfer from the cyclized cation to the carbanion regenerates the H-atom donor (2-phenylmalononitrile) and yields the desired product (Scheme 11).97 The scope of the intramolecular anti-Markovnikov hydroalkoxylation of alkenols has been examined, ranging from electron-rich (4-(MeO)C6H4, 80% yield) to electron-deficient (4-ClC6H4, 60% yield) compounds, and provided good yields of the desired 5-exo adducts.97 The anti-Markovnikov hydroetherification of alkenols shows sharp contrast to Brønsted acid-assisted Markovnikov hydroetherification.97

The same strategy used for intramolecular hydroetherification of alkenols, where the radical cations gave rise to anti-Markovnikov reactivity in Scheme 11, has also been applied for the intramolecular anti-Markovnikov hydroamination of unsaturated amines in which thiophenol was used as a hydrogen-atom donor.99 The photocatalytic system is effective for a range of cyclization modes to give important nitrogen-containing heterocycles.99

Photocatalytic cycloaddition between alkenes with alkenols

The intramolecular anti-Markovnikov hydroetherification of alkenols in Scheme 11 has been extended to the intermolecular cycloaddition of trans-β-methylstyrene and allyl alcohol in Scheme 12.100 The β-methylstyrene radical cation produced by electron transfer from β-methylstyrene to the ET state of Acr+–Mes reacts with allyl alcohol to produce the adduct radical cation, which undergoes a 5-exo radical cyclization with the pendant alkene.100 Hydrogen-atom abstraction from 2-phenylmalononitrile and the loss of a proton yields the tetrahydrofuran adduct (63% yield).100 The phenylmalononitrile anion is neutralized by the generated proton to regenerate the hydrogen-atom donor (2-phenylmalononitrile).100 Employing cis-β-methylstyrene gave an identical mixture of diastereomers as trans-β-methylstyrene (80% yield), demonstrating the loss of alkene geometry upon the one-electron oxidation.100 4-Chloro-β-methylstyrene gave the corresponding tetrahydrofuran adduct in good yield (70% yield), whereas 4-methoxy-β-methylstyrene was not reactive under these conditions, probably due to the stability of the resultant radical cation intermediate.100 Cyclic alkene substrates, such as indene and 1-phenycyclohexene, also afforded good yields of the corresponding cyclic ether adducts.95 Aliphatic trisubstituted alkenes with higher oxidation potentials, such as 2-methylbut-2-ene, also afforded highly substituted cyclic ethers.100 Thus, Acr+–Mes is used as an effective organic photoredox catalyst to synthesize highly substituted tetrahydrofurans from readily available allylic alcohols and alkenes.100

Photocatalytic intermolecular anti-Markovnikov addition of carboxylic acids to alkenes

The photocatalytic cycle in the intermolecular cycloaddition between β-methylstyrene and allyl alcohol in Scheme 12 has also been applied to the anti-Markovnikov hydroacetoxylation of styrenes, trisubstituted aliphatic alkenes and enamides, with a variety of carboxylic acids to afford the anti-Markovnikov addition adducts exclusively (Scheme 13).101 Electron-transfer oxidation of the alkene by the Mes+ moiety of the ET state of Acr+–Mes results in the formation of the alkene cation radical to which the carboxylate nucleophile is added to the less substituted position of the cation radical to produce the...
adduct radical.\textsuperscript{101} A rapid acid–base equilibrium with the excess carboxylic acid generates small quantities of benzenesulfonic acid, which acts as the active hydrogen-atom donor.\textsuperscript{101} Hydrogen-atom transfer from benzenesulfonic acid yields the anticipated anti-Markovnikov adduct.\textsuperscript{101} The hydrogen-atom transfer step is found to be the rate-determining because of the large deuterium kinetic isotope effect.\textsuperscript{101} The resultant benzenesulfinyl radical oxidizes the Acr\textsuperscript{+} moiety to regenerate Acr\textsuperscript{–}Mes and benzenesulfinate.\textsuperscript{101}

Photocatalytic hydrotrifluoromethylation of styrenes and unactivated aliphatic alkenes

The development of new methodologies for the highly efficient and selective incorporation of a CF\textsubscript{3} group into diverse skeletons has merited significant interest from synthetic chemists,\textsuperscript{102} because the CF\textsubscript{3} group is a useful structural motif in many biologically active molecules as well as materials.\textsuperscript{103} There have been several reports on photocatalytic trifluoromethylation using metal complexes as photosensitizers.\textsuperscript{104–107} Nicewicz and co-workers recently reported the metal-free hydrotrifluoromethylation of alkenes using Acr\textsuperscript{–}Mes as an efficient organic photoredox catalyst, as shown in Scheme 14.\textsuperscript{108}

The electron-transfer oxidation of sodium trifluoromethanesulfinate (CF\textsubscript{3}SO\textsubscript{2}Na, Langlois reagent)\textsuperscript{109} results in formation of the electrophilic trifluoromethyl radical (CF\textsubscript{3}\textsuperscript{•}). Together with the expulsion of SO\textsubscript{2}. Addition of CF\textsubscript{3}\textsuperscript{•} to the alkene occurs with anti-Markovnikov selectivity to produce the corresponding carbon-centred radical.\textsuperscript{108} Alkyl-substituted alkenes provide hydrotrifluoromethylated products without the use of thiols as a H-atom donor.\textsuperscript{108} In this case, trifluoroethanol used as a cosolvent acts as a H-atom donor. The produced trifluoromethylketyl radical oxidizes the Acr\textsuperscript{–} moiety of Acr\textsuperscript{–}Mes to regenerate Acr\textsuperscript{+}Mes. Methyl thiosalicylate is used as a H-atom donor for aliphatic alkenes, and thiophenol is used as a H-atom donor for styrenyl alkenes.\textsuperscript{108} The substrate scope for the photocatalytic trifluoromethylation is broad, including mono-, di- and tri-substituted aliphatic and styrenyl alkenes, with high regioselectivity.\textsuperscript{108}

**Photocatalytic C–C bond formation**

Acr\textsuperscript{–}Mes can also be used as an effective photoredox catalyst for the C–C bond formation of deprotonated radicals following formation of the radical cations of the substrates (vide infra). Although the photoexcitation of anthracene gives a [4 + 4] dimer through the singlet excimer intermediate,\textsuperscript{110,111} another type of anthracene dimer derivative, i.e., dimethyllepidopterene (5,6,11,12-tetrahydro-4b,12\textsuperscript{a}anthracene-4,12-dione) has been prepared by the photocatalytic carbon–carbon bond formation of 9,10-dimethylantracene (DMA) in chloroform via the electron-transfer oxidation of DMA with the ET state of Acr\textsuperscript{–}Mes (Scheme 15).\textsuperscript{112} Visible-light irradiation (λ > 430 nm) of the absorption band of Acr\textsuperscript{–}Mes (5.0 × 10\textsuperscript{–}4 M) in a de-aerated chloroform (CDCl\textsubscript{3}) solution containing DMA (1.5 × 10\textsuperscript{–}3 M) results in the formation of dimethyllepidopterene, 1,2-bis(9-anthracenyl)ethane, and 9-(β,β-dichloroethyl)-10-methylanthracene (Scheme 15).\textsuperscript{112} The isolated yield of dimethyllepidopterene was 12% after 4 h of photolysis at 298 K.\textsuperscript{112} The ORTEP drawing determined from the X-ray crystal structural analysis is also shown in Scheme 15.\textsuperscript{112} The bond length of the newly formed C–C bond (C\textsubscript{6}–C\textsubscript{6}) is 1.629 (2) Å, which is much longer than normal C–C single bonds due to the severe distortion of this compound.\textsuperscript{112}

The electron transfer from DMA to the Mes\textsuperscript{–} moiety of Acr\textsuperscript{–}Mes\textsuperscript{+} is followed by deprotonation from the methyl group of DM\textsuperscript{+} and the radical coupling reaction between 9-methylanthrylmethyl radicals occurs to yield dimethyllepidopterene together with 1,2-bis(9-anthracenyl)ethane.\textsuperscript{112} The Acr\textsuperscript{–}Mes, produced by electron transfer from DMA to Acr\textsuperscript{–}Mes\textsuperscript{+}, was
oxidized by dissociative electron transfer to CHCl₃ to produce CHCl₂ and Cl⁻. The CHCl₂ radicals dimerized to yield 1,1,2,2-tetrachloroethane (CHCl₂CHCl₂) or reacted with 9-methylanthrylmethyl radical to yield 9-(β,β-dichloroethyl)-10-methylanthracene (Scheme 15). The deprotonation from the methyl group of DM⁺ is the key step for the formation of dimethyllepidopterene. Thus, no photodimerization has occurred in the case of unsubstituted anthracene, which has no methyl group to be deprotonated, and nor in the case of 9,10-dimethylanthracene in which the deprotonation from the ethyl group may be too slow to complete with the back electron transfer. The acceleration of the deprotonation of DM⁺ by the presence of a base such as tetrabutylammonium hydroxide (TBAOH) resulted in an improvement of the isolated yield of dimethyllepidopterene (21%) as compared with the yield in the absence of a base (12%).

The C–C bond formation also occurs between the radical cation and radical anion of the same substrate, which are formed by the electron-transfer oxidation and reduction of the substrate by Acr⁻–Mes⁺. For example, the photocatalytic oligomerization of fullerene in toluene–acetonitrile solution occurs efficiently via the electron-transfer oxidation and reduction of C₆₀ with Acr⁻–Mes⁺, followed by the radical coupling reaction between C₆₀⁺⁺ and C₆₀⁻⁻ (Scheme 16). Because the free energy change of electron transfer (ΔGₑ) from C₆₀ (Eₒₓ = 1.73 V versus SCE) to the Mes⁺ moiety of Acr⁻–Mes⁺⁺ (Eᵣₑd = 1.88 V) in benzonitrile (PhCN) is negative (ΔGₑ = −0.15 eV), the electron-transfer oxidation of C₆₀ is energetically feasible to form C₆₀⁺⁺. On the other hand, the electron-transfer reduction of C₆₀ (Eᵣₑd = −0.43 V) with the Acr⁺ moiety of Acr⁻–Mes⁺⁺ (Eₒₓ = −0.49 V) is also thermodynamically feasible to give C₆₀⁻⁻ (ΔGₑᵗ = −0.06 eV). Thus, C₆₀ acts as both an electron donor and acceptor in the electron-transfer reactions of Acr⁻–Mes⁺ with C₆₀ to produce C₆₀⁺⁺ and C₆₀⁻⁻ together at the same time. The [2 + 2]cycloaddition occurs efficiently between C₆₀⁺⁺ and C₆₀⁻⁻ to afford the triplet excited state (⁰C₁₂₀⁺), because the driving force of charge recombination (2.16 eV) is larger than the triplet excited state energy of C₁₂₀ (ca. 1.5 eV). Further oligomerization occurs by the same process.

Photocatalytic cycloreversion of photochromic dithienylethene compounds

The photocatalytic cycloreversion (ring opening) of photochromic cis-1,2-dithienylethene (DTE) compounds occurs efficiently using Acr⁺–Mes as a photoredox catalyst. Thus, not only C–C bond formation (vide supra) but also C–C bond cleavage of the closed form of DTE has been achieved using the photoredox catalysis of Acr⁺–Mes. An exergonic electron transfer from DTE to the Mes⁺ moiety of Acr⁺–Mes⁺ initiates the ring opening of DTE (initiation) in competition with the back ET from the Acr⁺ moiety to the radical cation of the closed form (Scheme 17). The electron transfer from a closed
form of neutral DTE to the open-form radical cation completes the cycloeversion to regenerate the closed-form radical cation. This is the propagation step of the electrocatalytic chain mechanism in Scheme 17. The chain process is terminated by back electron transfer from Acr−→Mes to the open-form radical cation (termination).117 This strategy benefits from the catalytic nature of the electrochromism; in contrast to the photostoichiometric photochromism, the photon economy gains a leverage effect, leading to a greatly improved the quantum yield.117

Conclusions

A variety of novel organic synthetic transformations have been made possible by organic photoredox catalysis via photoinduced electron-transfer reactions. In particular, the use of the excited states of 2,3-dichloro-5,6-dicyano-p-benzoquinone (DDQ) and 3-cyano-1-methylquinolinium ion (QuCN+), which have a strong oxidizing ability, has made it possible to oxidize benzene to phenol via the formation of the benzene radical cation. An electron donor–acceptor-linked dyad, 9-mesityl-10-methylacridinium ion (Acr+→Mes), can be used as an efficient photoredox catalyst because the long-lived electron-transfer state of Acr−→Mes, produced upon photoexcitation, can oxidize and reduce external electron donors and acceptors to produce the corresponding radical cations and radical anions, respectively, leading to the selective oxidation, halogenation, C–C bond formation and cleavage of various substrates. Thus, metal-free photocatalytic reactions via the photoinduced electron transfer of organic photosensitizers and donor–acceptor dyads provide new ways to achieve environmentally benign organic synthesis. Photocatalytic organic synthesis can be finely controlled by choosing appropriate organic photocatalysts with tuned one-electron redox potentials. The scope and the applications of organic photoredox catalytic systems are expected to expand much further in the future.

Acknowledgements

The authors gratefully acknowledge the contributions of their collaborators and co-workers mentioned in the cited references, and support by an ALCA fund from Japan Science and Technology Agency (JST) and funds from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

Notes and references

5 S. Fukuzumi and Y. Yamada, ChemSusChem, 2013, 6, 1834–1847.