Photodynamic covalent bonds regulated by visible light for soft matter materials

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Photodynamic bond forming systems (i.e., systems that respond with defined bond formation at one wavelength and cleavage at a disparate yet defined wave-length) are essential for adaptive soft matter materials design. This emerging field has thus far been dominated by the need to use UV light to induce bond cleavage and to some extent to induce bond formation. The next critical frontier in the field is to substantially redshift both the bond formation and cleavage reac-tion into biologically benign irradiation regimes that commence beyond 400 nm. Herein, we concisely summarise, on the basis of critically selected examples, the progress that has been made to date both on the fundamental photochemical level as well as in the associated materials realm. In addition, we highlight future avenues and opportunities to progress the field.

Photodynamic covalent bonds in soft matter materials design

Dynamic covalent chemistry (DCC) is based on reversible covalent bonds that can cleave and reform autonomously or in response to stimuli such as pH, temperature, and light. While this subset of chemistry has been traditionally used in organic synthesis and medicine (e.g., in combinatory chemistry) [1], it has been applied increasingly in the design and development of soft matter materials with adaptable functions. In particular, the nature of dynamic covalent bonds (DCB) is a powerful tool for the preparation of polymers with unique self-healing and recycling properties, with significant relevance towards sustainable development [2]. Recent progress in DCCs has extended their applications towards smart and responsive polymer materials, such as malleable systems, artificial muscles, and microfluidic devices [3]. The dynamic nature of the bonds further enables various (macro)molecular mechanisms to manipulate polymer chain topologies (topological transformation), paving the way for programming polymer architecture, including reversible transformation between linear and cyclic polymers [4], or between block and star polymers [5], and the construction of quasi-living networks that continue to grow and evolve post-fabrication [6–8].

Light regulation of the bond cleavage and formation process provides a high degree of versatility in tuning specific material properties by varying the wavelengths and photon flux. The most striking feature of photodynamic materials is the on-demand spatial and temporal control that is critical for smart devices (e.g., actuators and soft robotics) designed to operate in delicate biological environments [9]. Indeed, light-controlled dynamic bonds have already established their own class of DCBs [i.e., ‘Photo Dynamic Covalent Bonds’ (PDCB)] [10]. In principle, PDCBs dissociate upon excitation into reactive building blocks, which recombine via thermal reversion or a different wavelength excitation to generate new bonds akin to those present before photoactivation (Figure 1, Key figure). Such dynamic exchanges can be utilised to form new chemical entities based on the incorporated photoreactive building blocks. The responses of PDCBs as well as the resultant structures can be fine-tuned through specific photoreactivity and light intensity, en-abling many advanced functions in soft matter materials. In particular, incorporation of PDCBs within polymer network allows for manipulation of their internal stress distribution, either through

Highlights

Photodynamic covalent bonds (PDCBs) are covalent linkages that can be revers-ibly cleaved and reformed by light irradia-tion. PDCBs hold key potential in soft matter materials design for advanced ap-plications, including self-healing, shape-shifting, materials recycling, and topolog-ical transformation.

Controlling the photodynamic exchange with visible light offers significant benefits in tuning the materials properties, broadening the applications of light-responsive soft matter materials in biological environments.

Significant progress has been made in redshifting the photoreactivity of commonly used photodynamic PDCBs, including the reversible [2+2] photocycloadditions and photo-induced radical exchanges. Recently introduced photodynamic interactions can also be in-fluenced by extremely mild conditions, such as cleavage in darkness, enabling formation of light-stabilised dynamic materials.

The activation wavelength of PDCBs can be extended further into the red/near-infrared region by combination with redshifted photoswitches.

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nonuniform stress relaxation in-plane using a photomask, or out-of-plane using light attenuation through the material thickness, affording unique shape-shifting profiles [11]. Further, light-induced topological network reorganisation offers unique advantages addressing performance weakening of polymeric materials in dental, adhesive, and coating applications, where other stimuli, such as pH and heat, may not be accessible.

The need for visible light control over photodynamic covalent interactions

The toolbox of PDCBs has been mostly built based on the available photochemical reactions that are induced by UV light. Examples of PDCBs include disulfide [12] or hexaarylbiimidazole (HABI)[13] derivatives, which are cleaved to afford reactive radicals by UV light irradiation. The principle of PDCBs also applies to photo-induced bond formation and cleavage in [2+2] or [4+4] photocycloadditions of coumarin, thymine, stilbene, and anthracene derivatives, which have

Key Figure

Concept of photodynamic covalent bonds able to be reversibly cleaved and formed using disparate wavelengths and examples of photodynamic covalent bonds together with their specific applications in soft matter materials

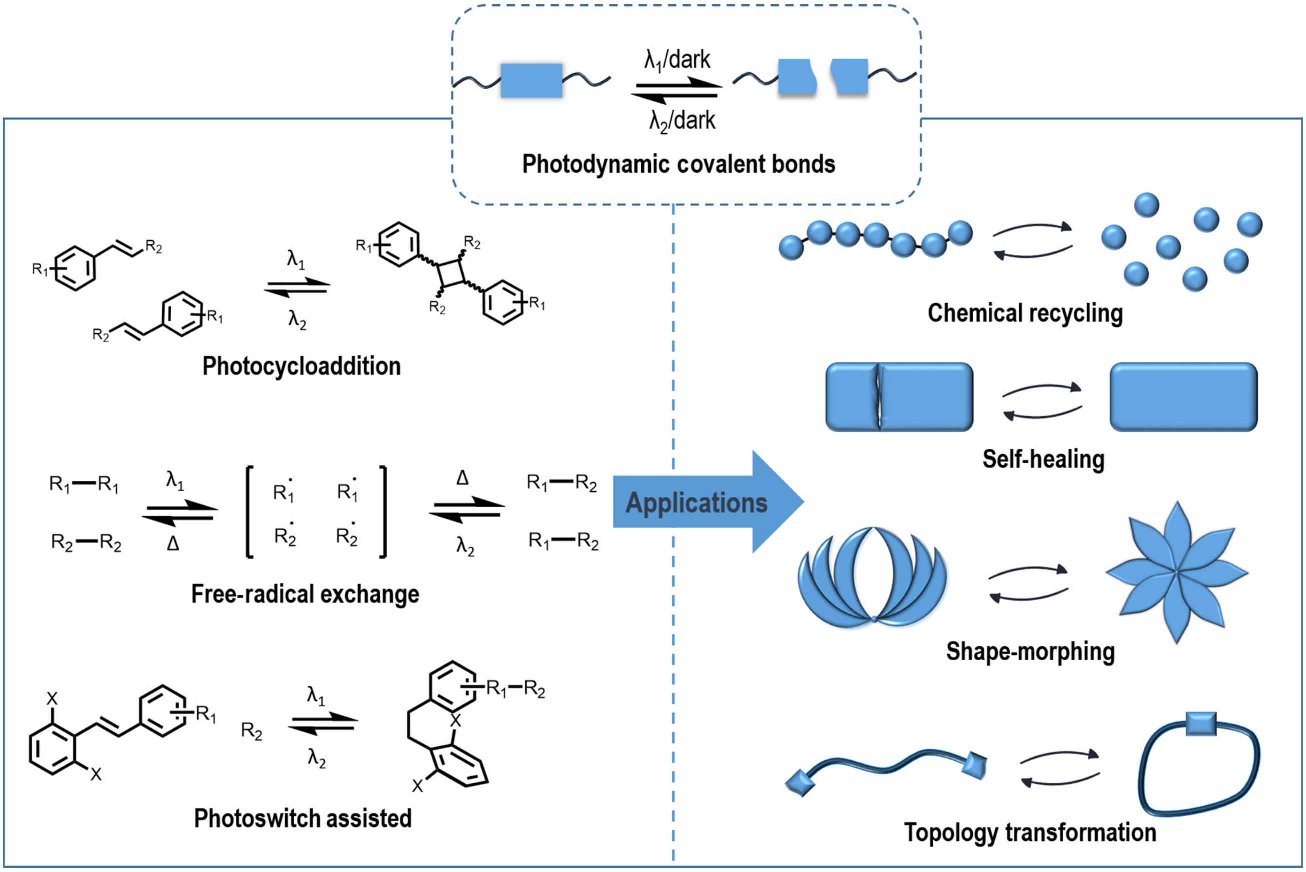

Figure 1.

been used in the context of dynamic covalent polymer materials [14,15]. In these systems, both single and coupled states are thermodynamically stable and UV wavelengths are required to trigger the transformation, with higher energy (shorter wavelength) UV light needed for the photocleavage due to the decreased π-conjugation of the cycloaddition products.

Applying UV light-activated photodynamic covalent interactions within biological systems is highly challenging, since many endogenous macromolecules, such as enzymes and proteins, are degraded by UV light [16]. The resultant damage, in conjunction with limited tissue penetration of short wave-length UV light, renders *in vivo* applications of such systems almost impossible [17,18]. Extension of PDCBs to *in vivo* settings entails the use of low-energy, long wavelength visible light, which is not only benign to biological species but also capable of penetrating further into skin and tissue [19]. Outside of biological applications, visible light activation offers significant advantages of flexibility in the wavelength range used in tuning network properties, accessible light sources, and thus inex-pensive light operating techniques. Furthermore, long wavelength visible light can minimise the forma-tion of nondesired free radicals and side reactions, such as photo-oxidative cleavage products [20] or photoisomerisation, often generated by UV-light irradiation [21].

Over the last 10 years, the drive to expand applications of dynamic covalent interactions in advanced materials has led to a substantial push towards redshifting the activation wavelength of PDCBs. These chemical advances, together with recent developments in photophysics to administer light at discreet wavelengths, are enabling exciting opportunities to modulate material properties under benign conditions and potentially in living systems. Herein, we highlight the recent advances in redshifted PDCBs, whose activation windows are in the visible light region, and their applications in soft matter materials design.

Redshifted photocycloadditions

Photoreversible pericyclic reactions, such as [2+2] and [4+4] photocycloadditions, have been widely used in the construction of photodynamic networks, whose micro- and macrostructures can be rearranged by different wavelengths of UV light, with applications in self-healing and shape-shifting materials (Figure 2A) [14,15]. Although a visible light absorbing chromophore, styrylpyrene (Figure 2B) that can undergo [2+2] photocycloaddition was reported in 1980 [22], only in 2016 was this chromophore utilised in the photo-induced reversible crosslinking of DNA strands [23]. Truong and co-workers further incorporated styrylpyrene into a four-arm poly(ethylene glycol) (PEG) for the fabrication of blue (λ_{max} = 445 nm) light-responsive photodynamic hydrogels [24]. It should be noted that the photocleavage of the dimer still requires UV light (λ_{max} = 340 nm). Concurrently, Barner-Kowollik and colleagues meticulously investigated the photocycloaddition of styrylpyrene with regard to the isomeric photo-adducts as well as the most efficient photochemical reaction conditions using a technique called wavelength-dependent photo efficiency analysis [25]. Such an analysis results in an action plot, presenting the trigger wavelength as the function of conversion under the supply of a constant number of photons [26]. Their study revealed that wavelengths of 435 and 330 nm are most efficient for dimerisation and dissociation, respectively. Frisch *et al.* demonstrated further the utility of the styrylpyrene in dynamic programming polymer structures [27–29]. These authors demonstrated that blue light (λ_{max} = 460 nm) enabled photopolymerisation of the styrylpyrene-functionalised tetraethylene glycol [27]. Interestingly, UVB irradiation (λ_{max} = 330 nm) on the resultant polymer triggered a rapid depolymerisation to linear oligomers, while violet light (λ_{max} = 410 nm) induced formation of cyclic polymers. Thus, by choice of colour of light, it is possible to gate the depolymerisation or topology switching for styrylpyrene-incorporated polymer systems. Further, the styrylpyrene photocycloaddition was applied in confined environments for the photo-induced folding/unfolding of single chain nanoparticles (SCNP) [30].

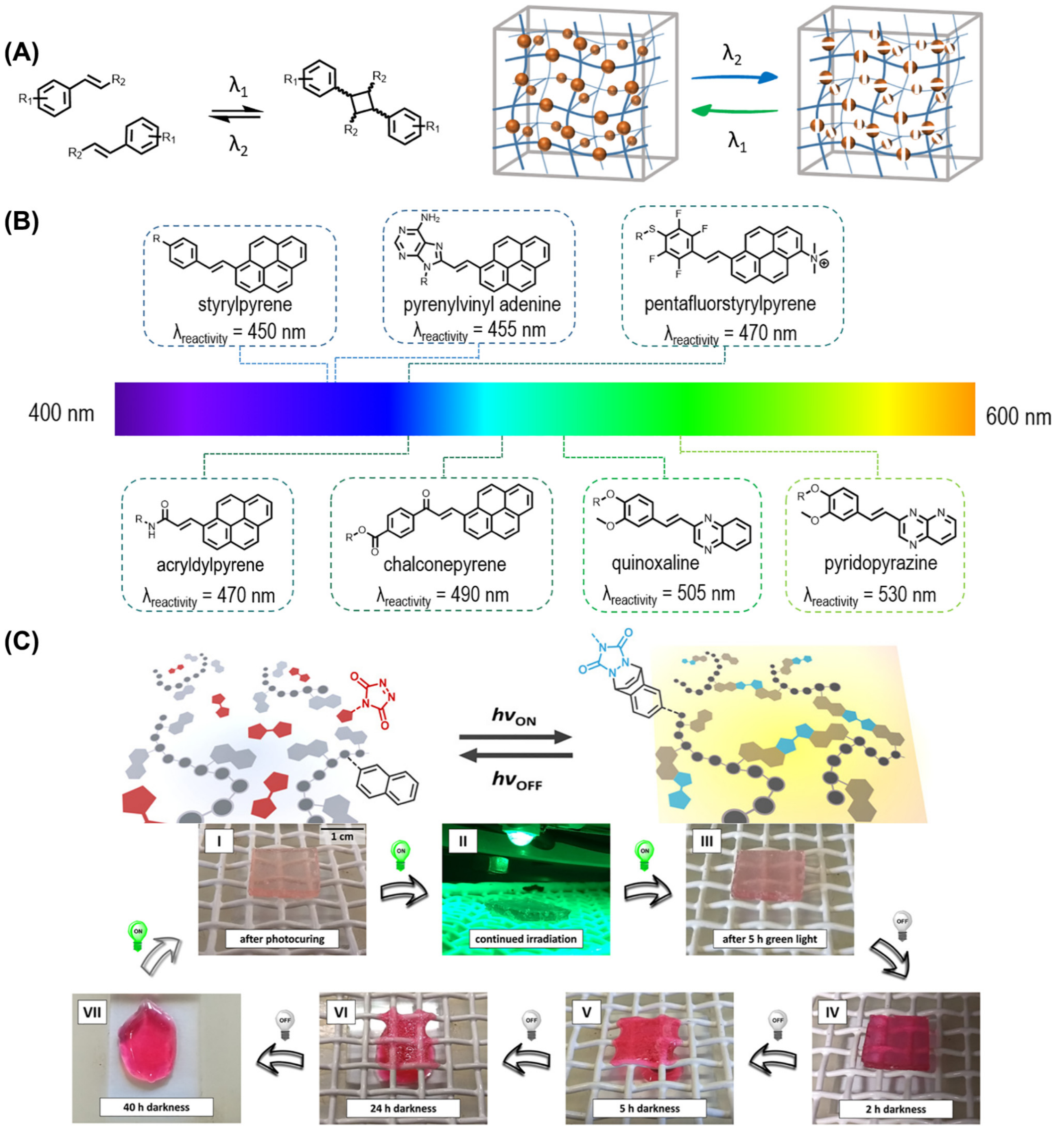

Figure 2. Visible light-enabled photocycloadditions. (A) Scheme of [2+2] photocycloadditions that are widely used in photodynamic polymer networks;

(B) chromophores developed within the last 5 years that can undergo [2+2] photocycloadditions by visible light; (C) photoreversible reaction between a triazolinedione and a naphthalene, forming the core of light-stabilised dynamic materials wherein a covalently crosslinked polymer material can be obtained through a visible light-driven cycloaddition, and switching off the light triggers the de-crosslinking, causing the material to collapse. Reproduced, with permission, from [45].

Within the last 5 years, the Barner-Kowollik group and others have further expanded the library of chromophores that can undergo [2+2] cycloadditions by light between 400 and 550 nm (Figure 2B). Based on the styrylpyrene motif, Barner-Kowollik and colleagues developed acryldylpyrene [31] and chalconepyrene [32], both with redshifted photoreactivity compared with styrylpyrene. Similarly, the team of Walther introduced a multifunctional quaternised 1-trimethyl-ammonium-6-pentafluorstyrylpyrene that, in addition to being able to undergo redshifted [2+2] photocycloaddition, has good solubility in water [33]. Further, Murayama and co-workers designed a pyrenylvinyl adenine moiety specifically for insertion into RNA strands for photoreversible RNA duplex formation [34]. Moving away from the pyrene core, we introduced the styrylquinoxaline function, which can perform [2+2] photocycloaddition in water by green light (λ_{max} = 505 nm) excitation [35]. Further modification of the heteroaromatic moiety resulted in the styrylpyridopyrazine function, which can be activated by light at λ_{max} = 530 nm, which is the longest wavelength used in [2+2] photocycloadditions in solution to date [36]. Such chromophores have demonstrated their potential in biology-focused studies, including bioorthogonal cell encapsulation and light-induced cell-sheet detachment [31,35]. Critically, the use of long wavelength visible light (λ_{max} = 520 nm) significantly improves the penetration depth in hydrogel crosslinking, enabling the formation of thick hydrogel samples compared with UV or blue light curing [35].

The photoreactivity of both styrylquinoxaline and styrylpyridopyrazine can be inhibited by acidic conditions, thus providing additional control over its photoreactivity. A major limitation of these [2+2] photocycloaddition systems is the inefficient dissociation of the dimer by long wavelength UV light (360–400 nm). Although near complete photocleavage can be achieved under diluted conditions (micro- or nanomolar), such as those used in SCNP or DNA/RNA studies, photodegradation of polymer networks, such as hydrogels, containing photocycloaddition adducts by UV light (340–400 nm) still remains a challenge. Specifically, photodegradation of styrylpyrene-based hydrogels at λ_{max} = 340 nm is highly dependent on the crosslinking density of polymer networks, with the light-induced bond cleavage inefficient at polymer concentration exceeding 4 mM (8 wt%) in water [24].

In contrast to [2+2] photocycloadditions, there are very few reports on catalyst-free and red-shifted [4+4] photocycloaddition systems. In the context of PDCBs, the photocycloaddition of anthracene is the most prevalent [4+4] photochemical system used in tuning soft matter material properties, with applications in self-healing and topological transformation [15,37,38]. For decades, the photocycloaddition of anthracene derivatives was initiated by UV light (340–360 nm), however recent analysis into wavelength dependence of its photokinetics revealed that violet light (400–410 nm) can be used as a trigger [39,40]. Redshifting the photoreactivity of anthracene was induced by attaching an electron-rich triazole moiety to the 9-position of the polyaromatic moiety. The resultant chromophore was used in the coding and erasing of solid surface by blue (420 nm) and UV light (360 nm), respectively [41]. It should be noted that the cycloreversion is highly inefficient, with a long irradiation period (48 h) required for erasing the surface coded information. When applied to crosslinked hydrogel systems, the crosslinking via the triazole anthracene group can be induced by blue light at λ_{max} = 445 nm, however, dissociation at λ_{max} = 365 nm is not possible [42]. Therefore, further improvement of such photochemical systems is necessary, especially to overcome the strong π–π stacking of the polyaromatic rings for photodissociation to extend their utility in photodynamic covalent interactions.

While conventional PDCBs used light to trigger the dissociation, our team, in collaboration with the team of Du Prez, recently reported the spontaneous dissociation of the adducts from Diels–Alder photoreaction between triazolinediones and naphthalenes (Figure 2C) [43].

Incorporation of such photochemical system in the context of polymer crosslinking results in the design of so-called light-stabilised dynamic materials, the structural integrity of which is maintained under a continuous photonic field of green light. In the dark and at ambient temperature, the crosslinked materials slowly degrade via spontaneous cycloreversion. This discovery provides a step forward in the field of PDCBs, where rearrangement of the bonds can progress under extremely mild conditions.

Visible light-enabled photoreversible radical exchange

Disulfide bonds are widely used in the construction of photodynamic polymers [12]. Disulfide bond formation and exchange reactions can progress via either anionic (thiolate) or radical pathways and the latter is often targeted for PDCBs. The photocleavage of the linear S–S bonds requires high energy short wavelength ($\lambda = 200$–300 nm) UV light. The absorbance of the S–S bonds can be extended into the visible region by incorporation of highly conjugated and electron-rich motifs, such as the thiuram disulfide structure (Figure 3A). Such structures are derived from the trithiocarbonate moieties, commonly used in photopolymerisation, displaying reshuffling reactions under UV light initiation [44,45]. Amamoto and colleagues examined the photodynamic behaviour of thiuram disulfide derivatives, demonstrating that the reshuffling was rapid at ambient temperature, reaching equilibrium after 20 min of irradiation with visible light [46]. Incorporation of the thiuram disulfide into the backbone of polyurethanes enabled the polymers to self-heal under visible light (400–600 nm) illuminance.

The energy requirement for S–S photocleavage can also be lowered by using strained structures, such as 1,2-dithianes and 1,2-dithiolanes (Figure 3B), enabling photolysis under milder UV light irradiation ($\lambda = 340$–360 nm) [47,48]. The team of Sumerlin introduced a phenyl-substituted 1,2-dithiolane derivative with absorbance extending into the blue light ($\lambda = 420$–440 nm) region, utilising this function in the fabrication of a photodynamic PEG hydrogel (Figure 4C) [47]. Although UV light ($\lambda_{max} = 365$ nm) was used in their study, it may be possible to induce the dynamic viscoelastic changes by blue light ($\lambda \geq 400$ nm) considering the absorption spectrum of the photoreactive species.

Compared with disulfide bonds, diselenide bonds possess a lower bond energy (diselenide bonds: 172 kJ mol^{-1}; disulfide bonds: 240 kJ mol^{-1}) [49], indicating that diselenide bonds can be dissociated under milder conditions. Inspection of the molecular orbitals involved in the excitation process reveals that the 4p orbitals of selenium is more diffuse compared with the 3p orbitals of sulphur in the S–S bonds and, thus, lower excitation energies for the Se–Se bonds. Particularly, the σ_{Se-Se} molecular orbitals are more destabilised than those of the S–S bonds, while the σ_{Se-Se} antibonding orbitals are more stabilised than the σ_{S-S} (Figure 5A) [50]. Such features enable Se–Se moiety to absorb light in the visible region, thus the photodynamic exchange can be induced by visible light. The visible light-enabled metathesis behaviour of selenide derivatives was first demonstrated by Xu and co-workers by irradiating a mixture of three compounds containing Se–Se bond with white light (400–600 nm), demonstrating via NMR spectroscopy that new exchange products were formed, reaching an equilibrium of 50% of exchanged products and 25% of each reactant (Figure 5B) [49]. Notably, the photolysis and recombination processes had no specific requirement for solvents, as both nonpolar and polar solvents are suitable for the photodynamic exchange. Capitalising on this finding, the team of Xu as well as others have prepared Se–Se bonds containing polyurethanes that can self-heal under irradiation with visible light [51–53], or display shape-memory functions [54,55]. The visible light responsiveness of the Se–Se dynamic exchange has also enabled elegant approaches to photodynamic transforming polymer architectures for applications in drug delivery [56,57,58], surface reconfiguration [59], and soft actuators [60,61].

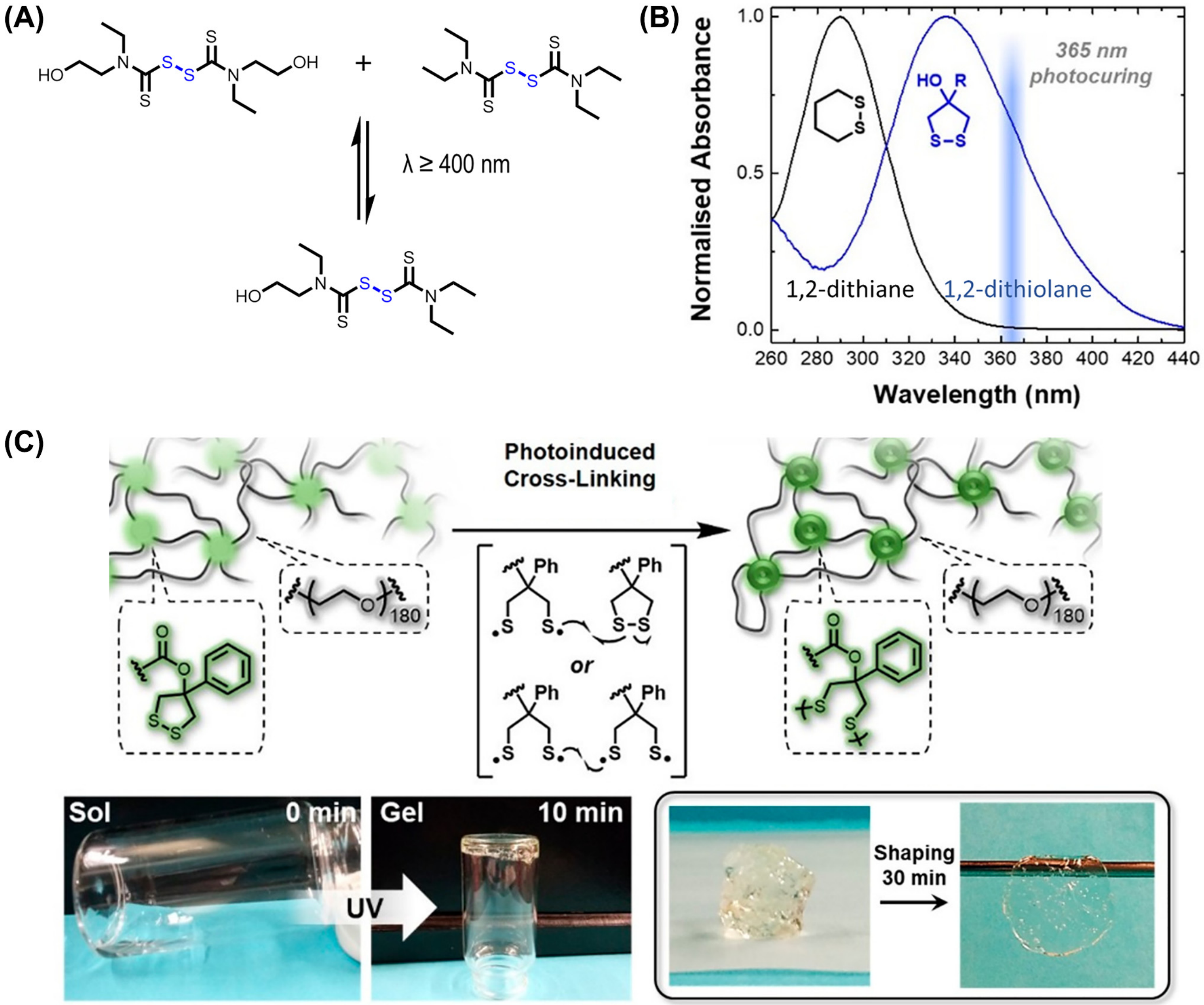

Figure 3. Redshifted disulfide exchange. (A) Visible light induced photodynamic exchange of the thiuram disulfide; (B) UV-vis absorbance of the cyclic disulfides with dithiolane moiety featuring an absorbance band extending into the visible light region; (C) application of the dithiolane in the photodynamic shuffling of hydrogel network structures. Reprinted, with permission, from [47].

The similarity between disulfide and diselenide bonds allows for fascinating transformations between S–S, Se–Se, and Se–S bonds, all gated by different wavelengths of light (Figure 4D). In particular, visible light irradiation of a mixture of disulfide and diselenide compounds results in new chemical entities with Se–S bonds, with the process being reversed by UV light [62]. The utility of such wavelength-selective photodynamic exchanges has been demonstrated in the photoswitching of molecular assemblies [62] and hydrogel network topology [63]. In addition, the Se–Se bond can undergo light-induced metathesis reactions with ditellurides, forming Se–Te bonds [64]. Since the Te–Te bond can also be cleaved by visible light, the team of Xu designed an elegant strategy to regulate the equilibrium by using the macrocyclic molecule to specifically lock in the Se–Se moiety via host guest interaction [65]. Recent expansion of the thiol/selenium-related PDCBs includes the Ru–S [66,67] and Ru–Se bonds [68], which

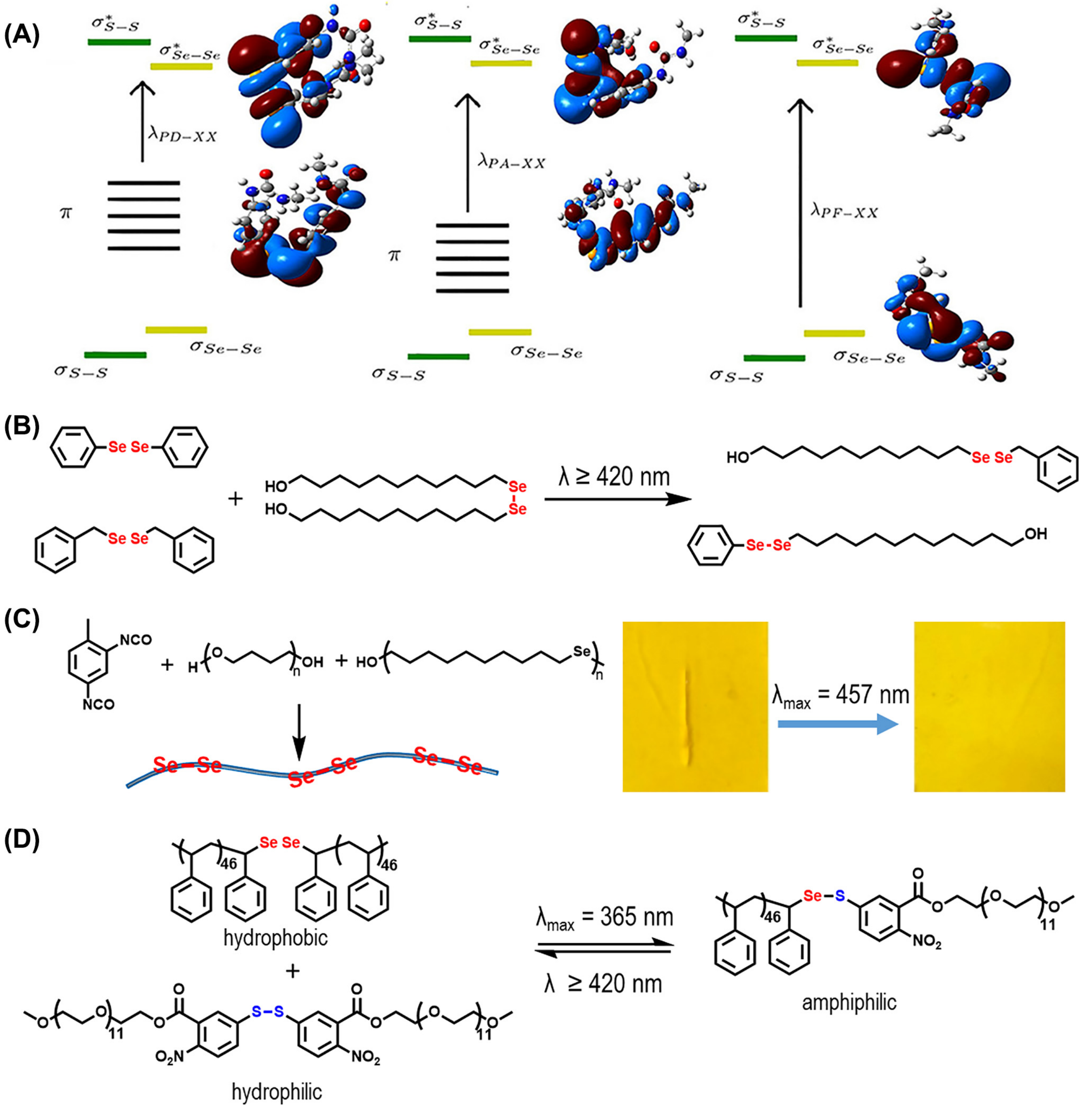

Figure 4. Visible light-enabled diselenide and disulfide exchanges. (A) Schematic representation of the molecular orbitals involved in the excitation process of S–S and Se–Se bonds; (B) visible light-induced exchange reaction of three model compounds featuring Se–Se bond; (C) scheme of the synthesis of Se–Se bond-containing polyurethane that can self-heal under visible light irradiation; (D) wavelength controlled photodynamic exchange between polymers containing disulfide and diselenide bonds. Reproduced, with permission, from [50] and [51].

can be dissociated by green light (λ_{max} = 530 nm). The Ru–Se and Ru–S dynamic exchanges are nonradical, occurring via metal–ligand coordination, and the recombination is generally slower than the free radical's recombination.

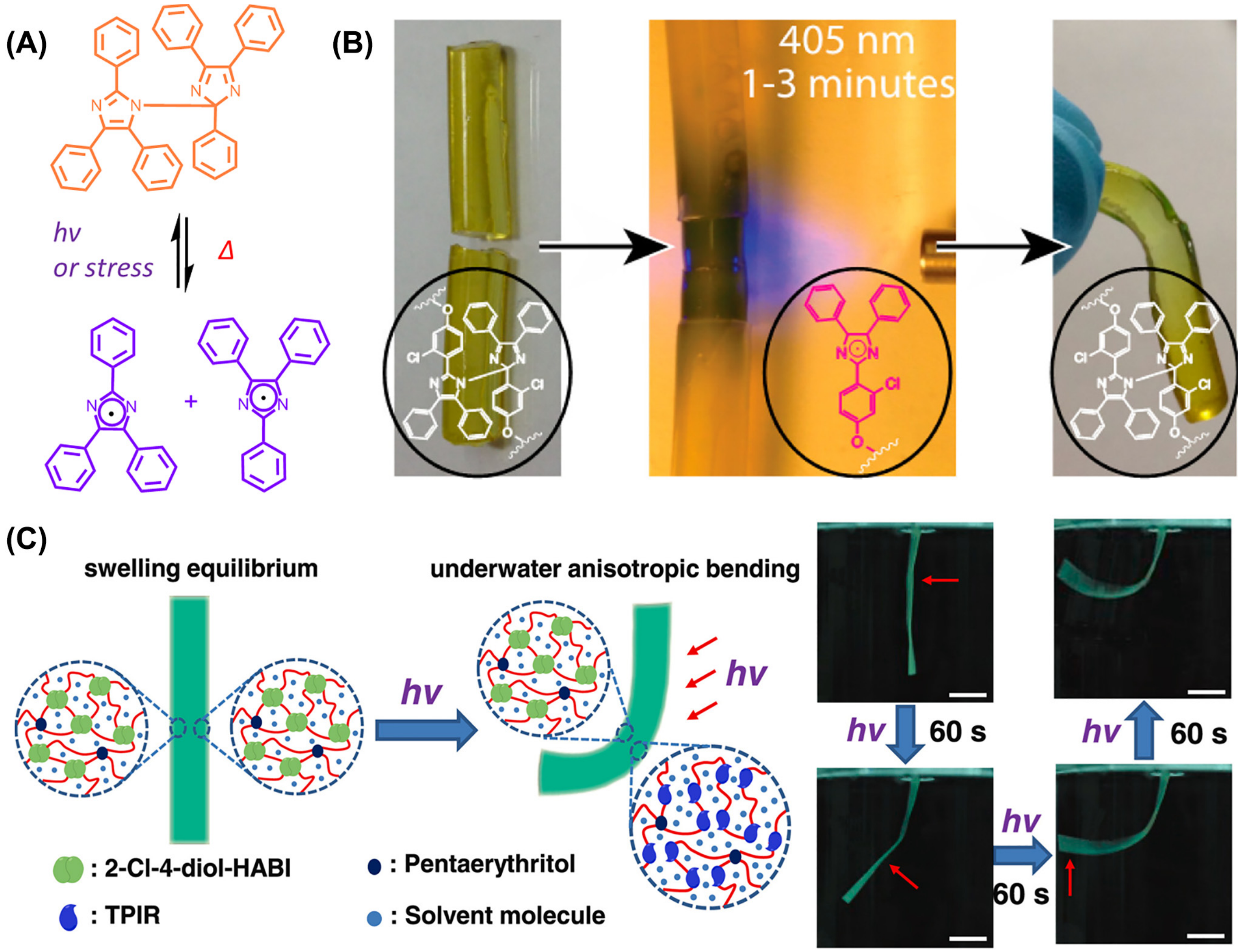

Figure 5. Visible light-induced dynamic exchange of hexaarylbiimidazole. (A) Photodynamic exchange of a hexaarylbiimidazole molecule, which is dissociated by light into lophyl radicals that rapidly recombine in the dark; (B) crosslinked polymer that contains hexaarylbiimidazole able to self-heal via reshuffling of the networks by violet light; (C) the photodynamic exchange of the lophyl radicals are utilised in changing the swelling/deswelling of a hydrogel, enabling the light-induced movement of the material under water. Reproduced, with permission, from [74] and [76].

HABIs are a well-known class of photoinitiators that display reversible photodissociation behaviour [69]. The C–N bond between the imidazole rings can be homolytically cleaved by either force or light (300–450 nm), generating coloured 2,4,5-triarylimidazoyl radicals (Figure 5A). These radicals thermally recombine to afford the original imidazole dimer and their recombination rate coefficients (k = 15–40 mM^{-1} s^{-1}) [70] are much larger than the recombination rate coefficients observed for thiol or selenium radicals. The photodissociation of HABI derivatives has been used in polymer decrosslinking [71–73] and, more recently, the photodynamic nature of these moieties has been applied in visible light responsive dynamic polymer systems. In particular, Ahn and colleagues incorporated HABI into a PEG network, crosslinked by a copper catalysed alkyne-azide cycloaddition, to form a polymer gel that can self-heal under violet light (λ_{max} = 405 nm) irradiation within 1 to 3 min when fully swollen in 1,1,2-trichloroethane (Figure 5B) [74]. In a similar report, Zhu and co-workers demonstrated the dynamic macroscopic transformation of a tetra-arm crosslinked PEG network under visible light irradiation, enabling photoplastic processing of the bulk gel [75]. Notably, the 2,4,5-triarylimidazoyl (lophyl) radicals are highly stable against water, which allows for applications in aqueous environment, such as light responsive hydrogel actuators. In such applications, the underwater movement is induced by the anisotropic change in swelling upon photocleavage and deswelling through combination of the lophyls (Figure 5C) [76]. Depending on the direction of light irradiation, multiple complex movements of hydrogels, such as folding, twisting, and forward motion, can be achieved. Further applications of HABIs as PDCBs include light-controlled shape-memory plastics [77] and topological isomerisation of polymer chains [78,79].

PDCBs assisted by photoswitches

So far, approaches to redshifting common photodynamic covalent reactions such as photocycloadditions and light-induced radical exchanges resulted in new systems with photoreactivity reaching green light (≤550 nm). Extending the photoreactivity of these photochemical systems into the longer wavelength window, such as the red and near-infrared (NIR) region (600–700 nm), is highly challenging due to the stability of the bonds and associated synthetic difficulties. Nevertheless, new photodynamic systems must respond to red and NIR light, which permits deeper penetration into skin and biological tissues, to be effective for *in vivo* applications [19]. A promising strategy to use long wavelength visible light activation on

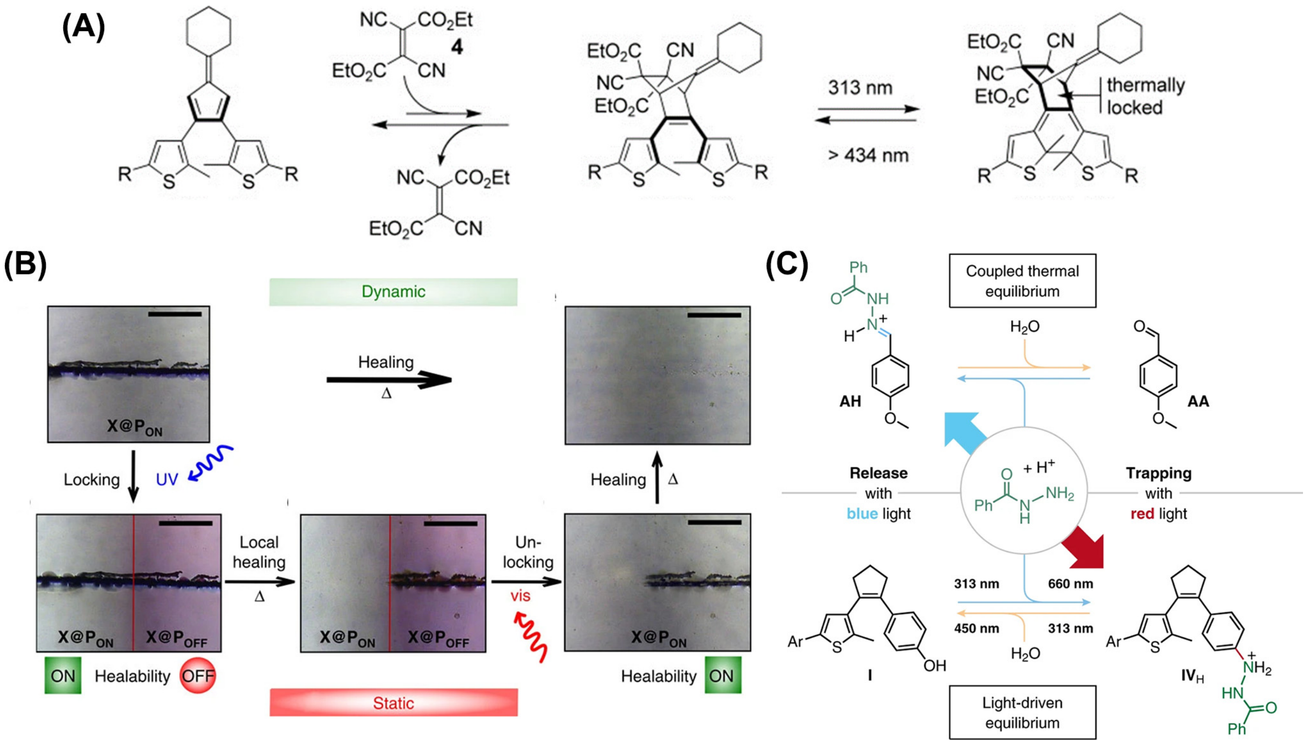

Figure 6. Photodynamic covalent bonds regulated by photoswitching of diarylethenes. (A) Reversible reaction between fulvenes and a dienophile to generate racemic dithienylethenes (DTEs), which undergo cyclisation when irradiated with UV light, the thermally stable states are unlocked with visible light to induce ring-opening, regenerating the cyclohexene necessary for fragmentation; (B) micrographs showing local healing of a crosslinked polymer film, which can be locked (i.e., unable to self-heal) by UV light and the healing ability is regenerated by visible light irradiation; (C) acylhydrazone exchange enables a non-photoresponsive dynamic covalent system, based on the DTE photoswitch, to be externally regulated via the light-driven trapping and release of the benzylhydrazide. Reproduced, with permission, from [82] and [84].

photodynamic system is to couple the exchange reaction with a substrate, such as a photoswitch, responsive to such wavelength regimes. This concept was first realised in the work of Branda and co-workers, where a photoswitchable dithienylethene (DTE) component was integrated into a Diels-Alder cycloaddition, effectively switching the reaction on and off, depending on the isomerisation state of the DTE [80]. Specifically, the open isomer dithienylfulvene can react with a dienophile in a thermal [4+2] cycloaddition, and the adduct was photoswitched to the closed isomer, locking it from participating in the Diels–Alder equilibrium (Figure 6A). Asadirad and colleagues applied this photodynamic system for regulating the strength of a polymer adhesive via photo-induced locking and unlocking of the polymerisation/depolymerisation processes [81]. The team of Hecht further developed the DTE-assisted PDCBs for applications in self-healing crosslinked polymers (Figure 6B) [82] and photoswitchable maleimide pro-drug and pro-tag for remote-control over pharmacological effect [83]. The use of DTE photoswitches further enables long wavelength (λ_{max} = 660 nm) response in controlling the formation of imine and hydrazone dynamic covalent bonds [84,85]. Based on the DTE core, Hecht's team developed an elegant photochemical system for the remote-controlled capture and release of a chemical reagent, even overcoming unfavourable thermodynamic conditions (Figure 6C) [84]. Such photochemical systems provide fine control over their 'static' and 'dynamic' states, establishing on–off behaviour that is fully controlled by light, opening opportunities for applications in adaptive materials and molecular machinery.

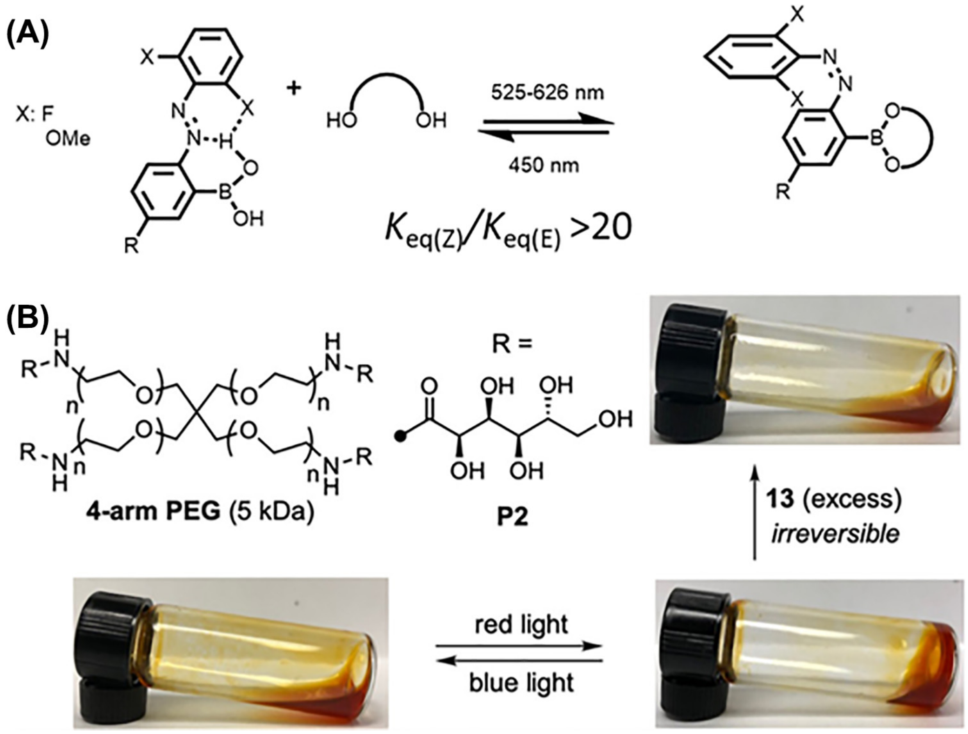

Figure 7. Photodynamic covalent bonds regulated by photoswitching of redshifted azobenzenes. (A) Boronic acid–ester dynamic bond regulated by the photoisomerisation of redshifted azobenzene moieties; (B) application of the photodynamic boronic acid–ester in crosslinking of poly(ethylene glycol) (PEG)-based hydrogel for photodynamic control of the viscoelastic properties by red and blue light. Reproduced, with permission, from [88].

While photoswitching of the DTE derivatives can be induced by green/red light, the reversion in these systems requires UV light. To generate a photodynamic system that can be controlled by wavelengths in the visible light region, Kalow and co-workers used azobenzene photoswitches which, depending on the substituents (electron-withdrawing groups such as methoxy or halogen) at the *ortho*- or *para*- positions on the phenyl rings, have addressable switching wavelengths in the visible regime [86]. Isomers of azobenzene boronic acids (Figure 7A) have different biding affinities to diol compounds, with the *cis*- form having significantly higher binding constant compared with the *trans*- isomer [87]. This feature was utilised to photo-manipulate covalent interaction between the boronic acid moiety and the diol function, using green/red (525–626 nm) and blue (450 nm) light, enabling photoreversible covalent binding with biomacromolecules and dynamic tuning of hydrogel viscoelastic properties [88].

Concluding remarks

As our analysis has demonstrated, substantial progress has been made in redshifting PDCB formation and reversion. On the photochemical level, there remains ample scope to redshift not only the formation, but critically, the dissociation reaction. To date, most photochemical reactions that offer the opportunity to be reversible, such as [2+2] and [4+4] systems, require relatively harsh UV irradiation. Shifting these into the visible light regime, enabling bond cleavage and formation to proceed with ideally orthogonal colours of visible light, is a key priority (see Outstanding questions). Likely, progress in this area will come from exploiting systems that take inspiration from nature for photon-harvesting and transmission, including chlorophyll/haemoglobin-type structures. Further, a critical challenge is to identify pairs of photoreversible covalent bonding systems that can be activated in their forward and reverse reactions fully independently with distinct colours of light. Identifying such system will require the continued careful mapping of photochemical reactivity in action plot analyses of especially [2+2] reaction systems, yet also other reversible photochemical processes, including [4+4] cycloadditions. Indeed, our wavelength resolved action plot protocol is, in principle, capable of mapping any photochemical process, provided an appropriate method for determining its conversion is available [26]. These efforts should be directed at exploiting differences in absorptivity and quantum yields, similar to our recent effects in establishing truly λ-orthogonal unidirectional reaction systems [89]. In parallel, as noted in our latest summary on action plot analysis [26], it is critical that in a concerted effort of theoreticians and photochemists, the underpinning causes of disparity between the UV/Vis spectra and the wavelength-dependent reactivity profile are established, as an in-depth understanding may lead to predictable (reversible) photochemical reactivity behaviour. Even establishing two orthogonal systems would constitute enormous progress, as it will open avenues for controlling disparate material properties with individual colours of light (four in this specific case). Access to such systems will enable generation of materials that may be switchable between not only soft and hard states, but perhaps between conducting/isolating as well as hydrophilic/hydrophobic, merely by the colour of light shining on the material.

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Declaration of interests

No interests are declared.

Outstanding questions

How can the reversion of photocycloadditions be achieved under mild irradiation conditions, (i.e., long wavelength light)? Achieving this will broaden their applications into the biological realm.

What are the programmable functions beyond simple thermomechanical properties that have been demonstrated so far (e.g., healing or shape-shifting)? A photodynamic system can be considered a quasi-living system and thus can be tailored further with adaptable functions, including conductivity, fluorescence responses, and biological activity.

Can other concepts of dynamic systems, such as light-induced reversible deactivation radical polymerisation, inspire photodynamic covalent bond forming systems? As illustrated in the review, there is a growing range of photodynamic covalent chemistries, including light-stabilised dynamic system and PDCBs assisted by photoisomerisation, and thus new strategies for PDCBs are quite possible by broadening the definition of PDCBs.

How can these smart and light-responsive materials be used in biological environments, specifically inside a human body? Ideally, photodynamic materials should be responsive to red or NIR light, while advanced engineering methods are needed to deliver shorter wavelength (green or blue) of light deep inside the body to trigger the needed response for *in vivo* applications.

While visible light activation is beneficial, how can the dynamic functions be controlled distinctly from naturally present visible light (i.e., sun light or ambient ceiling light), in the context of spatial and temporal applications? A 'safety lock', requiring an additional trigger such as pH or temperature, may be installed for applications where materials are exposed to natural light sources.

Can multiple photodynamic processes be incorporated into a single material system? Achieving wavelength-selective control over multiple responses will enable more complex applications such as soft robotics with advanced autonomous performance, programmable microfluidic devices, and rewritable data storage/encryption. This will require

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