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Water/Alcohol-soluble Organic Luminophores: A Review

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Abstract Water/alcohol-soluble organic luminophores are a crucial subclass of luminescent materials that uniquely enable biomedical applications and eco-friendly optoelectronics that are inaccessible to their conventional hydrophobic counterparts. This review systematically outlines two fundamental strategies for achieving this essential solubility: chemical modification through covalent functionalization and physical encapsulation *via* supramolecular assembly. We analyzed the inherent trade-offs of each approach in terms of stability, luminescence properties, and synthetic complexity. Subsequently, we trace the evolution of these design principles across three major classes of luminophores: fluorescent, phosphorescent, and thermally activated delayed-fluorescence systems. Furthermore, we highlight their transformative applications in bioimaging, biosensing, anti-counterfeiting, and sustainable electronics. By mapping these strategies and applications, this review underscores how solubility design paves the way for broader utilization of organic luminophores in cutting-edge luminescent technologies.

Keywords Water/alcohol-soluble; Organic luminophores; Fluorescent; Thermally activated delayed fluorescence; Luminescent technologies

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INTRODUCTION

Organic luminophores have attracted considerable attention owing to their exceptional advantages including tunable optical properties, high fluorescence quantum yield, versatile processability, and cost-effectiveness. These properties make them highly promising for a wide range of applications, such as lighting,[1] display,[1,2] bioimaging,[3–5] and chemical sensors.[6,7] However, these materials are traditionally processed using nonpolar organic solvents that are often volatile, toxic, and environmentally hazardous, thus posing a major barrier to their bio-friendly and sustainable applications. Therefore, the development of organic luminophores that are readily soluble in green solvents, particularly in water and alcohol, is of critical importance.[8–26] Such water/alcohol-soluble organic luminophores not only mitigate environmental and health hazards but also significantly expand their utility in biological and environmentally conscious applications, such as biosensing and *in vitro* diagnostics,[27] biomedicine,[28] bioimaging,[3–5] anti-counterfeiting and information encryption,[14,29] and eco-friendly optoelectronics.[14]

Numerous strategies have been developed to endow organic luminophores with water and alcohol solubility. These approaches can be broadly classified into two complementary paradigms: chemical modifications and physical encapsulation. The chemical strategy directly connects permanent hydrophilic units to the core scaffold of the luminophore through strong covalent bonds.[9,24,30–38] This strategy allows for precise molecular engineering and yields materials with superior stability, albeit often requiring more complex synthesis. This physical strategy leverages non-covalent interactions, utilizing amphiphilic carriers or macrocyclic hosts to encapsulate hydrophobic luminophore micelles, vesicles, or molecular cavities.[13,39–46] This route is simple, rapid, and adaptable to a broad library of luminophores. The choice between the two strategies typically reflects a trade-off involving synthetic effort, luminescent properties, batch-to-batch reproducibility, and specific constraints of the target application.

The journey toward water/alcohol-soluble organic luminophores has progressed from a primary reliance on covalent derivatization to a more complex synergy of chemical and physical approaches.[26,47] After outlining the two strategies, we will then survey their applications across three major classes of organic luminophores, fluorescent, phosphorescent, and thermally activated delayed fluorescence (TADF), illustrating how solubility requirements have driven molecular innovation in each class. This review provides a comprehensive overview of the methodologies developed to confer aqueous and alcoholic solubility to these organic luminophores. We first dissect the working principles and landmark examples of both covalent (chemical) and noncovalent (physical) solubilization strategies. We then surveyed this evolution across three major classes of organic luminophores: conventional fluorescent, phosphorescent, and TADF, illustrating how solubility requirements have driven molecular innovation in each class. Finally, we highlight how the resulting water/alcohol luminophores are transforming biomedicine,

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safety, anti-counterfeiting, and sustainable optoelectronics. By benchmarking current achievements, we highlight that solvent compatibility has evolved into a pivotal design parameter that critically influences the performance and application of next frontier of luminescent technologies.

STRATEGIES FOR ACHIEVING WATER/ALCOHOL SOLUBILITY

Rendering the water/alcohol solubility of organic luminophores, thereby overcoming their intrinsic hydrophobicity, can be accomplished *via* two basic paradigms: chemical modification[30–38,48–53] and physical encapsulation.[39,41,43–45,54] The choice between the two strategies typically reflects a trade-off involving synthetic effort, luminescent properties, batch-to-batch reproducibility, and specific constraints of the target application. For instance, while chemical modification with poly(ethylene glycol) (PEG) or glycerol (PEGylation) can permanently anchor hydrophilic chains to the luminophore core, ensuring excellent stability against dilution, it may alter the emission wavelength or reduce the quantum yield owing to perturbation of the conjugated system.[34,51] In contrast, physical encapsulation using amphiphilic copolymers preserves the pristine luminophore structure and optical properties, but suffers from potential disassembly under dilution, heating, or changes in ionic strength, limiting its use in demanding biological environments.[39]

Although these two modifications have not yet been applied to luminophores, to the best of our knowledge, the respective advantages suggest that a combined approach could synergistically optimize solubility and luminescence. The ethylene glycol chains ensured permanent hydrophilicity and prevented aggregation, whereas the micellar shell further suppressed non-radiative decay through spatial confinement and isolated triplet excitons from quenchers. This hierarchical protection strategy can decouple the conflicting requirements of solubility and luminescence efficiency, offering a promising direction for designing high-performance water/alcohol-soluble luminophores.[40,48]

Chemical Strategies: Molecular Designing and Engineering

Chemical modification involves covalent attachment of hydrophilic moieties, such as zwitterionic groups, oligo (ethylene glycol) chains, or other polar groups, directly to the luminophore core (Fig. 1a). This strategy enables precise control over solubility and confers long-term stability in aqueous and alcoholic environments. Because these hydrophilic groups are permanently anchored, the resulting chromophores resist phase separation, even under stringent conditions.[48,49] However, this precision comes at the cost of multi-step syntheses[50] and potential adverse effects on photophysical properties, including spectral shifts[51] or diminished quantum yields.[50,52,53]

Chemical engineering by ionization

Ionization refers to the chemical modification of luminophores with permanently charged groups, which is a highly effective route for water/alcohol solubility. By introducing permanent charges such as quaternary ammonium groups, the materials gain dual water/alcohol solubility through strong ionic hydration (Fig. 1b).[30,31] These ionic species impart high aqueous solubility through hydration effects, while also exhibiting good miscibility with alcoholic solvents owing to their intrinsic polarity. For instance, quaternized perylene diimides retain strong emissions and remain stable in water or ethanol, making them suitable for biosensing[30] and solution-processed optoelectronic devices.[30,31] Similarly, polyfluorenes functionalized with quaternary ammonium side chains readily dissolve in water/alcohol and serve as efficient electron-injection/transporting layers in optoelectronic devices[24] such as organic solar cells (OSCs)[55–57], organic light-emitting diodes (OLEDs),[31,58–62] and organic light-emitting transistors (OLETs).[63–66] Thus, the ionization strategy serves as a direct and robust approach to endow organic luminophores with reliable and high solubilities in both aqueous and alcoholic solvents.

Chemical engineering by PEGylation

Grafting polar units, especially ethylene glycol chains, to organic luminophores represents a straightforward and effective chemical strategy for conferring water/alcohol solubility (Fig. 1c).[32–34] This approach works by attaching PEG chains to accessible sites on the luminophore skeleton. The incorporated polar groups formed a hydrative shell around the luminophores, facilitating dissolution in polar media. Critically, this modification is often achieved with only a few such groups per skeleton, which significantly enhances the solubility while minimally disrupting the essential π-conjugated system.[34]

The utility of this strategy has been demonstrated across different material platforms. For example, in conjugated polymer systems, appending PEG chains to the backbone successfully preserves intrinsic optoelectronic properties while imparting substantial water/alcohol solubility and improved film-forming ability, which is crucial for solution-processed devices.[32,34] For small molecules, this method effectively addresses the aqueous solubility challenge without sacrificing the key luminescent properties. A prominent example is PEG-modified tetraphenylethylene, an aggregation-induced emission (AIE) luminogen that exhibits markedly enhanced water dispersibility while retaining highly efficient solid-state emission, thereby enabling applications such as cellular imaging.[48]

Thus, PEGylation achieves an essential transformation of organic luminophores from hydrophobic to hydrophilic. It strategically decouples the solubility function from light-emitting cores, allowing for the independent optimization of each property and offering a versatile route to water/alcohol-soluble luminescent materials without compromising their luminescent and electronic performance.[33,34]

Chemical engineering with other polar groups

In addition to the widely used PEGylation, the incorporation of other nonionic polar functional groups also offers a versatile pathway to achieve water/alcohol solubility (Fig. 1d).[35–38] Groups such as carboxyl, hydroxyl, and triphenylphosphine oxide impart hydrophilicity primarily by forming extensive hydrogen-bonding networks with water, while their inherent polarity ensures good compatibility with aqueous and alcoholic solvents.

For example, conjugated polymers bearing carboxyl side chains demonstrate excellent water solubility, which ionizes in water, generating negative charges that create electrostatic repulsion and strong hydration, preventing the chains from

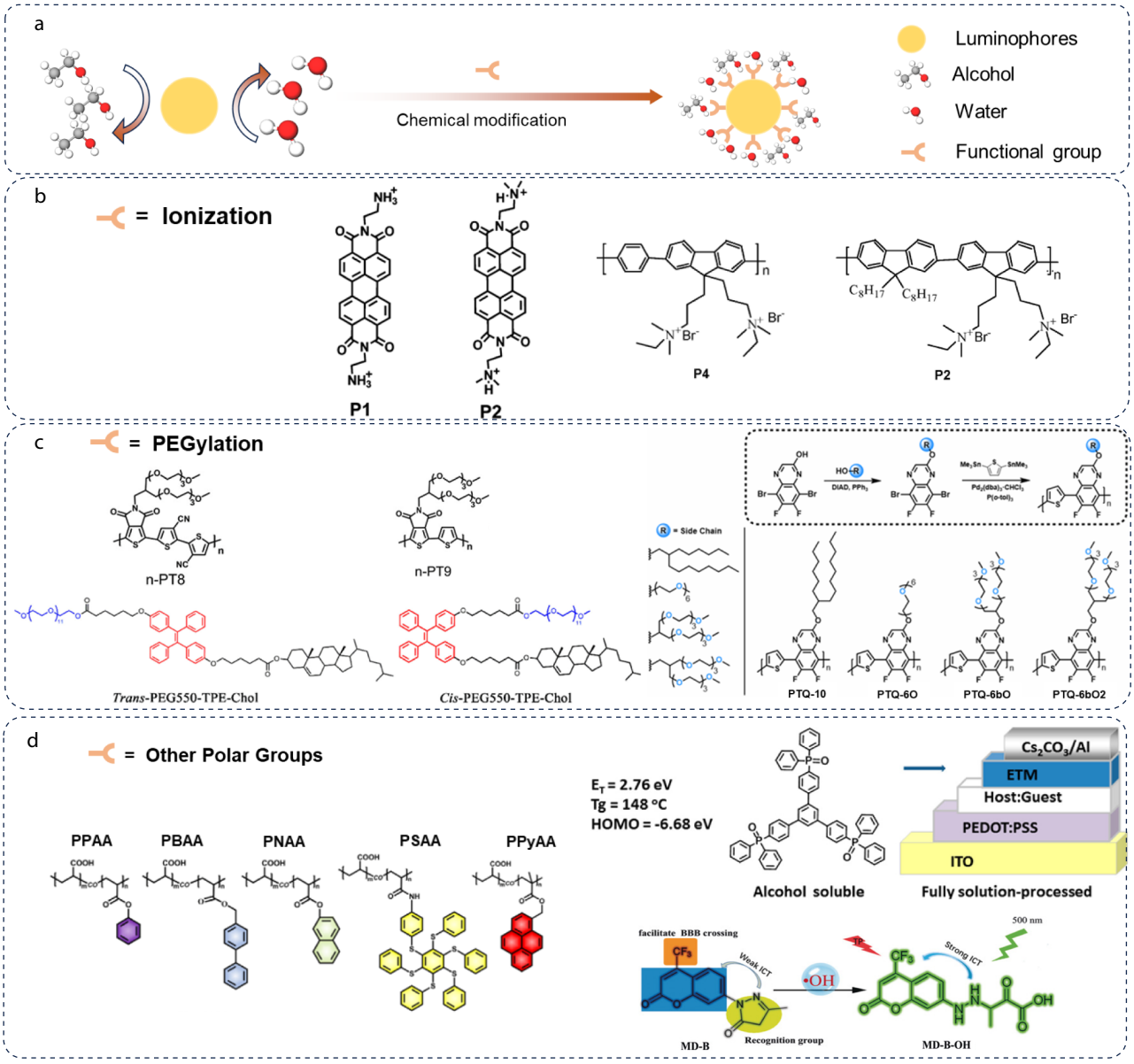

Fig. 1 (a) Schematic illustration of chemical modification strategies for achieving water/alcohol solubility in organic luminophores; (b) Example of ionization strategy (Reproduced with permission from Refs. [30, 31]; Copyright (2015, 2004), American Chemical Society). (c) Example of PEGylation strategy (Reproduced with permissions from Ref. [32]; Copyright (2024), Wiley; Ref. [33]; Copyright (2021), American Chemical Society; Ref. [34]; Copyright (2023), American Chemical Society). (d) Example of incorporation of other polar groups strategy (Reproduced with permissions from Ref. [35]; Copyright (2025), Wiley; Ref. [36]; Copyright (2014) American Chemical Society; Ref. [37]; Copyright (2019) John Wiley and Sons Ltd.).

coiling and allowing them to dissolve.[35] The incorporation of multiple triphenylphosphine oxide units has been shown to confer high solubility in alcohols, offering a robust platform for fabricating solution-processed OLEDs from environmentally friendly solvents.[36]

A key benefit of this approach is that it maintains electrical neutrality of the material. This not only prevents common stability issues in ionic systems but also minimizes undesirable perturbations to the core electronic structure. Consequently, the intrinsic luminescence properties, including the emission profile and quantum yield, were better retained. This makes nonionic modification a robust strategy for developing high-performance, solution-processable organic luminophores from water/alcohol solvents.

Physical Strategies: Encapsulation by Amphiphilic Molecules

Physical encapsulation employs noncovalent strategies to suspend hydrophobic organic luminophores in water/alcohol solvents. In a typical approach, amphiphilic molecules (*e.g.*, surfactants or block copolymers) self-assemble into nanoscale structures such as micelles or vesicles, with their hydrophobic interiors serving to encapsulate luminophores. This method is rapid, widely applicable, and synthetically undemanding. However, their non-covalent nature often compromises stability because the encapsulating assemblies can disassemble or undergo phase separation under stresses such as dilution, heating, or

changes in ionic strength, which may limit their use in demanding environments.

Micelles and vesicles by self-assemble

The self-assembly of amphiphiles into micelles or vesicles in aqueous media offers a direct and versatile route for solubilizing hydrophobic luminophores (Fig. 2a). A widely used implementation of this strategy employs amphiphilic block copolymers such as distearoyl-sn-glycero-3-phosphoethanolamine-poly(ethylene glycol) (DSPE-PEG2000) to form micellar structures capable of encapsulating luminophores.[39,40] In these assemblies, the hydrophobic core functions as a protective microreactor, stabilizing guest luminophores through π-π stacking and van der Waals interactions. As the self-assembly process and final morphology are dictated by the molecular structure of the amphiphile, the system offers tunable and reversible properties. This enables straightforward experimental control over the luminophore microenvironment, bypassing the need for complex covalent syntheses.

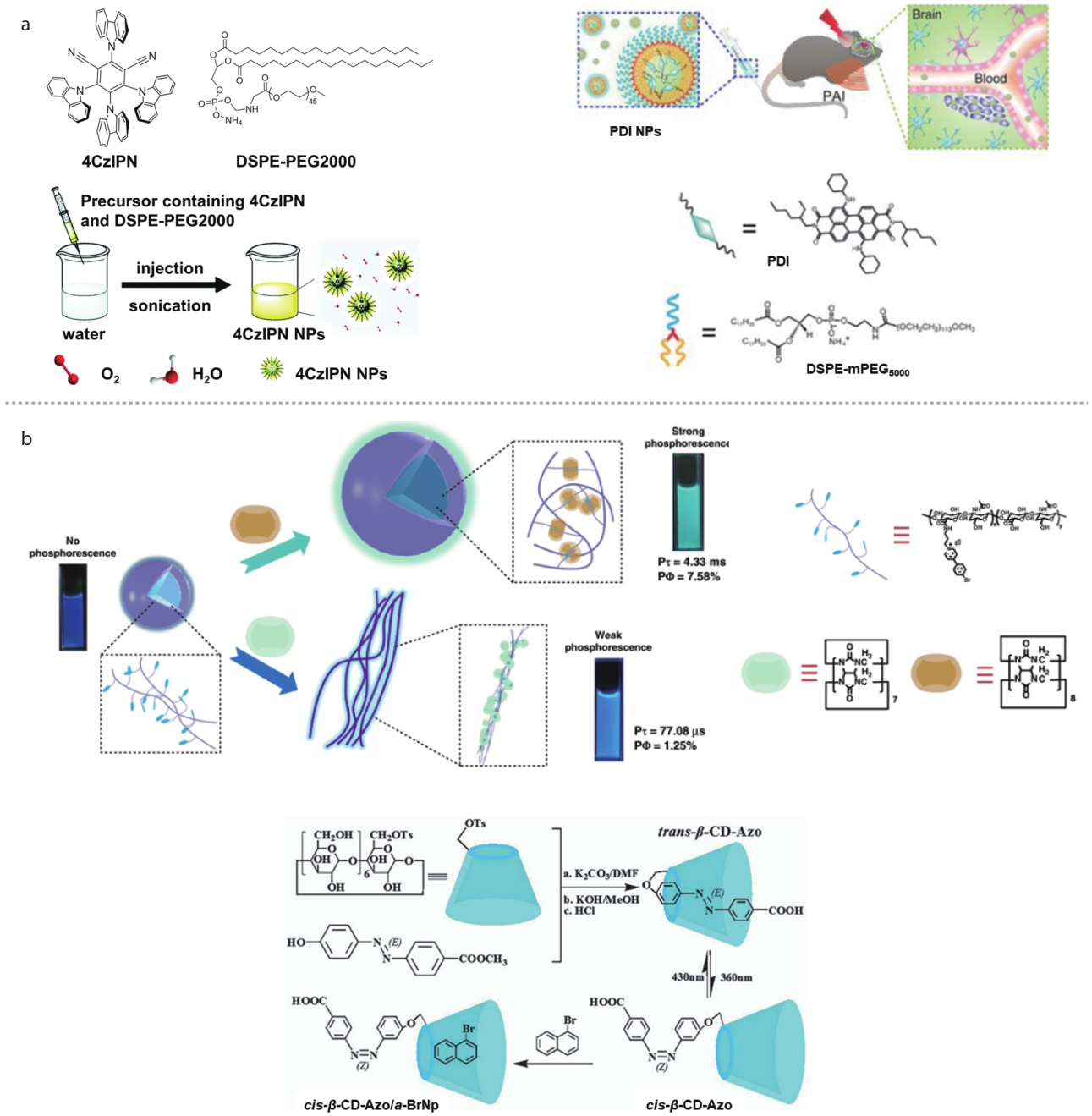

Fig. 2 (a) Schematic of achieving water/alcohol solubility through the self-assembly of micelles and vesicles *via* the introduction of amphiphilic groups (Reproduced with permissions from Ref. [39]; Copyright (2021), Royal Society of Chemistry; Ref. [40]; Copyright (2014), Wiley). (b) The hydrophobic luminophore are encapsulated within the hydrophilic host molecule (*e.g.*, cyclodextrin, cucurbituril) by host–guest complexation (Reproduced with permissions from Ref. [41]; Copyright (2020), Springer Nature; Ref. [42]; Copyright (2014), Royal Society of Chemistry).

Self-encapsulation by host-guest complexation

Supramolecular host-guest chemistry provides a powerful and general strategy for conferring water/alcohol solubility to organic luminophores (Fig. 2b). This approach utilizes the unique cavity structure of macrocyclic molecules, such as cyclodextrins, to achieve the encapsulation of small molecular luminophores through host-guest interactions.[41–43] For instance, classical luminophores can be effectively encapsulated within the cavity of *β*-cyclodextrin. The hydrophobic interior of these cavities selectively accommodates aromatic luminophores of specific sizes, whereas their hydrophilic exterior confers water solubility to the entire complex.[42] The same principle has been extended to AIE molecule-tetraphenylethylene complexes, which are now routine building blocks for turn-on fluorescent sensors in water.[45] This molecular encapsulation forms complexes with well-defined stoichiometries, providing effective isolation and protection without relying on complex self-assembled morphologies.

DEVELOPMENT OF WATER/ALCOHOL-SOLUBLE LUMINOPHORES

These two strategies provide fundamental methodologies for achieving water and alcohol solubility. The successful implementation of these two strategies, chemical modification and physical encapsulation, has driven substantial progress across distinct luminophore families. In this section, we trace the evolution of these design principles for three major classes of organic luminophores: fluorescent,[36,67–70] phosphorescent,[41,71–73] and TADF materials.[74,75] This progression has substantially broadened their application scope, enabling their use in bioimaging,[3–5] chemical sensing,[6–8,22,27,28,47,54,76–79] and printable electronics.[14,59,80] The subsequent sections provide a systematic review of recent progress in water/alcohol-soluble fluorescent, phosphorescent, and TADF materials.

Fluorescent Materials

Strategies for achieving water/alcohol solubility in fluorescent materials have undergone a significant paradigm shift. Initially, established strategies focused on chemically modifying classic organic fluorophores such as perylene diimides and boron-dipyrromethenes.[19,22,40,81–84] Recently, the field has evolved toward a more integrated engineering approach that concurrently optimizes solubility, photophysical properties, and aqueous/alcoholic stability through sophisticated design at both molecular and nanoscales.

A key observation in a fluorescent system is that the efficiency loss in a water/alcohol environment is often minimal. This resilience arises because fluorescence predominantly involves singlet excitons that are less susceptible to quenching by water or oxygen. For example, ether-modified rhodamines retain >85% of their original photoluminescence quantum yield (PLQY) in aqueous media, an effect attributed to the shielding provided by hydrophilic side chains that suppresses aggregation-caused quenching.[12] However, in cases where the fluorophore undergoes twisted intramolecular charge transfer (TICT), polar solvents can stabilize charge-separated states and open non-radiative decay pathways, reducing brightness.[12] Therefore, molecular engineering must consider not only the solubility but also the suppression of solvent-induced deactivation mechanisms.

Recent studies have demonstrated this trend. For instance, Yang *et al*. employed a supramolecular strategy using bovine serum albumin to encapsulate deep near-infrared triarylmethane luminophores. The protein-binding pockets restricted molecular rotation and provided spatial shielding, resulting in a 26-fold increase in NIR-II (near-infrared-II) fluorescence intensity *in vivo* imaging.[11] Besides, Xu *et al*. modified rhodamine luminophores with hydrophilic ether chains. These chains serve a dual purpose: the inductive effect of ether chains decreases the electron-donating strength of the amino groups, suppressing quenching caused by twisted intramolecular charge transfer, whereas their conformation helps shield the hydrophobic core in water. This design overcomes the issues of low brightness, aggregation, and non-specific binding, achieving high signal-to-noise ratios in live-cell super-resolution imaging.[12] Furthermore, Liu's group developed a red-shifted emission probe through frontier orbital engineering and polymer coating, enabling its application in single-cell cancer and bone imaging (Fig. 3a).[13]

Collectively, these studies mark a clear paradigm shift: the goal has evolved from merely imparting solubility to a comprehensive optimization of photophysical performance and application efficacy in aqueous/alcoholic media. This was achieved through the concerted use of multifunctional molecular design, supramolecular assembly, and nanocomposite engineering.

Phosphorescent Materials

Phosphorescent materials, which are characterized by their long-lived emission from triplet excitons, offer distinct advantages over conventional fluorescent probes. Their extended luminescence lifetime (microseconds to milliseconds and even seconds) enables powerful applications such as time-gated imaging, which effectively eliminates short-lived background autofluorescence to achieve an ultra-high signal-to-noise ratio in biological detection, and allows luminescence lifetime to serve as a stable sensing parameter independent of probe concentration. To harness these unique capabilities in aqueous environments, rendering them water-or alcohol-soluble has become a pivotal research direction for phosphorescent systems. Current strategies predominantly employ supramolecular encapsulation and host-guest assembly to achieve this goal while protecting triplet excitons.

For instance, Liu *et al*. reported aqueous room-temperature phosphorescence by leveraging cucurbit[8]uril to assemble fluorescently functionalized hyaluronic acid polymers. The supramolecular assembly created a rigid confinement environment, which resulted in a long phosphorescence lifetime of up to 4.33 ms (Fig. 2b).[41]

A key advancement was achieved by Huang *et al*., who constructed an efficient, ultralong-lived, blue-emitting water-soluble polymeric phosphorescent system *via* hydrogen bond induction. Subsequently, they expanded the emission from blue to red through phosphorescent Förster resonance energy transfer, achieving a wider color gamut for the water-soluble phosphorescent luminophores (Fig. 3b).[14]

This supramolecular strategy was further developed by Song *et al*. They covalently anchored the phosphors to cyclic peptides, which were then co-assembled with amphiphilic block copolymers to form rigid hydrophobic microdomains.

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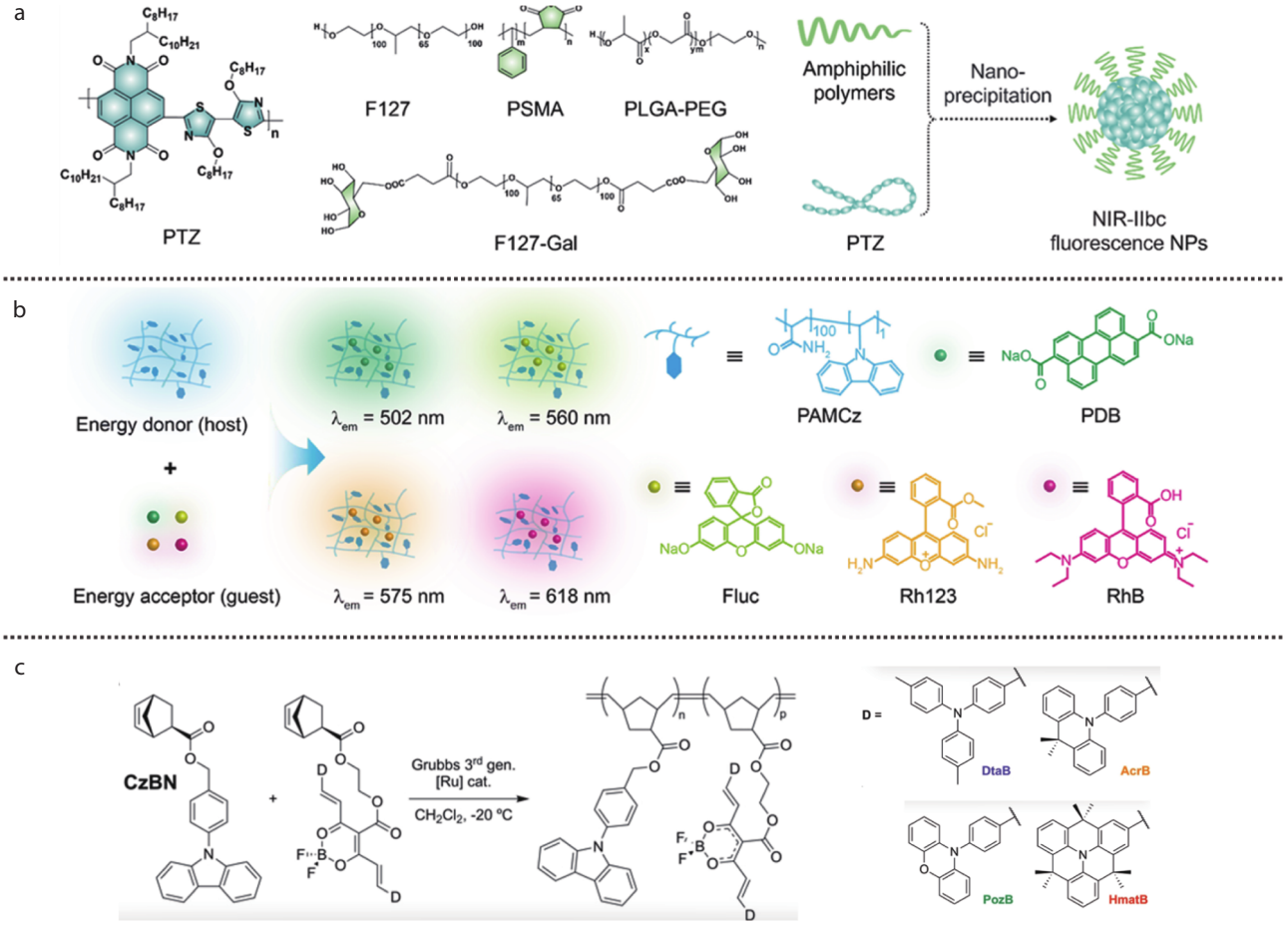

Fig. 3 Designs for achieving water/alcohol-soluble luminophores based on: (a) fluorescent systems (Reproduced with permission from Ref. [13]; Copyright (2025), American Chemical Society); (b) Phosphorescent systems (Reproduced with permission from Ref. [14]; Copyright (2022), AAAS); (c) TADF systems (Reproduced with permission from Ref. [18]; Copyright (2021), John Wiley and Sons Ltd.).

This system enables RTP from multiple phosphors in water, with one derivative achieving a lifetime of 755.8 μs.[15]

Furthermore, complementary strategies, such as matrix rigidification and elemental doping, have been developed, particularly for carbon dot systems. Liu *et al*. stabilized triplet excitons by encapsulating carbon dots within a crystalline sodium yttrium fluoride matrix. Spatial confinement and a stable surface ionic bond network endowed the carbon dots with stable phosphorescence in both the aqueous and organic solvents.[16]

The efficiency loss in phosphorescent materials becomes more pronounced in a water/alcohol environment owing to the high sensitivity of triplet excitons to oxygen and polar surroundings. For example, the PLQY of a representative phosphor decreases significantly when incorporated into a water-dispersible poly(vinyl alcohol) (PVA) matrix, primarily owing to residual oxygen and water-mediated vibrational quenching.[29] Although supramolecular encapsulation provides rigidity and shields triplet states, it cannot entirely eliminate quenching.

Collectively, these advances overcome the key obstacle of solubility, thereby unlocking the full application potential of phosphorescent materials. Notably, these strategies predominantly rely on physical confinement or matrix encapsulation to achieve water solubility. An alternative approach, the direct covalent modification of phosphors with hydrophilic moieties, is also being actively pursued.[29,85,86] For instance, Zhao's group demonstrated an effective method by introducing inherently water-soluble phosphonium salts, achieving high quantum yields.[86] However, current strategies remain dominated by physical confinement or matrix encapsulation, and chemical modification strategies remain in their infancy.

TADF Materials

TADF materials represent a revolutionary advancement in organic electronics, distinguished by their ability to harvest both singlet and triplet excitons *via* efficient reverse intersystem crossing (RISC). This unique mechanism enables a theoretical internal quantum efficiency of 100% with pure organic structures, offering a cost-effective and highly emissive platform for next-generation bioimaging, biotherapy, and optoelectronics. Nevertheless, a major barrier to their practical application lies in the requisite aqueous or alcoholic environment. Their inherent hydrophobicity, coupled with the pronounced susceptibility of their triplet states to quenching by oxygen and water, severely constrains their performance and utility in aqueous and alcoholic media.

To bridge this gap, sophisticated solubilization strategies have been developed. For instance, Li *et al*. encapsulated the

benchmark TADF emitter 4CzIPN within DSPE-PEG2000, creating nanoparticles that retained 21.6% PLQY in water and pioneered their use in aqueous electrochemiluminescence (Fig. 2a).[39] In a molecular design approach, researchers modified a fluorescein-based TADF scaffold with acrylic pendants, producing the water-soluble derivative DCF-BXJ, which maintained efficient RISC in a phosphate buffer solution.[17] TADF polymers have also shown recent advances in water solubility (Fig. 3c). The hydrophobic boron-difluoride-curcuminoid-based monomers were made water-soluble by embedding them into Pdots. This process involved nanoprecipitation with an amphiphilic block copolymer that self-assembled into nanoparticles with a hydrophilic shell. These Pdots were then functionalized with antibodies and used as effective near-infrared probes for imaging SK-BR-3 breast cancer cells.[18]

However, compared to fluorescence and phosphorescence systems, TADF materials face the most severe efficiency losses in water/alcohol systems because they rely on RISC, which is highly sensitive to environmental polarity and oxygen. For example, 4CzIPN loses over 70% of its PLQY after nanoencapsulation in water.[39] Strategies to mitigate this loss include incorporating heavy atoms to accelerate RISC or using rigid hosts that restrict molecular motion and suppress non-radiative decay. Balancing RISC efficiency and water solubility remains a core challenge in unlocking the full potential of TADF materials in biological applications.

In summary, current strategies for water/alcohol-soluble TADF materials have successfully demonstrated proof-of-concept, achieving moderate solubility and retaining decent emission properties in aqueous/alcoholic media. The primary advantage lies in the unlocking of the high-efficiency potential of TADF for biological and green solvent processing. However, significant challenges remain, including generally lower PLQYs in water compared to organic solvents, long-term stability against aggregation and oxygen quenching, and complex synthetic or formulation steps. Future efforts must focus on molecular and nano-engineering to simultaneously optimize RISC efficiency, solubility, and robustness in aqueous/alcoholic environments.

APPLICATIONS OF WATER/ALCOHOL-SOLUBLE LUMINOPHORES

Transitioning organic luminophores from traditional hydrophobic systems to water/alcohol-soluble variants marks a strategic leap, enabling functionalities beyond reach in organic solvents. By conferring compatibility with green polar solvents, this key attribute unlocks a suite of otherwise inaccessible properties: enhanced biological compatibility for direct use in living systems, facile integration into aqueous formulations for inks and coatings, and intrinsic environmental friendliness. Consequently, these attributes enable transformative applications that are central to next-generation technologies, including high-contrast bioimaging, *in vivo* sensing, printable electronics, and advanced anti-counterfeiting. The following sections detail these applications and highlight the pivotal role of solubility engineering in their realization.

Biomedical Applications

Bioimaging and therapeutics

Water/alcohol-soluble luminescent materials are crucial for

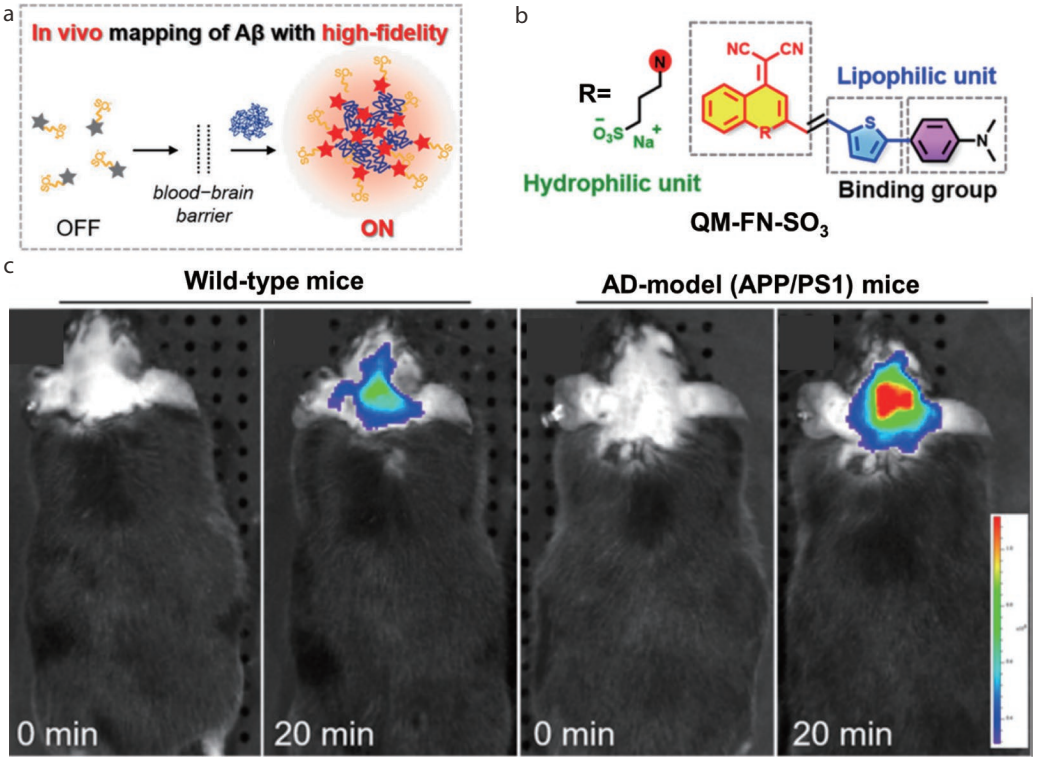

Fig. 4 (a) *In vivo* mapping of Aβ plaques; (b) The structural composition of QM-FN-SO_3; (c) *In vivo* mapping of Aβ deposition in AD model (APP/PS1 transgenic) mice (Reproduced with permission from Ref. [87]; Copyright (2019), American Chemical Society).

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bioimaging and therapeutics because their solubility enables their direct use in biological systems. The advantages of water/alcohol-soluble luminescent molecules for bioimaging are exemplified by the near-infrared AIE probe QM-FN-SO_3 designed by Zhu *et al*. (Figs. 4a–4c). The rational incorporation of a hydrophilic sulfonate group ensures good aqueous solubility and dispersion in circulation, keeping the probe in a fluorescence-"off" state before reaching the target to minimize background noise. Its lipophilic π-conjugated structure enables effective blood-brain barrier penetration and the targeting of amyloid-β (Aβ) plaques. Upon binding to the hydrophobic pockets of the plaques, the probe underwent restricted intramolecular motion, triggering a significant near-infrared fluorescence turn-on. This work demonstrates how sophisticated molecular design balances the solubility, targeting, and luminescence properties, providing a paradigm for developing intelligent optical probes for precise *in vivo* diagnostics.[5,87]

In addition to imaging, the biological safety of these probes is of paramount importance for clinical translation. Cytotoxicity assays (*e.g.*, MTT or CCK-8) are routinely performed to evaluate acute toxicity, and most water-soluble luminophores based on FDA-approved building blocks (such as PEG, amino acids, and cyclodextrins) show low toxicity at working concentrations.[9] However, long-term biocompatibility studies remain scarce; factors such as metabolic pathways, bio-distribution, and potential accumulation in organs require systematic investigation. Recent studies have begun to address these issues by designing fully biodegradable probes that undergo renal clearance, thereby minimizing chronic exposure.[13]

Biosensing

In the realm of biosensing, the molecular-specific responsiveness of water-soluble luminophores forms the basis of highly selective detection platforms. A sophisticated example is probe PN 910, which operates *via* a base-regulated intramolecular charge-transfer mechanism. Engineered to activate specifically in alkaline inflammatory microenvironments (pH>7.4), PN 910 responds to the biomarkers H_2O_2 and $OONO^-$. Upon analyte-

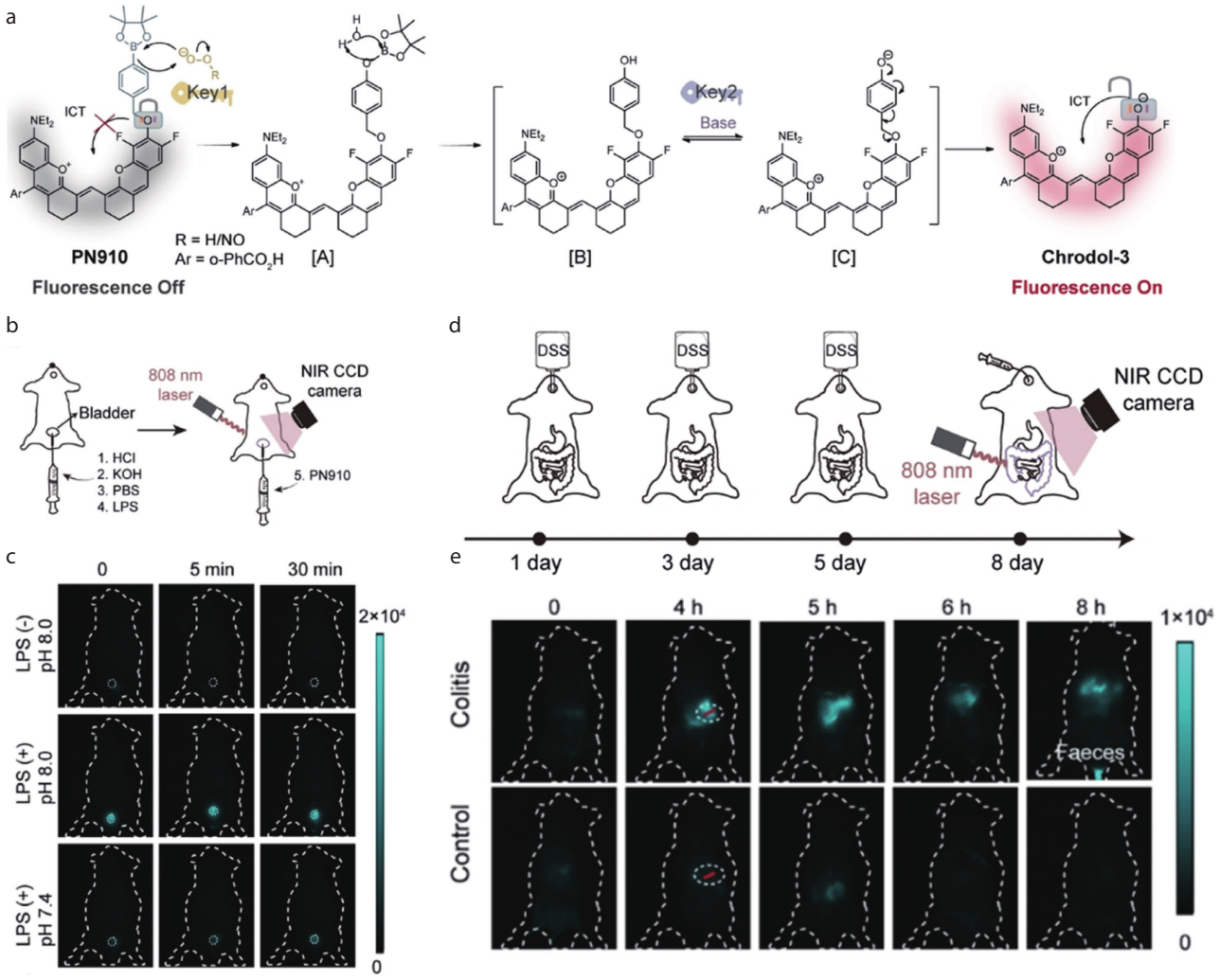


Fig. 5 (a) Rational design strategy of probe PN910 and its proposed responsive mechanism. Key 1: H_2O_2 or $ONOO^-$, Key 2: base; (b) Schematic illustration of cystitis mice model of PN910 for cystitis monitoring; (c) Images recorded with an InGaAs CCD at different time points under 808 nm laser excitation; (d) Schematic illustration of cystitis mice model and the application of PN910 for colitis monitoring; (e) Images recorded with a NIR-II CCD at different time scales under 808 nm excitation (Reproduced with permission from Ref. [88]; Copyright (2021), John Wiley and Sons Ltd.).

specific cleavage, fluorescence is restored, allowing for accurate, real-time monitoring of pathological models such as cystitis and colitis with high selectivity to minimize false positives (Figs. 5a–5e).[88]

Metal ion detection

Similarly, the unique photophysical behavior of AIE also makes it particularly advantageous for sensing aqueous media. Water-soluble AIE-active polymers exhibit a distinctive "turn-on" fluorescence response upon binding to trace metal ions, creating a versatile platform for environmental monitoring and detection of disease-related biomarkers.[8,78,89,90] This principle is exemplified by the work of Sahu *et al.*, who achieved sensitive and selective detection of copper ions using AIEgen-3 system (Figs. 6a–6e).[90]

Security and Anti-counterfeiting

The programmable, stimuli-responsive luminescence of

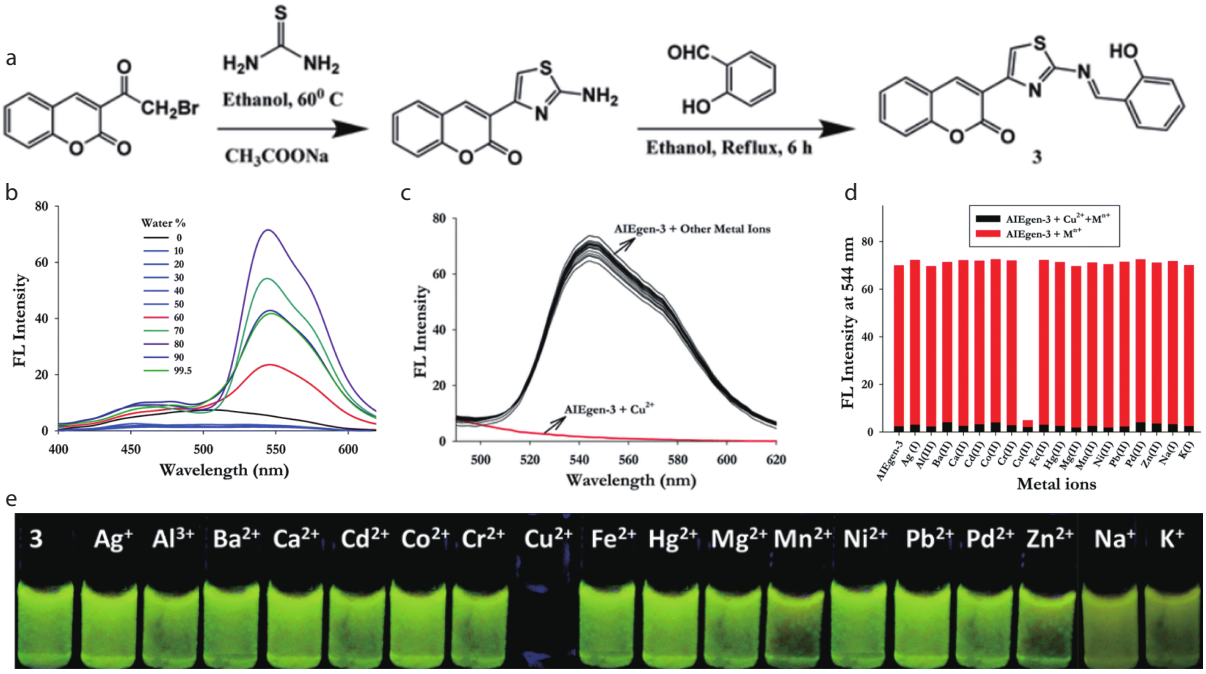
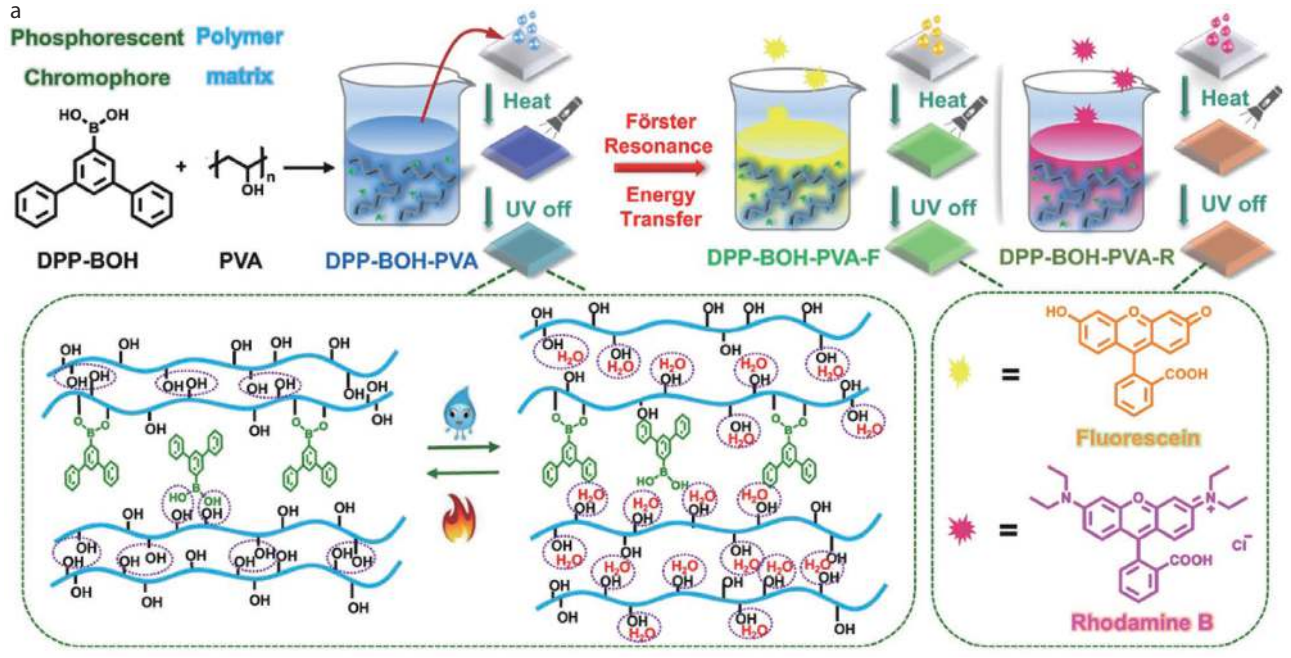


Fig. 6 (a) Synthetic route for probe 3; (b) Fluorescence response of probe 3 in DMSO-water solutions; (c) Emission spectra of probe 3 upon addition of various metal ions; (d) Histogram showing the fluorescent intensity of probe 3 at 544 nm with various metal ions; (e) Visual fluorescence response of probe 3 under a UV-lamp (Reproduced with permission from Ref. [90]; Copyright (2019), Royal Society of Chemistry).



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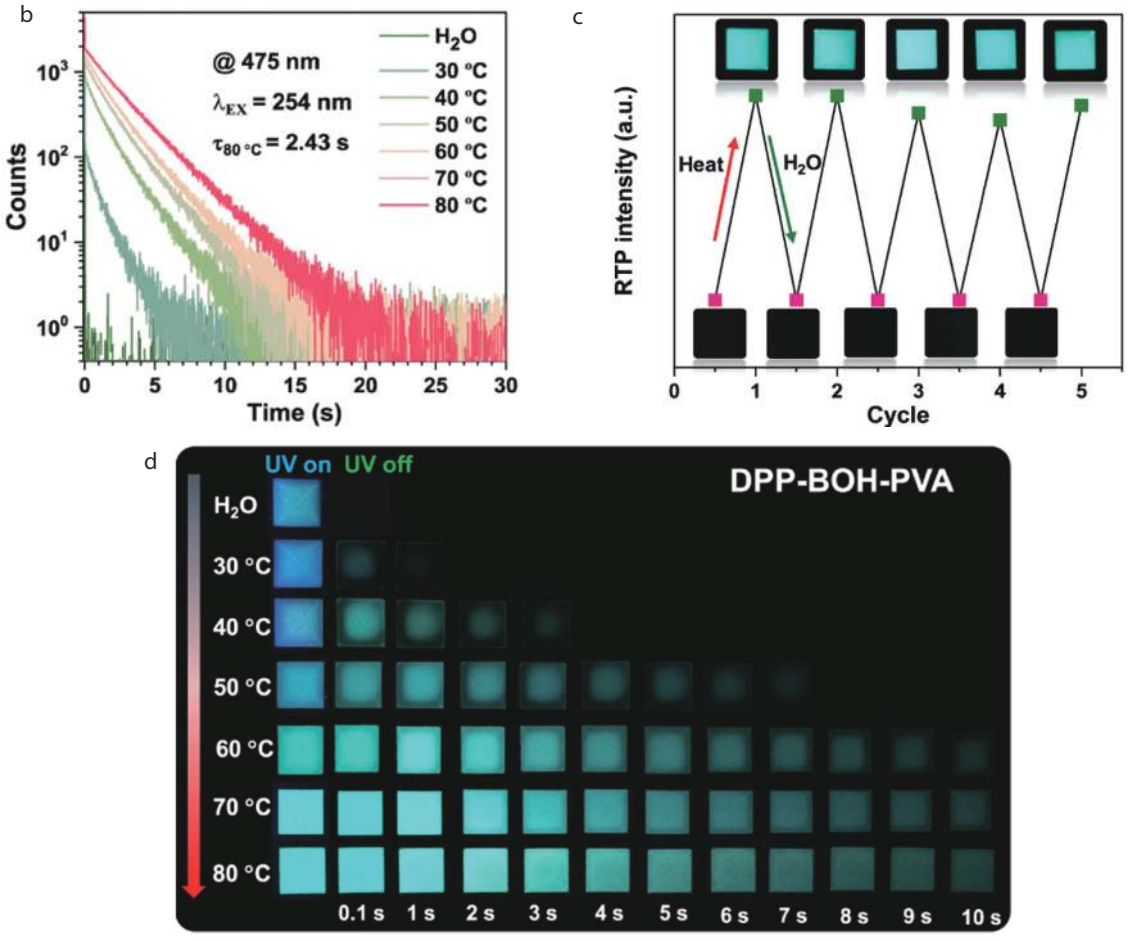

Fig. 7 (a) Stimulus-responsive room-temperature phosphorescent system; (b) Time-resolved emission-decay profiles of water-fumed DPP-BOH-PVA film after heating at different temperatures; (c) Repeated cycles of the heating/water fuming processes and the corresponding photographs of DPP-BOH-PVA film after turning off the UV irradiation; (d) Photographs of water-fumed DPP-BOH-PVA film after heating at different temperatures (Reproduced with permission from Ref. [29]; Copyright (2022), Springer Nature).

water/alcohol-soluble luminophores makes them particularly well suited for advanced security and anti-counterfeiting technologies. Through molecular engineering, these materials can be designed to exhibit reversible changes in emission color, intensity, or lifetime in response to specific triggers, such as light, heat, or chemical vapors.[14,29]

This capability enables the creation of sophisticated, multi-level encryption systems. For example, the phosphorescence lifetime and intensity of luminophores can be precisely and reversibly tuned through controlled heating and water vapor fumigation cycles, offering a dynamic platform for information encoding (Figs. 7a–7d).[29]

Sustainable Optoelectronics

Water/alcohol-soluble materials represent a key design solution for the sustainable and integrative manufacturing of organic electronics. Their defining characteristic is orthogonal solvent processability, namely solubility in environmentally benign polar solvents (water/alcohols) that do not redissolve the underlying layers processed from conventional non-polar organic solvents. This property inherently unifies two critical advances by enabling sequential solution-based deposition of multilayer device stacks and simultaneously replacing hazardous processing solvents with green alternatives. A prominent implementation of this dual capability is the conjugated polymer, poly[(9,9-bis(3'-(*N*,*N*-dimethylamino)propyl)-2,7-fluorene)-*alt*-2,7-(9,9-dioctylfluore-ne)] (PFN). Processed from alcohol or aqueous solutions, it can be deposited as an efficient electron-transport interlayer on the hydrophobic active layers in optoelectronic devices.[24,59,60,91–95] In OSCs, PFN-based derivatives are widely employed as cathode interfacial layers to modify the electrode work functions and enhance electron extraction.[55–57] In OLEDs and OLETs, PFN-based derivatives (*e.g.*, PFN-Br)[31] are usually combined with water-soluble poly(ethylenimine ethoxylated) (PEIE)[96] to serve as efficient electron injection/transport layers to balance charge carriers (Figs. 8a–8d).[31,58–66] While water/alcohol-soluble interfacial materials such as PEIE and PFN-Br have demonstrated excellent electron injection/transport performance and enabled highly efficient OLEDs and OLETs, their long-term device stability remains an ongoing research priority.

The applications reviewed herein demonstrate that water/alcohol solubility is no longer a mere processing aid but a cornerstone for engineering advanced luminescent functions. We have observed its critical role in enabling biomedical precision, secure information dynamics, and

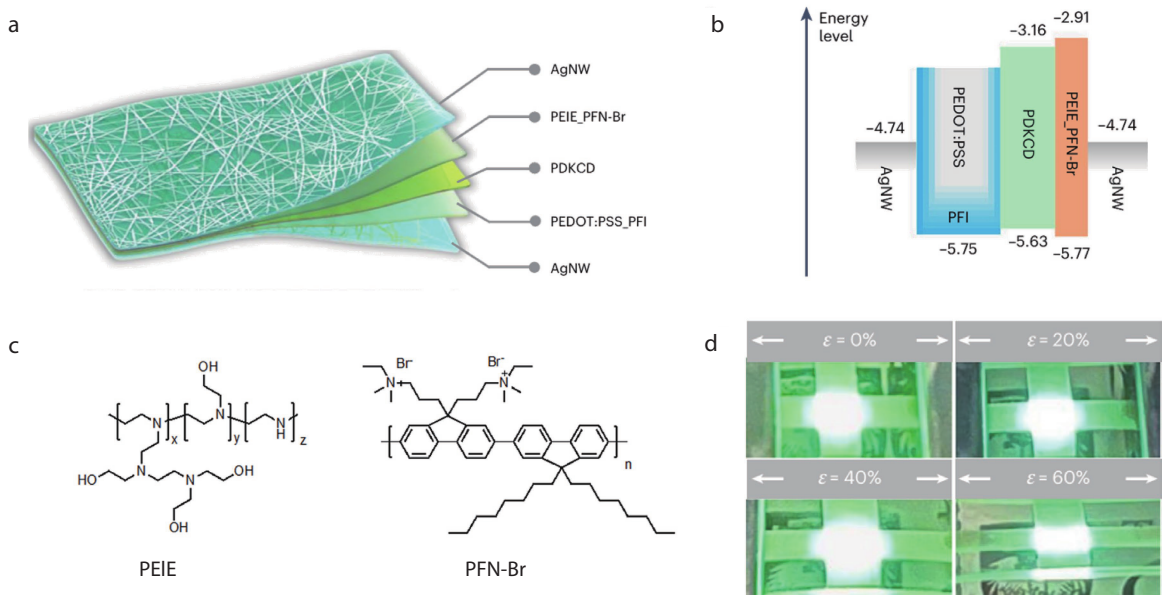

Fig. 8 (a) Example of PEIE_PFN-Br serving as electron injection layer in stretchable OLEDs; (b) Energy-level diagram of the device; (c) Molecular structures of PEIE and PFN-Br. (d) Photographs of a stretchable OLED under strains (Reproduced with permission from Ref. [59]; Copyright (2023), Springer Nature).

green electronic performance.

The next frontier is the convergence of these domains. Future innovations may focus on bio-optoelectronic interfaces, where water/alcohol-soluble luminophores serve as seamless conduits between biological signals and electronic readouts in implantable devices. Another promising avenue is adaptive and interactive photonic systems, such as displays or coatings, that change their luminescent properties in response to user interaction or environmental conditions, powered by soluble, processable active layers. Advancing these concepts will require deeper synergy among molecular design, nanotechnology, device engineering, and system-level integration.

SUMMARY

In summary, the pursuit of water/alcohol solubility has become an emerging design criterion for organic luminescent materials, driven by the demand for green processing and biological compatibility. This review systematically outlines two foundational strategies to achieve this goal: chemical modification through covalent attachment of hydrophilic groups, which provides molecular precision, enhanced stability, and physical encapsulation via supramolecular assembly, which offers simplicity and versatility. The emerging trend of hybrid approaches, which synergistically combine covalent design with supramolecular ordering, is blurring traditional boundaries and pointing toward the next generation of intelligent luminophores.

Promising directions include the development of dynamic or stimuli-responsive solubility for on-demand assembly, design of biomimetic or bioderived encapsulation systems for improved biocompatibility, and integration of data-driven approaches to accelerate the discovery of optimal molecular structures and formulation protocols. By navigating these scientific and engineering frontiers, water/alcohol-soluble organic luminophores have been poised to transition from advanced prototypes to indispensable components in sustainable technologies, enabling transformative applications across biology, information technology, energy, and ecology.

BIOGRAPHY

Wei Liu received his Ph.D. degree from Beijing Institute of Technology (BIT) in 2019. During his doctoral studies, he spent one year as a joint training Ph.D. student at the Center for Organic Photonics and Electronics Research (OPERA) at Kyushu University, under the supervision of Professor Chihaya Adachi. He did postdoctoral research at the University of Chicago (2019–2024) working with Professor Sihong Wang, and at the University of Tokyo (2024–2025) with Professor Takao Someya. He joined the Institute of Functional Nano & Soft Materials (FUNSOM) at Soochow University as a Professor in 2025. He leads a group working on bio- & eco-friendly organic optoelectronic materials and devices.

Conflict of Interests

The authors declare no interest conflict.

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Graphical Abstract

Water/Alcohol-soluble Organic Luminophores: A Review

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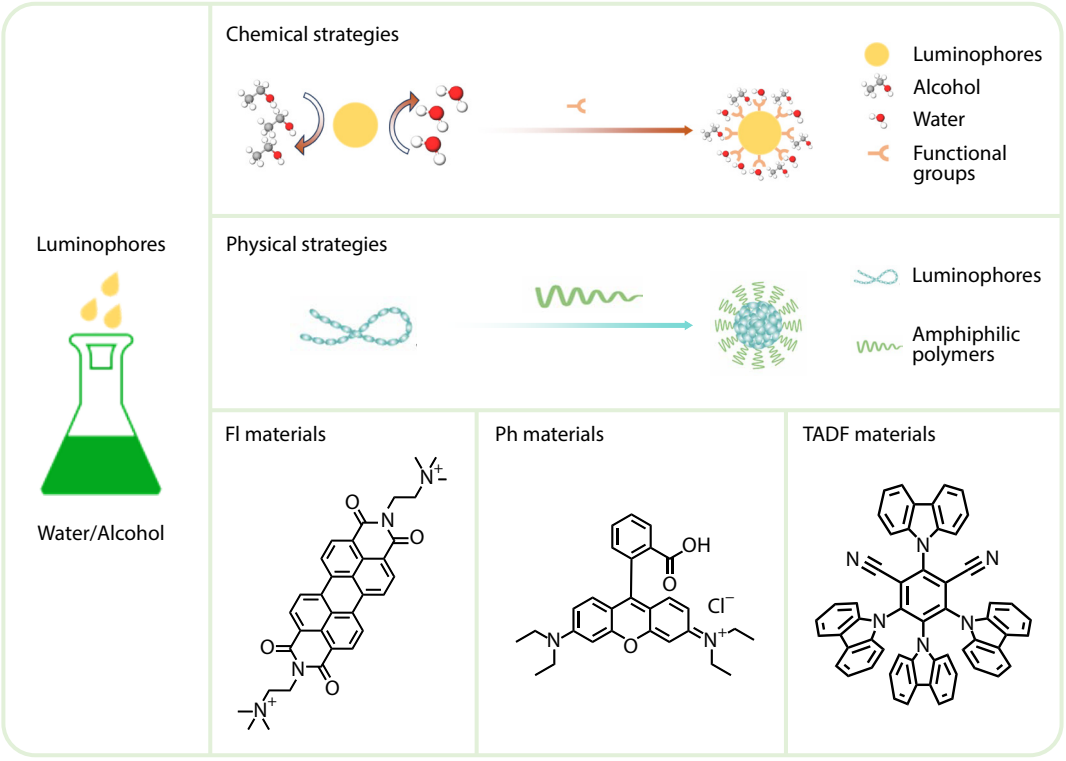
Soochow University

This review covers chemical modification and physical encapsulation strategies for water/alcohol-soluble organic luminophores, enabling advances in bioimaging, sensing, anti-counterfeiting, and sustainable optoelectronics *via* solubility design.



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