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Stilbene stilbene shining bright: α-Cyanostilbenes as functional organic materials

Beena Kumari & Sriram Kanvah*
Department of Chemistry, Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar 382 355, India
E- mail: sriram@iitgn.ac.in; kanvah@gatech.edu

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π-Conjugated organic molecules with suitable donor or acceptor substituents have evolved as an attractive platform for optoelectronic or biological applications. α-cyanostilbenes, due to their characteristic elastic twist, exhibit excellent photophysical properties and form self-assemblies in favorable solvent media. The ease of synthesis and capability to introduce several desired substituents has allowed their extensive use as stimuli-responsive materials. The uniqueness of these scaffolds is the observance of characteristically enhanced emission in aqueous media due to the formation of nanoparticles or aggregates. The enhanced emission is in contrast to the observation of quenched emission for many fluorophores which limits their aqueous media applications. Such a distinct emission behavior of α-cyanostilbene derivatives has led to their extensive photophysical investigations in solution and solid-state emissive properties yielding remarkable structural or morphological changes in response to pressure, heat, light radiation or the presence of a solvent. This article briefly reviews the functional properties of cyanostilbenes.

Keywords: α-Cyanostilbenes, photophysical properties, fluorescence, aggregates, self-assembly, optoelectronic applications

Since the first discovery of stilbene (in Greek 'to shine') in 1843 by Laurent, the investigations of structural, photophysical, photochemical, phytochemical and biological applications of suitably substituted π–conjugated stilbenoid systems garnered tremendous interest[1-3]. This is due to their synthetic simplicity through the incorporation of different π-spacers, alkylchains or steroidal groups, heteroaromatic rings and incorporation of the electron donor or acceptor moieties. Subsequently, these substitutions result in significant emissive properties in solution or solid state, resulting in their applications towards organic electronics, self-assembling systems, liquid crystalline materials, organogels, sensors or fluorescence probes, amongst other applications[4-10]. Among the stilbenes, in the past two decades, diarylethylenes based on cyanostilbene scaffold have attracted significant interest owing to their interesting properties in solution and solid state. These systems are characterized by the presence of aromatic or heteroaromatic rings bearing suitable substituents at the terminals separated by a π-conjugated bridge and an electron withdrawing cyano group on the double bond. The cyano group on the double bond is expected to wield both thermodynamic and kinetic effects. In 2002, the group of Soo Young Park had designed and synthesized 1-Cyano-trans-1,2-bis-(4′-methylbiphenyl)-ethylene (Figure 1) based on α-cyanostilbene scaffold motivated by their attractive potential for optoelectronic applications[11]. The molecules show unusually strong enhanced emission due to the formation of organic nanoparticles of 30-40 nm diameter. This enhanced fluorescence is attributed to the formation of J-aggregates that result in spontaneous assembly. Such unusual fluorescence in aggregated or solid state is due to the restriction of molecular motions thereby decreasing the nonradiative deactivation processes or fluorescence quenching. This behavior, first reported by Tang and co-workers in 2001,with ~330 fold enhanced emission intensity with silole derivatives (Figure 1) is termed Aggregation induced enhanced emission (AIEE)[12]. These two research papers have catapulted the field and generated enormous interest in the development of such materials[13,14] and are subject to immense investigations for the development of fluorescence probes[15-17],'light-up' sensors, theranostics amongst others[18-20]. Structural examples (Figure 2) include molecular scaffolds based on pentacenequinones[21-23], hexaphenylbenzenes[24], triphenylethylenes[25], and most extensively investigated tetraphenylethylenes[26-28], anthanthrene[29], triphenylamine[13,30,31], fluorenone, naphthalimides[32,33] and other related structural derivatives (Figure 2). These molecules have been utilized for analyte detection, bioimaging, and organic electronic applications. Reviewing the entire literature

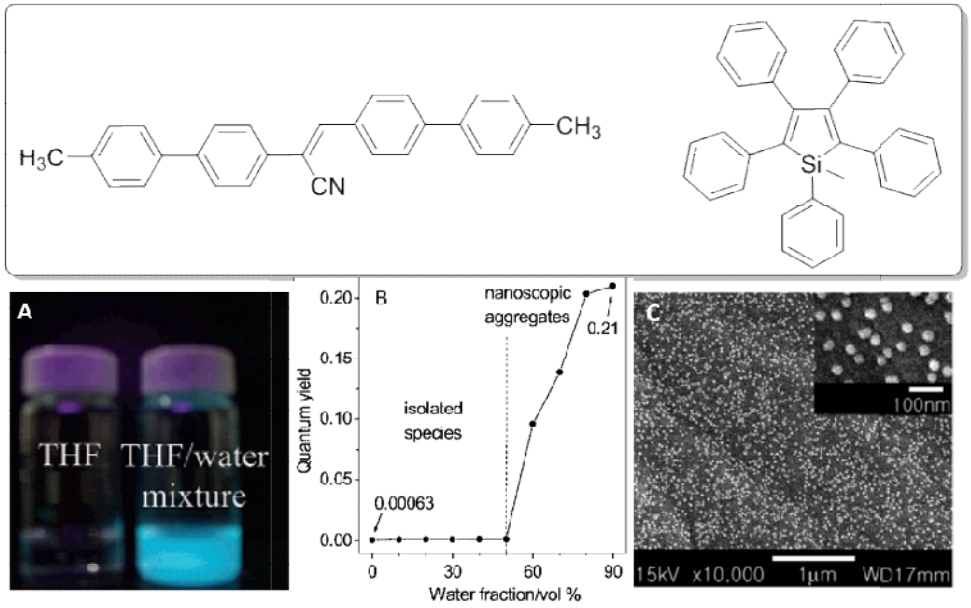

Figure 1 — The molecular pioneers of aggregation-induced emission.A, B and C: Reprinted with permission from American Chemical Society [© 2002]- J. Am. Chem. Soc., 2002, 124, 14412-14415 and Royal Society of Chemistry [©2001]; Chem. Commun., 2001, 1740-1741)

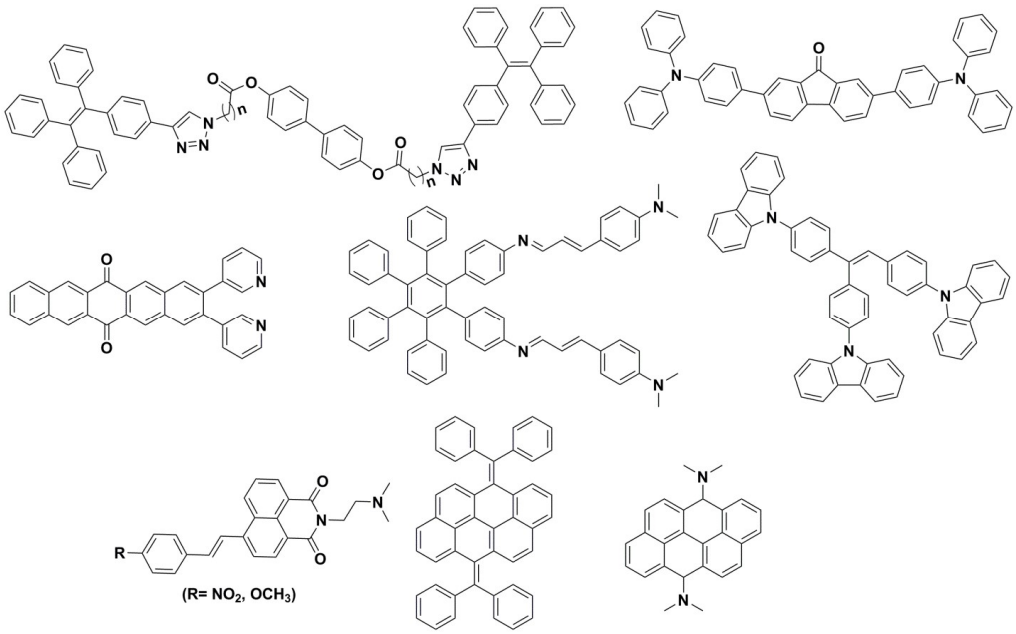

Figure 2 — Examples of molecular structures that exhibit aggregation-induced emission other than cyanostilbenes.

on these molecular materials exhibiting aggregation induced emission is beyond the scope of the article. In *sync*, with our group's research interest on design and synthesis of molecular structures based on α-cyanostilbene scaffold (Figure 3), in this article, we review some of the established molecular systems built on this scaffold and discuss their applications.

Photophysical studies of cyanostilbenes

Cyanostilbenes exhibit emission that is similar to other organic fluorophores. Depending on the nature of the substituents, weak or strong intramolecular charge transfer behavior is noted. However, the uniqueness of these molecules materials is due to their characteristic emission in water. The molecules are water-insoluble and hence tend to aggregate or form nanostructures.

Unlike other substrates where usual quenching of emission is observed, they show remarkable emission in aqueous media characterized by enhanced emission intensity or emission wavelength shifts[34]. Consequently, α-cyanostilbenes have been greatly utilized for studying the emission behavior in aqueous media. As an example, compound (**1**; Figure 3) shows weak emission in organic solvents but show remarkable and bathochromic emission shifts in water attributed to the formation of aggregates[35]. Figure 4 shows the emission of compound (**1**) in dioxane-water binary mixtures which shows gradual emission changes and sudden spurt in the emission intensity at higher water percentages (Figure 4). The SEM images of the sample in water indicate the formation of aggregates stabilized through non-covalent interactions.

Effect of *p*H

Considering its remarkable emission in aqueous media, stilbene (**1**) was utilized as a fluorescence probe

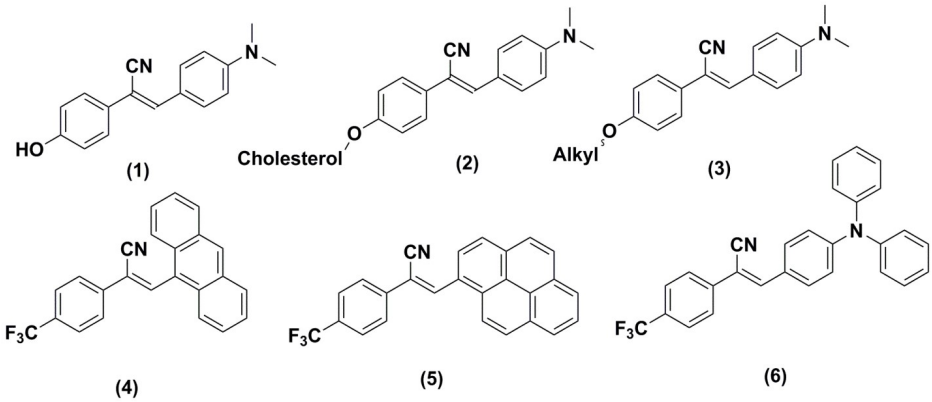

Figure 3 — Examples of compounds based on cyanostilbene scaffold synthesized in our laboratory at Indian Institute of Technology Gandhinagar

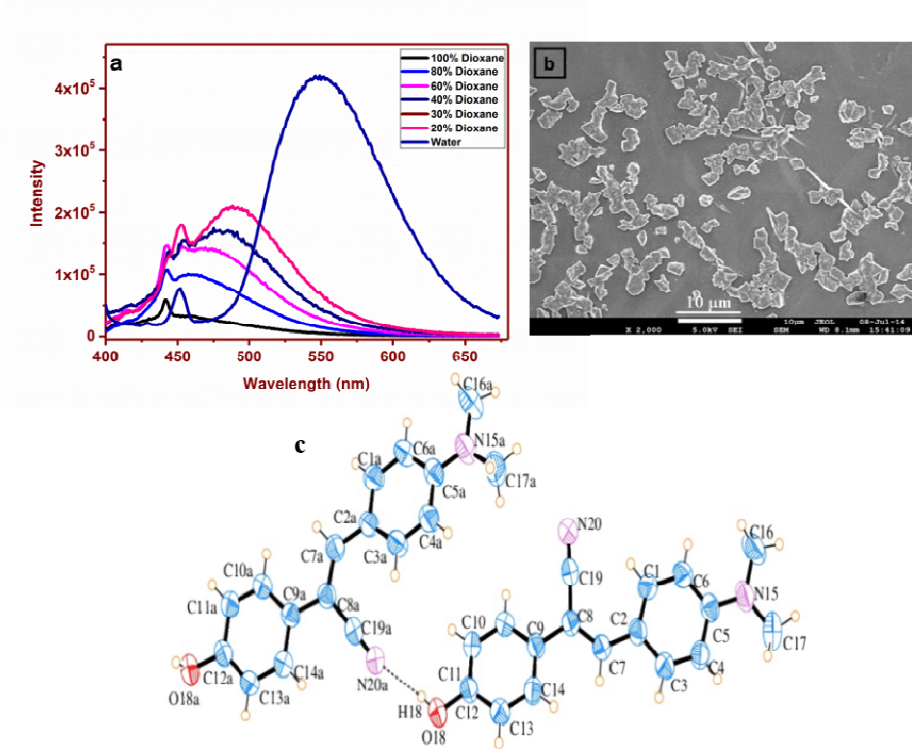

Figure 4 — (a) Emission spectra of (**1**) in dioxane-water binary mixtures, (b) Scanning electron microscopy image of (**1**) in water- Scale: 10 µM and (c) the ORTEP diagram of (1) with dotted lines representing the intermolecular contacts[36]. Adapted with permission from Royal Society of Chemistry, ©2014 (New J. Chem., 2014, 38, 5736-5746); ©2016; (New J. Chem., 2016, 40, 4588-4594)

for *p*H and surfactant media. Stilbene (**1**) has acid and base sensitive groups, and this design allows monitoring of the absorption and emission through a change in *p*H. The emission spectra of (**1**) at different *p*H show hypsochromic shifts in acidic (459 nm; *p*H = 2.09) and basic media (517 nm; *p*H = 13.06) media (Figure 5a). The shifts in acidic and basic media are due to protonation of the dimethylamino group and the formation of the phenoxide ions respectively contributing to the changes in the delocalization and intramolecular charge transfer[35] (Figure 5b) and also provide visual demarcation.

Upon varying the surfactant concentrations, stilbene (**1**) shows a '*turn-off*' aggregated emission at higher concentrations of the surfactant, and at lower concentrations, the emission at 550 nm is regained. This is due to the localization of the probe in the hydrophobic regions of the micelles with a visual '*on-off*' detection[36] (Figure 6a). The critical micellar concentrations determined by a plot of the change in

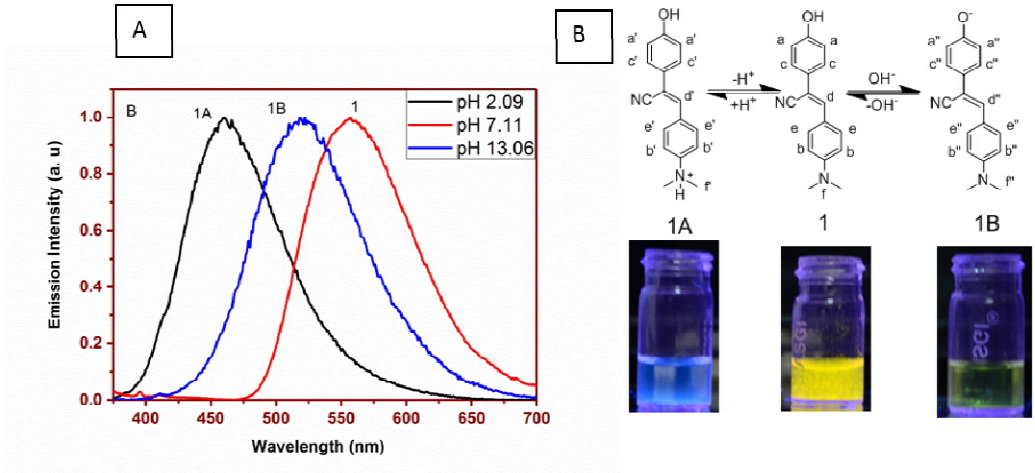

Figure 5 — (a) Emission spectra at stilbene (**1**) with a change in *p*H and (b) switching mechanism of stilbene in acidic, neutral and basic *p*H conditions[35]. Adapted with permission from Royal Society of Chemistry, ©2014 New J. Chem., 2014, 38, 5736-5746

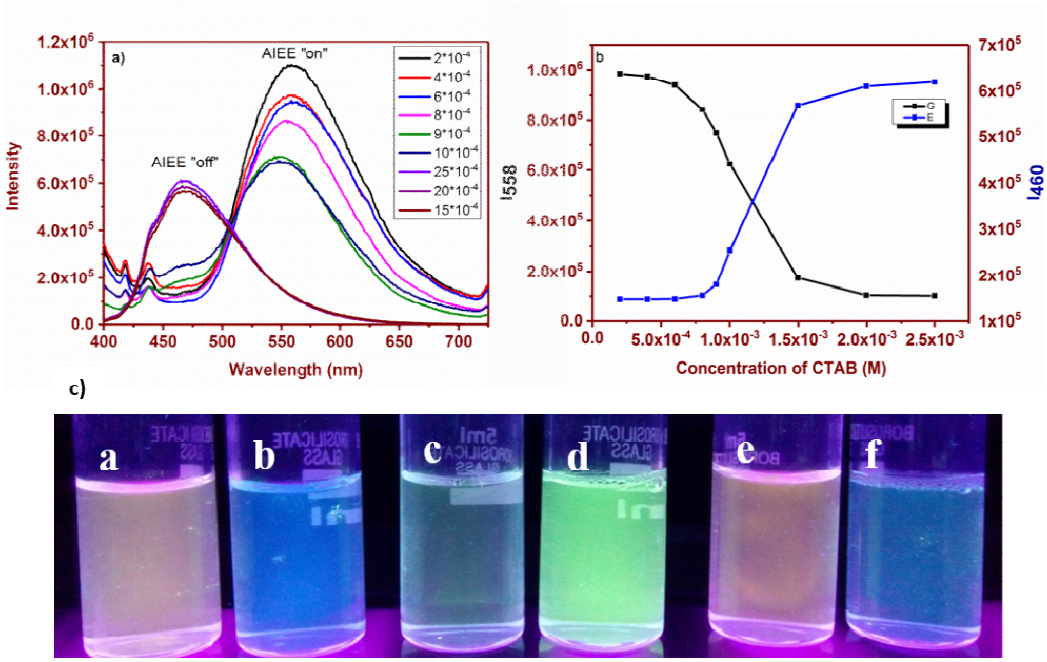

Figure 6 — (a) Emission spectral changes of (1) with varying surfactant concentration CTAB and (b) a plot of emission intensity changes as a function of concentration and (c) Visual colors of stilbene (**1**)(2×10^{-5}M) under different concentrations of surfactants. (a & b); SDS 2×10^{-3}M & 9×10^{-3}M; (c & d) CTAB 0.4×10^{-3}M & 2×10^{-3}M; (e & f): Triton X-100 at 0.05×10^{-3}M & 0.5×10^{-3}M[36]. Adopted with permission from Royal Society of Chemistry, ©2016; (New J. Chem., 2016, 40, 4588-4594)

emission intensity either at 460 nm or 558 nm (Figure 6b) show comparable data with earlier established methods. Importantly, visual detection is also noted with the change in surfactant concentration (Figure 6c).

Host-guest Systems: Enhanced emission with cyanostilbenes

Host-guest systems, first introduced by Donald Cram in 1976, offers exciting molecular recognition applications and their response to external stimuli have offered tremendous applications in the field of sensing, the formation of supramolecular polymers, drug delivery, and biological imaging[37]. The weakly emitting α-cyanostilbene derivatives become strongly emissive in the presence of CB-8 in water forming highly fluorescent supramolecular polymers (Figure 7). This enhanced emission due to increased rigidity of the chromophore due to host-guest interaction. Upon the addition of tryptophan, the photoluminescence of CB-cyanostilbene complex is quenched with a Limit of detection of 30 nM indicating the utility of carefully designed modulated fluorescence of host-guest systems for biological applications[38]. Similarly, the introduction of moieties such as thiophene, quaternary ammonium groups on the cyanostilbene scaffold yield bright blue, green, yellow, and red fluorescence in the presence of macrocyclic host CB[8][39].

Mechanochromism

Cyanostilbene derivatives also show interesting color changes when put under stress in the solid state through mechanical grinding, and such unique emission characteristics have promising applications in materials chemistry. This phenomenon is called mechanochromism (or under pressure Piezochromism). Suitably substituted cyanostilbenes bearing carbazole or triphenylamine exhibit multiple colored emission switching in the solid state with morphological changes. Typically, the as-prepared solids show one color and gently ground samples show a different color. A Carbazole derivative listed in Figure 8 shows a blue emission and upon grinding yellow emission was observed[40,41]. Annealing or fuming with a suitable solvent recovers the original blue emission suggesting reversibility of the mechanochromic process. Similarly, triphenylamine or imidazole substituted cyanostilbene scaffolds (Figure 8) also show reversible sensitivity to mechanical grinding with the observation of different emission properties for the crystalline powder and post-grinding mixtures[42,43]. In another example, derivatives bearing alkoxy linkers[44] or phenothiazine substituted cyanostilbene[45] show similar absorption and emission changes. Some of these derivatives depending on the nature of the substitution are also active for other stimuli such as *p*H[42].

Detection of Analytes

Substitution of the cyanostilbenes with reactive substrates can allow detection of metal ions at ultralow concentrations in water or biological samples. Introduction of a propargyl substitution and subsequent reaction of palladium chloride in water yields the corresponding hydroxyl product enabling strong fluorescence emission enhancement[46]. Similar strategy upon incorporating vinyloxy linker yields nanomolar detection of mercuric ions in aqueous samples. Unlike the enhancement noted earlier, the addition of mercuric ions leading to significant fluorescence quenching accompanied by color changes[47]. The cyanostilbene-boronate probe, on the other hand, yielded emission quenching in the presence of H_2O_2 with detection ability in solution, solid state as well as industrial samples[48]. A cyanostilbene derivative with triphenylamine donor and electron withdrawing nitro group or with azide linker was utilized to detect hydrogen peroxide with rapid detection times. The strong solvatochromic emission due to the nitro group (616 nm) decreased with concomitant formation of an emission band at the lower wavelength

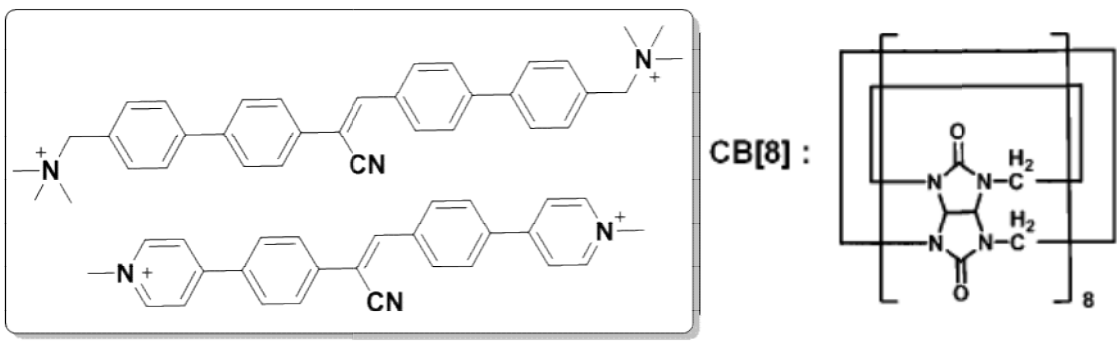

Figure 7 — Structures of biphenyl units with cyanostilbene scaffold and structure of CB-8

(525 nm). Similar results were also obtained with an azide substitution where a fluorescence '*turn-on*' was observed.

Both these reactions are a result of the reduction of nitro or azide group to form an electron donating amine moiety[49]. The structures of some of the cyanostilbene scaffolds used to detect analytes are shown in Figure 9. In another structural variant, Yang *et al*., have synthesized Schiff based functionalized α-cyanostilbene derivative and utilized the excellent emission '*turn-on*' emission response to detect Hg^{2+} through a coordinate complex[50]. A Schiff derivative with a crown ether substitution was utilized to selectively detect copper ions in aqueous media[51].

Self-Assemblies and Tunable Materials

The interesting emission features of α-cyanostilbene derivatives were extended to generate self-assemblies through covalent conjugation of the alkyl group or cholesterol (Figure 10). The cholesterol cyanostilbene conjugates self-assembles to vesicles accompanied by enhanced emission due to aggregation. When irradiated, the morphology of the aggregates changed from vesicular structures to nanotubes due to the isomerization of the double bond[52] (Figure 10). Similarly, Zhu *et al*. demonstrated color tuning of cyanostilbenes conjugated to the surface of the quantum dots *via* a disulfide bond (Figure 10D). The cyanostilbene unit and the QD core were linked through a 10-carbon alkoxy linker that reduces the electron transfer from the cyanostilbene unit to the QD surface. Upon irradiation or heat treatment, the molecules switches from *trans* to *cis* configuration yielding luminescent colors from purplish-blue to greenish yellow and white light emission[53].

Conjugation of cyanostilbene with large biomolecules such as cholesterol results in the formation of aggregates as exemplified in an increased emission in

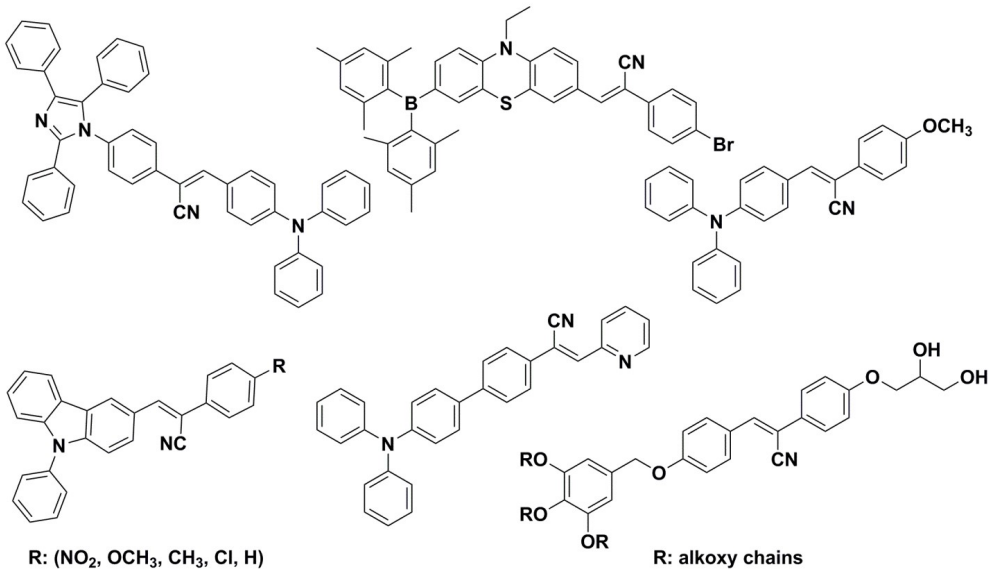

Figure 8 — Cyanostilbene derivatives that exhibit mechanochromism or piezochromism.

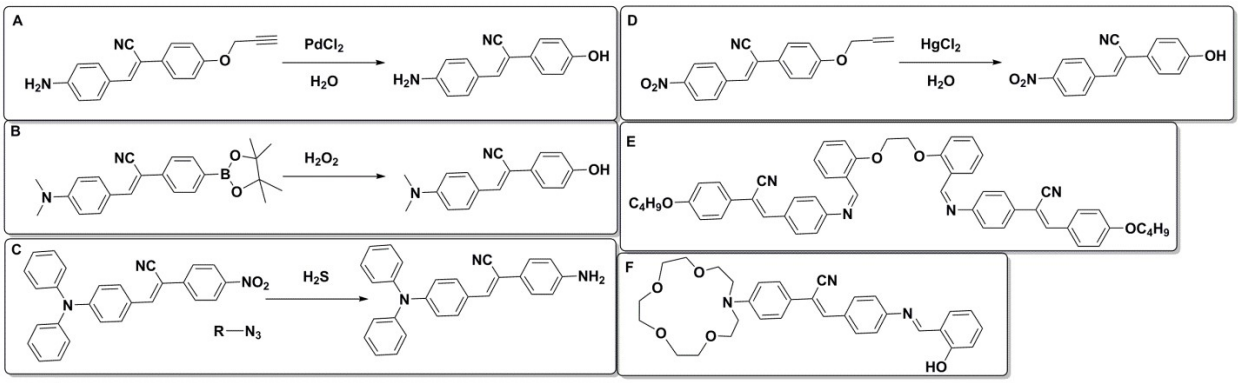

Figure 9 — Structure of various cyanostilbene molecules used for analyte detection.

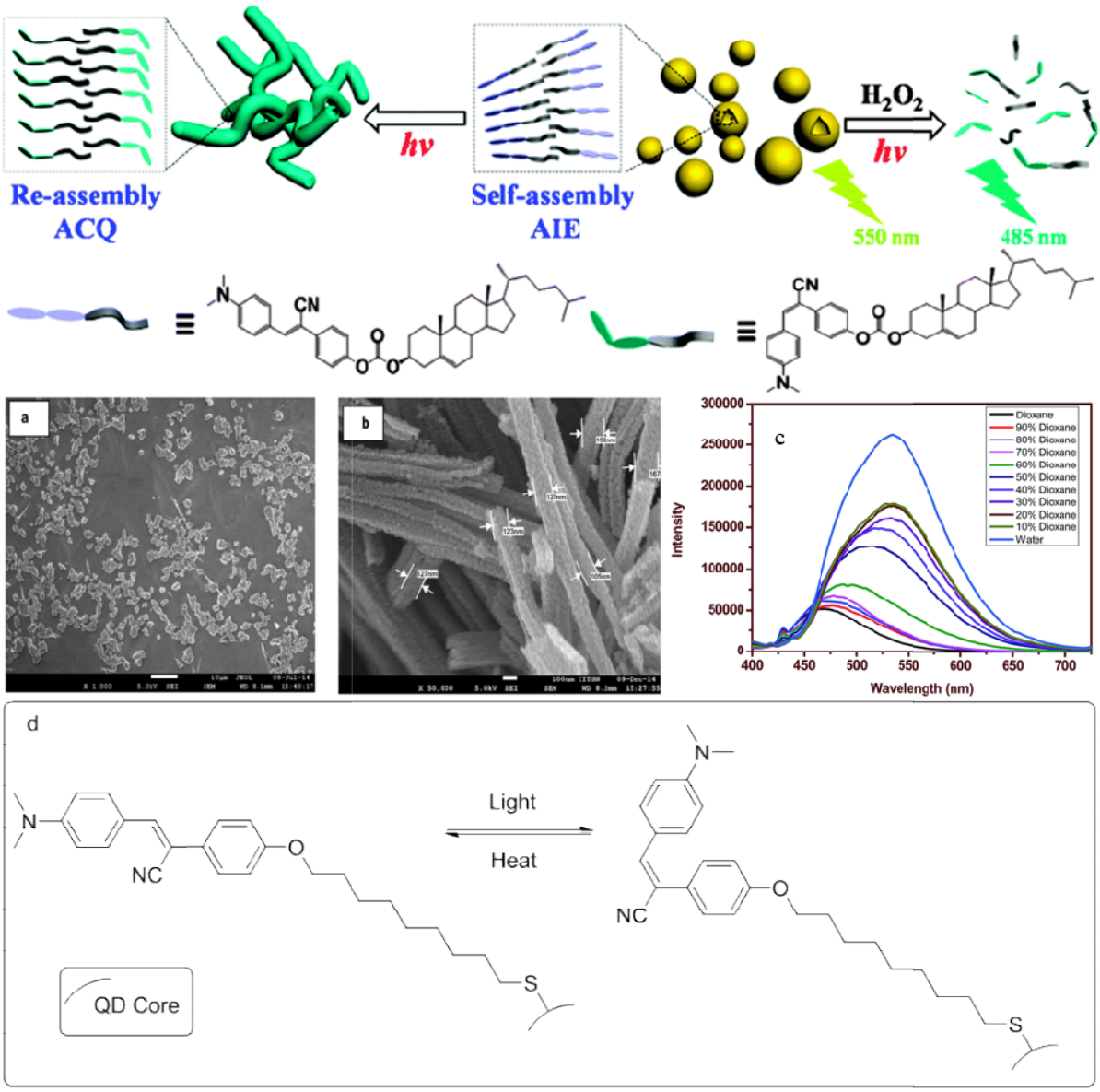

Figure 10 — Structures of photoswitchable or self-assembly materials bearing cyanostilbene scaffold. Adapted with permission from Royal Society of Chemistry, ©2015 (Chemical Communications, 2015, 51, 9309-9312; RSC Advances, 2015, 5, 33049-33057)

binary solvent mixture (Figure 10c). Subsequently, the cholesterol conjugate in the presence of another biomolecule, sodium cholate, show the formation of organized nanorod-like structures (Figure 10a, Figure 10b). Such an interaction reveals localization of the fluorophore-bioconjugates within the primary and secondary aggregates of sodium cholate[54]. Apart from the cholesterol, cyanostilbene cores with alkoxy side chains were also synthesized and examined for their ability to form thermostable gels or formation of self-assemblies. The interaction of alkoxy side chains enables dense packing due to hydrophobic interactions resulting in the formation of stable liquid crystalline structures with reversible emissive properties[44] and yields organized nanostructured self-assemblies[55] (Figure 11a, Figure 11b). In a recent report, bolaamphiphiles bearing cyanostilbene- biphenyl moiety were synthesized (Figure 11c), and show concentration-dependent self-assembly in aqueous solution and distinct photoresponsive morphologies[56]. Cyanostilbene cores with alkoxy side chains were also shown to exhibit high thermal stability and smectic liquid crystallinity with the length of the alkoxy side chain influencing the quantum efficiency of the fluorophore[57]. The alkylchains are

expected to densely pack and effect the overall planarization benefiting the emission.

Organogels with cyanostibene scaffold

Organogels have solid-like rheological behavior composed of low gelator (<15%) concentrations of with continuous structure of macroscopic dimensions and can self-assemble *via* co-operative non-covalent interactions. Considering their vast biological or sensing applications, several organic molecules were utilized for the formation of stable low molecular weight organogels[58]. Typically organogels require the use of long hydrophobic tails such as cholesterol or alkyl or alkoxy chains. However, the unique aggregation and self-assembly properties of suitably substituted cyanostilbenes were utilized to check for the formation of the organogels. Soo Young Park *et al*. have demonstrated outstanding gelation property of a few biphenyl analogs of cyanostibenes substituted with trifluoromethyl groups[59]. Some of the molecular structures that show the formation of gels were shown in Figure 12. We have recently demonstrated the

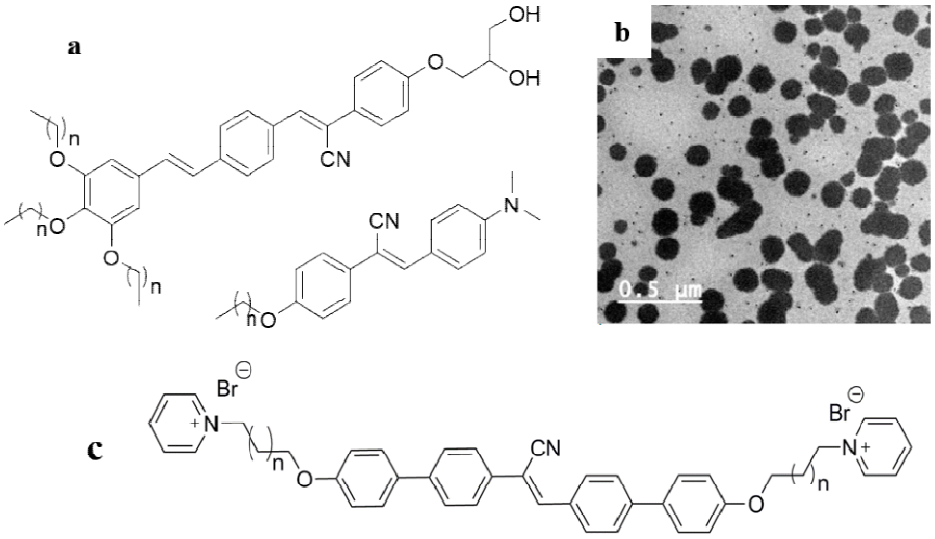

Figure 11 — Structures of molecules with cyanostilbene framework exhibiting self-assemblies. Figure adapted with permission from American Chemical Society © 2014 [*J. Phys. Chem.C*, 2017, **121**, 22478-22486]

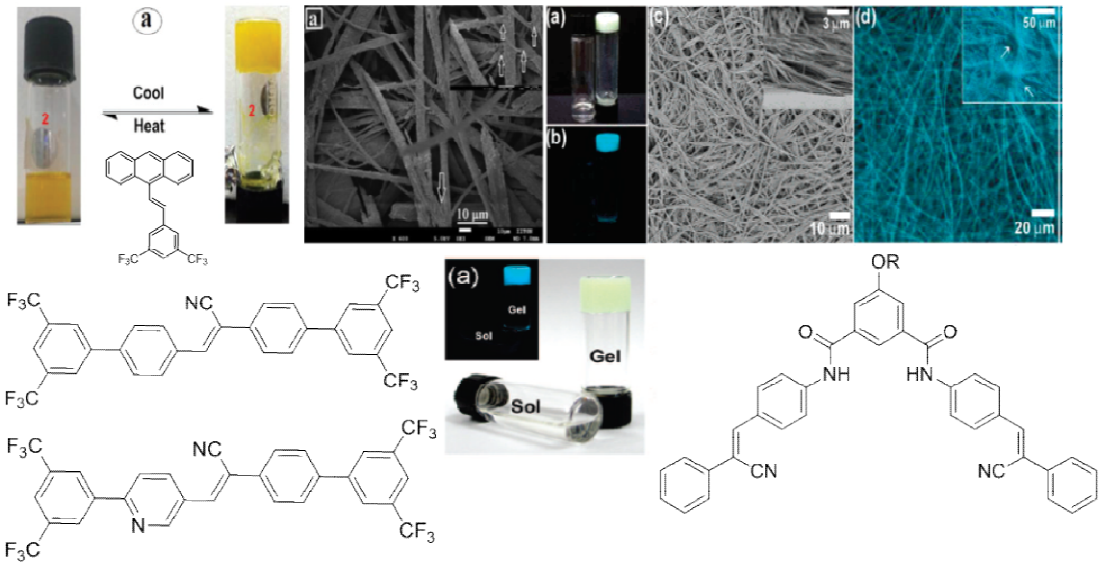

Figure 12 — Structures of molecules exhibiting gelation and representative gel and Scanning electron microscopy images of the organogels formed[62]. Adapted with permission from American Chemical Society (2004); © *J. Am. Chem. Soc*. 2004, 126, 10232-10233] and © Royal Society of Chemistry (2018).*Photochem.Photobiol. Sci*., 2018, 17, 395-403.

formation of organogels with fused ring systems such as anthracene and pyrene. In these systems, cyanostilbene with anthracene and pyrene moieties were synthesized with trifluoromethyl substituents on the aromatic ring (Figure 2, **4** and **5**). These molecules also show characteristic emission due to aggregation and at higher concentrations of the molecules form organogels that are stabilized through a combination of hydrophobic and π–π stacking interactions[60]. The same strategy of incorporation of trifluoromethyl groups for a cyanostibene bearing triphenylamine (Figure 2, **6**) fails to yield organogels. These organogels are thermoreversible with gel-to-sol phase transitions alongside concomitant fluorescence intensity changes[61].

Bioimaging

Non-invasive imaging using fluorescence is extremely important for the biological research, and this is achieved through the intelligent use of

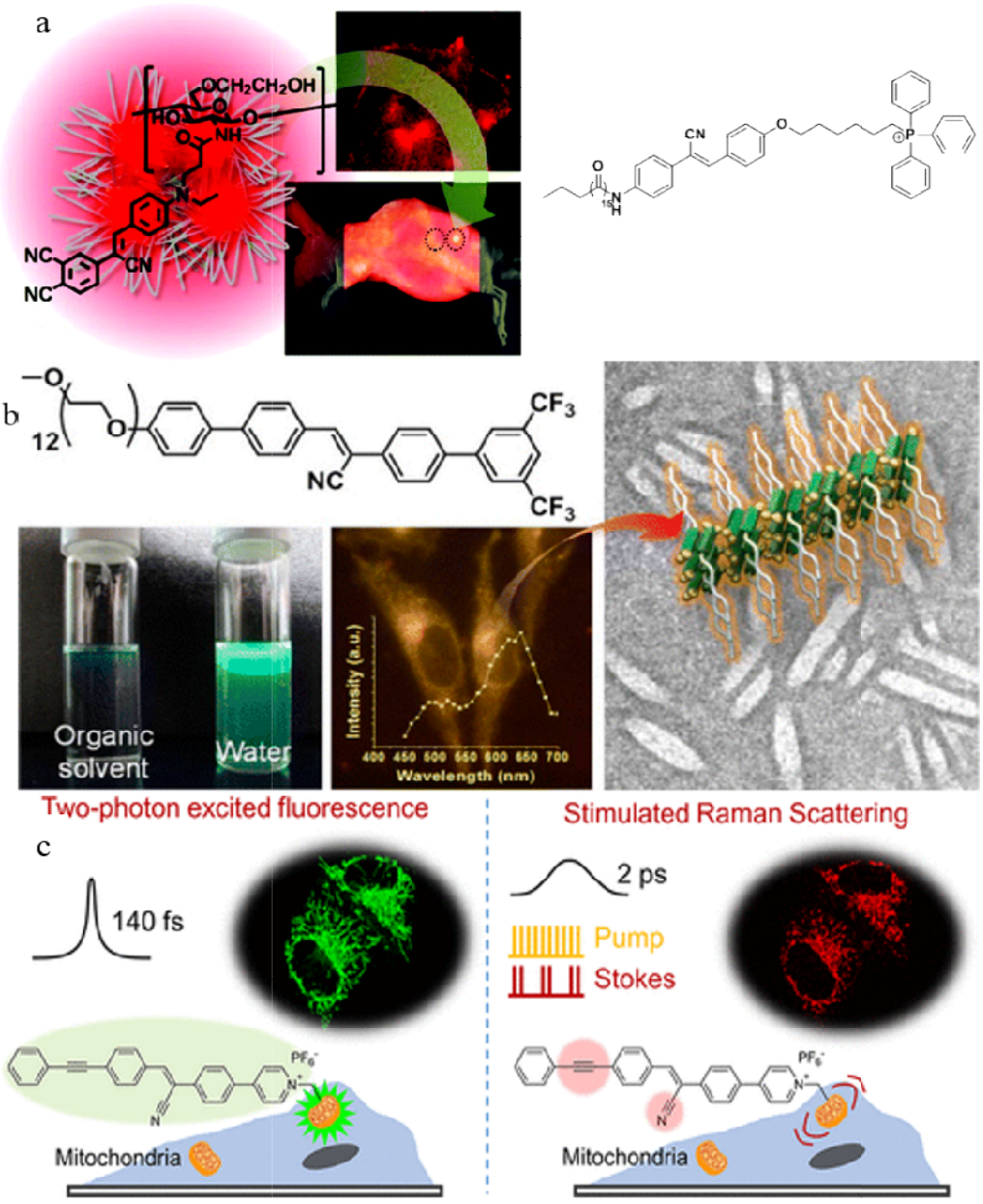

Figure 13 — Cyanostilbene derivatives that exhibit bioimaging and efficient intracellular uptake: Adapted and reprinted with permissions from American Chemical Society: (Copyright ©2009; 2013; 2017); Chem. Mater., 2009, 21, 5819–5825; Chem. Mater., 2013, 25, 3288–3295; J. Am. Chem. Soc., 2017, 139, 17022–17030

fluorescent materials. Typically these materials have donor or acceptor groups that shift the emission to near IR region for easier cell penetration as well provide safe imaging methods. The architecture of cyanostilbene allows for incorporation of suitable substituents or conjugate biomolecules of interest. Some examples of cyanostilbene molecules utilized in the biological imaging are given in Figure 13. Amphiphilic structures bearing hydrophobic pendants in the form of dipolar tricyanostilbene and hydrophilic glycol chitosan derivatives were synthesized and showed great potential for biological imaging with efficient cellular uptake and enhanced fluorescence[63] (Figure 13a). Fluorescent PEGylated derivatives with α-cyanostilbene were synthesized and demonstrated as a self-signaling fluorescent nano-carriers for the intracellular delivery of hydrophobic cargos (Figure 13b). Recently a mitochondrial probe based on a cyanostilbene scaffold was designed and investigated using Raman spectroscopy (Figure 13c)[64]. The enhanced emission of cyanostilbene with triphenylphosphine moiety was also utilized to target subcellular and simultaneous tumor imaging and drug delivery in cancer therapy. The long alkylchain in the designed system leads to the formation of nice self-assemblies that helps in easier localization exhibiting higher cytotoxicity than the normal healthy cells[65]. Star-shaped triphenylamine containing cyanostilbenes are also considered as potential substrates for bioimaging[66]. Several other scaffolds with cyanostilbene have also been synthesised as functional organic materials and meant to give a brief overview of several cyanostilbene moieties.

Conclusions

In summary, donor-π-acceptor conjugated systems with cyanostilbene scaffold have been extensively investigated for vast applications in organic electronics and bioimaging. The design of chromophores typically follows the following steps depending on the intended application- (i) Extending the delocalization for the design of red-emitting fluorophores. (ii) Incorporation of suitable functional moieties for specific sensing applications or organic electronic applications for device fabrication;
(iii) Incorporation of suitable hydrophobic or hydrophilic moietiesfor the formation of self-assemblies and (iv) Incorporation of suitably biocompatible substrates or suitable macrocyclic complexes to tune emission for potential use in biological systems. The field of fluorescent organic particles utilizing this approach has received tremendous attention yet continuously growing, and this article is solely meant to introduce readers to several interesting electronic or biological applications based on the cyanostilbene scaffold.

Acknowledgments

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