Fluorescent supramolecular assemblies have attracted significant attention for their application as bioimaging agents, biological and chemical sensors, light-emitting materials, and gene and drug vectors. The introduction of supramolecular coordination complexes constructed by the spontaneous formation of dative metal–ligand bonds through coordination-driven self-assembly into fluorescent supramolecular assemblies is of particular interest. This is because the introduction of metal coordination renders the synthesized assemblies excellent stability in addition to providing unique emissions that are different from the fluorescent ligands or metal ions. The discovery of aggregation-induced emission (AIE), wherein the fluorophores are nonfluorescent in the molecular state, but become highly emissive in the aggregate state, presents new chances for fluorescent supramolecular assemblies since such assemblies are often required to be employed at high concentrations or in the solid state. This progress report provides a summary of the recent design, construction, and application of metallacycle/metallacage-cored fluorescent supramolecular assemblies based on coordination-driven self-assembly, wherein the assemblies exhibit AIE properties. Example applications discussed in detail include light-emitting materials, chemical and biological sensors, bioimaging agents, and cancer therapy. Moreover, several unsolved issues related to metallacycle/metallacage-cored fluorescent supramolecular assemblies are discussed in the context of possible future applications of this field.

1. Introduction

Molecular self-assembly is a common phenomenon that exists widely in both biological and chemical systems. As is well known, nature is able to assemble simple molecular precursors into complex biomolecules (e.g., through protein folding, nucleic acid assembly, and tertiary structure formation, to generate phospholipid membranes, ribosomes, and microtubules), which are crucial for a range of vital processes. Nature also takes advantage of weak noncovalent interactions, such as van der Waals forces, charge–charge interactions, donor–acceptor interactions, hydrogen bonding, and hydrophilic and hydrophobic interactions, to achieve highly complex and often symmetrical architectures.

Currently, molecular self-assembly is not only experiencing a transformation from simple-component to multicomponent assembly and single-step to multistep processing, but it is also developing into an efficient tool to build supramolecular assemblies for applications in materials science and biomedicine.

Among the different noncovalent interactions (i.e., metal–ligand coordination, host–guest interactions, hydrogen bonding, π–π stacking, van der Waals forces, and hydrophobic forces), metal–ligand coordination is especially interesting due to its high strength and directionality, which approaches that of covalent bonds. In addition, coordination-driven self-assembly has been demonstrated to be an effective approach for preparing supramolecular assemblies with well-defined sizes and shapes, and this process provides a greater control over the rational design of 2D and 3D architectures by capitalizing on the predictable nature of the metal–ligand coordination sphere and the ligand lability to encode directionality. Furthermore, coordination-driven self-assembly also endows the resulting assemblies with higher stabilities compared to the cases where noncovalent interactions are employed. This strategy therefore presents an alternative pathway to better implement the “bottom-up” synthetic strategy for designing molecules with ideal dimensions, ranging from a few cubic angstroms to over a cubic nanometer. For instance, a wide array of 2D systems (rhomboids, squares, rectangles, and triangles) and 3D systems (trigonal pyramids, trigonal prisms, cubes, cuboctahedra, double squares, adamantantoids, dodecahedra, and different cages) have been developed to date. Although many well-defined (2D and 3D) discrete supramolecular assemblies have been built in the past three decades, their further applications have been limited due to the use of rigid yet fairly inert building blocks. With the aim of constructing functional assemblies via coordination-driven...
self-assembly, important efforts have been dedicated to the syntheses of functionalized building blocks (donors and acceptors) through rational design,[31–37] providing supramolecular coordination complexes (SCCs) for application in materials chemistry and biotechnology.[38–43]

Aggregation-induced emission (AIE), which was first developed by Tang and co-workers in 2001, has attracted great attention throughout a range of fields.[44–50] In general, AIE-active fluorophores (AIEgens) are almost nonemissive at low concentrations but emit strong fluorescence at high concentrations or the condensed state because of the restriction of intramolecular rotations.[51–53] A number of AIE luminogens (e.g., tetraphenylethylene, tetra-(4-pyridylphenyl)ethylene, pentaphenylpyrrole, and 1,8-diphenylnaphthalene) have been designed and developed in the past two decades.[54] Among them, tetraphenylethylene (TPE) has been widely used due to its facile synthesis and easy modification.[54–60] Importantly, the incorporation of AIE fluorophores into supramolecular assemblies (especially SCCs, or metal–organic frameworks (MOFs)) gives new vitality to fluorescent materials.[61–66] For example, SCCs are easily regulated in terms of the dimensions of the metallacycle or metallacage with only minimal synthetic design, and they are also advantageous in terms of the versatility of the metal and ligand precursors, the facile introduction of functional groups through pre- or post-assembly modification, and their rich host–guest chemistry associated with the internal cavities, which results in supramolecular assemblies abundant in topological structures.[60,61,62–65] In addition, fluorophores that exhibit AIE properties can enhance the emission of supramolecular assemblies at high concentrations or in the solid state, thereby overcoming the weak fluorescence associated with supramolecular assemblies based on traditional dyes due to aggregation-caused quenching (ACQ).[70–74] This review therefore focuses on the decade-long journey of early coordination-driven self-assembly paradigms to more complex and discrete 2D and 3D supramolecular ensembles that exhibit AIE properties. The preparation and application of metallacycle/metallacage-cored fluorescent supramolecular structures exhibiting AIE properties are also discussed in detail.

2. AIE-Active Metallacycles

Since the development of metal-cored molecular assemblies by Fujita and Stang in the early 1990s, a range of different metallacycles consisting of 2D geometries ranging from triangles and rhomboids to hexagons have been produced through coordination-driven self-assembly.[75,76] Rigid complementary precursors with suitable angles and symmetric structures, in addition to the appropriate corresponding ratios, are the basic requirements for constructing 2D metalloccyclic assemblies, as these factors determine the shapes of the metallacycles and thereby that of the resulting assembly. Previously, we summarized the various types of ligands employed for the construction of metalloccyclic architectures, with examples including bis-pyridyl, ter-pyridyl, and heterotopic ligands (Table 1).[8,13] Stimulated by the successful preparation of multifunctionalized metal-cored supramolecular assemblies, the construction of metal-cored fluorescent supramolecular assemblies with precise control over the shapes and sizes was successfully realized by the combination of chromophoric units into metallacycles. Indeed, AIE-active metallacycles constructed through metal–ligand coordination-driven self-assembly have attracted widespread attention since such fluorescent supramolecular assemblies tend to be multistimuli responsive, in addition to exhibiting particular emissions that differ from those of the corresponding ligands and metal ions.

As shown in Figure 1, Stang and co-workers prepared a 60° diplatinum(II) acceptor and three 120° dipyrpylid donors to construct three Pt(II) rhomboidal metallacycles 1–3, which emitted orange, cyan, and green fluorescence by coordination-driven self-assembly.[27] Further examination of the emissions of these supramolecular assemblies and metallacycles showed...
that fluorescence of the metallacycles 1–3 resulted from the dipyridyl precursors, namely, the triphenylamine-, tetraphenylethene-, and pyrene-based fluorophores, respectively, with the metal–ligand coordination significantly influencing the fluorescence. Metallacycles 1–3 were further linked to the supramolecular assemblies by the addition of a fluorescent bis-ammonium linker 4 exhibiting the ACQ property, and the fluorescence emissions of the resulting supramolecular assemblies were found to show concentration dependence over a wide color range. In terms of the fluorescent supramolecular assemblies constructed using metallacycle 1 and linker 4, a yellow color was observed at high concentrations because the intramolecular rotations of the TPE core are limited by the formation of metal–ligand bonds. However, compared to fused double triangle 12, fused double rhomboid 11 displayed a weaker fluorescence in the dilute solutions. This can be accounted for by two main points. First, the relative flexibility of the rhomboidal skeletons allowed 11 to form larger aggregates than 12, and second, double triangle 12 contained a large number of Pt atoms than 11, thereby increasing the intersystem crossing and causing a drop in emission. These studies therefore demonstrate that the properties of AIE-active metallacycles can be easily and precisely adjusted at the molecular level by altering their geometries.

Tian et al. first described a 1D rod-like tobacco mosaic virus (TMV) with a 2D TPE-based metallacycle 13 to form 3D biohybrid complexes through electrostatic interactions (Figure 3). The native TMV was able to self-assemble into a discrete 1D rod-like shape with a diameter of ~18 nm. After the addition of 13, the 1D rod-like shape changed to a network-like morphology measuring several micrometers, which was constituted of bundle-like structures measuring a dozen to hundreds of nanometers. In addition, the emission of metallacycle 13 was markedly enhanced due to the nanoconfinement effect in the resultant biohybrid assemblies. Moreover, the dissociation of these final constructs and subsequent release of individual viruses was achieved by the addition and removal of tetrabutylammonium bromide (TBAB) into the biohybrid complexes.
hierarchical assemblies exhibiting disassembly activity and AIE ability are therefore candidates for dynamic optical materials or as biocarriers, which may provide new approaches for the formation of functional biohybrid materials based on metal–organic assemblies and shaped bionanoparticles.

Yang and co-workers reported the construction of two AIE supramolecular polymer gels via hierarchical coordination-driven self-assembly and host–guest interactions, which exhibited multiple stimuli-responsive behaviors. From a novel synthesized dipyridyl donor containing a TPE scaffold and two pillar[5]arene units, a rhomboidal metallacycle with four pillar[5]arene units and a hexagonal metallacycle with six pillar[5]arene units were designed. At high concentrations, both 15>G2 and 16>G3 (G is the neutral dinitrile guest molecule for pillar[5]arene) exhibited AIE properties due to supramolecular polymer formation via host–guest interactions. Further increases in concentration gave rise to a new family of cross-linked supramolecular gels. Both the 15>G2 and 16>G3 gels exhibited gel-sol transitions under stimulation by temperature, competitive guest molecules, and halides, in addition to demonstrating “on-off” fluorescence. Thus, hierarchical self-assembly was successfully employed to construct supramolecular polymer gels exhibiting the AIE phenomenon and multiple stimuli-responsive properties, which could be applied in molecular sensors, biological imaging, and drug delivery.

Supra-amphiphiles have recently been demonstrated to exhibit diverse self-assembly characteristics in water, and their latent application has been discussed. Inspired by the supra-amphiphiles presented in their research, Yang and co-workers developed a simple approach to develop biocompatible TPE-based supra-amphiphilic metallacycles. They formed a hexagonal organoplatinum(II) metallacycle by combining °TPE functionalized dipyridyl donors with °di-Pt(II) acceptors decorated with chain transfer agents (CTAs) via metal–ligand coordination-driven interactions. The periphery of the metallacycle was influenced by the positions and number of the TPE and CTA moieties through the exo-functionalization strategy. The postassembly polymerization of N-isopropylacrylamide generated a new kind of supra-amphiphilic metallacycles embellished with three polymeric arms. Metallacycle exhibited typical AIE characteristics because of the incorporation of the TPE moiety. Due to its amphiphilic properties, star supramolecular polymer was able to spontaneously self-assemble into ordered and fluorescent nanoparticles in water, whereby metallacycle aggregated in the core and the hydrophilic PNIPAAm extended into the water at room temperature. The favorable biocompatibility of the TPE-based supra-amphiphilic metallacycles therefore indicates their potential for biological application in cell imaging. Indeed, this research offered the first instance of a TPE-based supra-amphiphilic metallacycle, thereby offering a new chance for producing functional metallo-supramolecular structures with possible application in biomaterials.

3. AIE-Active Metallacages

In addition to discrete 2D metallacycles, metal–ligand coordination-driven self-assembly has also been testified to be an
efficient strategy for the construction of 3D metallacages with well-defined shapes and sizes. Metallacages represent an important kind of self-assembled architecture in metal–ligand coordination-driven chemistry since the inner cavities of metallacages can selectively encapsulate some guest molecules (Table 2).[8,83,84] In recent decades, a high number of fluorescent metallacage-cored supramolecular assemblies have also been prepared.[85,86] In addition, through the introduction of TPE and its derivatives that exhibit AIE properties with highly efficient emission, the development of supramolecular assemblies with highly emissive properties in the aggregate state could be achieved.[87,88]

Yin and co-workers designed a fluorescent metallacage-cored supramolecular gel via the metal–ligand coordination self-assembly and host–guest interactions between the 21-crown-7 (21C7) and ammonium salts.[89] A tetragonal prismatic cage with four appended 21C7 moieties in its pillar sections was prepared by the metal–ligand coordination of a TPE-based sodium benzoate, cis-Pt(PEt₃)₂(OTf)₂, and a 21C7 appendant dipyridyl ligand, which further complexed with a bisammonium linker to form a supramolecular polymer gel through host–guest interactions (Figure 6). The resulting gels exhibited high emissions because of the introduction of metallacages with TPE derivatives, which averted the fluorescence quenching issue resulting from the highly aggregated state of the molecules in the gels. The supramolecular polymer gel also showed invertible sol-gel transitions induced by heat and potassium ions, which resulted from dynamic metal–ligand coordination-driven assembly and host–guest interactions. The storage and loss moduli of this metallacage-cored supramolecular polymer gel were tenfold greater than in the absence of metallacage cores, which indicates that the rigid metallacage may enhance the stiffness of the supramolecular gels. This strategy therefore provides an efficient pathway to replenish the functionalization of fluorescent metallacages via elegant ligand design and opens a new avenue for the preparation of dynamic yet robust supramolecular materials.

In 2015, Huang and co-workers successfully designed various highly emissive tetragonal platinum(II) metallacages through metal coordination-driven self-assembly.[90] As shown in Figure 7, they constructed a new TPE-cored multi-pyridyl...
ligand 33, which was nonfluorescent in CH₂Cl₂ due to the nonradiative decay induced by intramolecular rotations. Through self-assembly of ligand 33 with dicarboxylate ligand 34 or 35 and 90° Pt(II) acceptor 26 in a fixed ratio, tetragonal platinum(II) metallacages 31 and 32 were obtained, each of which included two TPE-based ligands in a cofacial arrangement. The optical properties of the two metallacages were evaluated in a range of different solvents, and in contrast to the ACQ or AIE fluorophores, these cages exhibited tunable visible light emission upon molecular aggregation with metallacage 32 emitting unusual white light emission at room temperature in THF. Furthermore, the emission of metallacage 32 was sufficiently sensitive to structurally similar ester compounds as observed by wavelength shifts in the visible region, thus providing a foundation for further applications in sensing.

Sun et al. also reported multicolor emissions from TPPE-based metallacages, which were arranged in complex structures. First, dicarboxylate ligands with different substituents (i.e., sodium sulfonate, nitro, methoxyl, and amine) were prepared, and subsequently, the metallacages were obtained via the combination of dicarboxylate ligand derivatives, TPPE, and cis-(PEt₃)₂Pt(OTf)₂. Finally, the hybrid metallacage building blocks were further assembled to form 1D, 2D, and 3D suprastructures with broad emissions (λₑₓ ranging over 451–519 nm). It was found that the 1D nanofibers exhibited green emission in water, while in organic solvents, 2D and 3D structures with various emissions were acquired via the assembly of cages 36–39 in ethanol and THF. In addition, cages 37 and 39 tended to constitute 2D structures. For example, nitro-functionalized cage 37 formed microfilms (510 nm) and microplates (461 nm) in EtOH and THF, respectively, while amine-functionalized cage 39 self-assembled to give microleaf structures (459 nm) in THF. However, cage 36 and 38 tended to form 3D structures in organic solvents. More specifically, 3D methoxyl-functionalized hollow microspheres (451 nm) and sodium sulfonate functionalized microspheres (506 nm) were obtained in THF. These results indicated that diverse suprastructures and wide emissions (λₑₓ from 451 to 519 nm) could be acquired by the careful selection of appropriate substituents and solvents (Figure 8). This study not only bridged the potential gap between small molecules

![Figure 5](image_url)

**Figure 5.** a) Graphical representation of the synthesis of TPE-based organoplatinum(II) metallacycle 23 and star supramolecular polymer 24. b) Fluorescence spectra of 24 in different water fractions with a concentration of 1.0 mg mL⁻¹ and c) relative fluorescence intensity (I/I₀) of 24 in the THF/H₂O system at 485 nm. d) PL spectra of an aqueous solution of 24 with an increase in temperature from 20 to 70 °C, and e) relative fluorescence intensity of 24 in water at 485 nm over a range of temperatures. Reproduced with permission. Copyright 2017, The Royal Society of Chemistry.

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**Table 2.** Different ligands utilized as building blocks for the construction of metallacages. Reproduced with permission. Copyright 2011, American Chemical Society.
with suprastructures, but also revealed connections between the spatial order and function on multiple scales, thereby laying the foundation for entertaining applications in optoelectronics.

Zhang and co-workers prepared two emissive poly(ethyleneglycol)-decorated tetragonal prismatic platinum(II) cages \(^{48}\) and \(^{49}\) via the self-assembly of TPE-based sodium benzoate ligands \(^{25}\), dipyridyl ligands \(^{46}\) or \(^{47}\), and cis-Pt(PEt\(_3\))\(_2\) (OTf)\(_2\).\(^{[92]}\) Metallacage \(^{49}\) was able to self-assemble into micelles due to the hydrophilicity of eight poly(ethylene glycol) (PEG) chains and the hydrophobicity of the internal framework of the metallacage (Figure 9). Metallacage \(^{49}\) exhibited strong emission at 511 nm with a 24% quantum yield, which overlapped the absorption of eosin Y. Thus, an efficient light-harvesting system could be successfully constructed using metallacage \(^{49}\) as the donor and eosin Y as the acceptor. This light-harvesting system exhibited enhanced photocatalytic activity compared to eosin Y alone because in addition to using visible light, it could also exploit UV light from the absorption of metallacage \(^{49}\) via fluorescence resonance energy transfer to activate eosin Y. As a result, this investigation not only presents a class of metallacycle/metallacage-cored fluorescent supramolecular assemblies.

4. Functional Applications

In general, supramolecular assemblies possessing multiple functionalities are attractive because of their significance and potential application in science and technology. Indeed, metallacycle/metallacage-cored supramolecular assemblies have been found to exhibit outstanding potential for applications in the fields of light-emitting materials, chemical and biological sensors, cell imaging, and cancer therapy, among others.\(^{[93-95]}\) These applications profit from the design and discovery of such new fluorescent materials by the incorporation of many highly emissive fluorescent chromophores. During the last few years, increasing attention has been paid to the construction of well-defined metallacycle/metallacage-cored fluorescent supramolecular assemblies.

4.1. Light-Emitting Materials

To date, a high number of light-emitting materials have been designed for applications in a wide range of chemical and biological subjects.\(^{[13,96]}\) In addition, the introduction of AIE fluorophores to supramolecular assemblies has been shown to be vital for the development and application of light-emitting materials.\(^{[97]}\) More specifically, Stang and Huang prepared TPE-based di-Pt(II) acceptors and TPE-based dipyridyl and tetrapyridyl donors\(^{[98]}\) and subsequently constructed pure TPE-based 2D hexagonal metallacycles and 3D drum-like metallacages with three diverse counteranions via metal–ligand coordination-driven self-assembly (Figure 10). Metallacycles \(^{55}\) possessed alternating TPE donor and acceptor units that arranged on...
resulting in eight freely rotating phenyl rings decorating the building blocks, specifically two donors and four acceptors, Metallacages providing the foundation for the observed AIE behavior. 12 pendant phenyl rings along the outer perimeter, thereby cis oxyl, and amine), tetra-(4-pyridylphenyl) ethylene, and (PEt3)2Pt(OTf)2 boxylate ligands with various substituents (sodium sulfonate, nitro, methyl).

Suprastructures (1D, 2D, and 3D) with tunable surface modifications and emissions were prepared by multilevel assembly. In the first level, dicarboxylate ligands with various substituents (sodium sulfonate, nitro, methoxy, and amine), tetra-(4-pyridylphenyl) ethylene, and cis-(PEt3)2Pt(OTf)2 were used as building blocks to fabricate four shape-controllable metallacages. In the next stage, the as-prepared metallacages were used as building blocks to fabricate four shape-controllable metallacycles. In the next stage, the as-prepared metallacages were used as building blocks to fabricate four shape-controllable metallacycles. Upon molecular aggregation, the multi-TPE metallacycles clearly displayed AIE activity, which was reflected by fluorescence enhancements as well as increased quantum yields. On account of their AIE characteristics in the condensed state, multi-TPE metallacycles 64, 65, and 68 were further explored for application in the detection of a model explosive, namely, picric acid, and high quenching constants were observed (Figure 11). These findings provide a comprehensive understanding of the influence of structural factors on the light-emitting properties and sensing applications of multi-TPE metallacycles, which paves a promising route to elaborate metal–organic materials based on SCC platforms by coordination-driven self-assembly.

4.2. Sensors

In the case of self-assembled metallacycles/metallacages supramolecular assemblies exhibiting AIE characteristics, sensor applications are of particular interest. Due to the formation of coordination bonds between the electric donor ligands and the metal ions, many self-assembled metallacycle/metallacage supramolecular assemblies are positively charged, and so they can be used to interact with anions via multiple electrostatic interactions. Heparin is a sulfated glycosaminoglycan polymer that has been widely employed as an anticoagulant drug because it can effectively prevent the formation of blood clots. Yang and co-workers constructed a TPE-based cationic organoplatinum(II) metallacycle to select and detect quantified heparin via the hierarchical self-assembly of a metallacycle with heparin driven by multiple electrostatic interactions (Figure 12). Upon the addition of heparin to the tris-TPE metallacycle, highly ordered aggregates were

Figure 8. a) [2 + 8 + 4] assembly of 40, 41, and 42 to furnish cage 36; 40, 41, and 43 to furnish cage 37; 40, 41, and 44 to furnish cage 38; and 40, 41, and 45 to furnish cage 39 via the heteroligation-directed self-assembly of 90° Pt(II) acceptors and pyridyl and carboxylate ligands. b) λmax values of cages 36–39 in six solvents, and c) photographic images of cages 36, 37, 38, and 39 (from top to bottom) in six solvents. d) Multidimensional suprastructures (1D, 2D, and 3D) with tunable surface modifications and emissions were prepared by multilevel assembly. In the first level, dicarboxylate ligands with various substituents (sodium sulfonate, nitro, methoxy, and amine), tetra-(4-pyridylphenyl) ethylene, and cis-(PEt3)2Pt(OTf)2 were used as building blocks to fabricate four shape-controllable metallacages. In the next stage, the as-prepared metallacages were used as building blocks for the second-level assembly. Diverse structures with different surface substituents and emissions were prepared based on the nature of the substituents and solvents. Reproduced with permission.[93] Copyright 2018, American Chemical Society.

12 pendant phenyl rings along the outer perimeter, thereby providing the foundation for the observed AIE behavior. Metallacages 56 were similarly prepared from TPE-based building blocks, specifically two donors and four acceptors, resulting in eight freely rotating phenyl rings decorating the prismatic core. The fluorescence of these cages in the dilute solution was enhanced when hexane was added to their CH2Cl2 solutions, which was indicative of aggregation-induced enhanced emission. The influence of the counteranions on the photophysics of the assemblies was also investigated, whereby the molar absorption coefficients (ε), fluorescence emission intensities, and quantum yields (Φ) of the SCCs with different counteranions in CH2Cl2 followed the order PF6− > OTf− > NO3−. The same trend was observed for the AIE characteristics of the SCCs in the aggregated state. As a result, this work not only enriches a newly emerging library of self-assembling AIE metallacycles and cages that are promising candidates for turn-on fluorescent sensors and advanced optical devices, but also provides an understanding of how structural factors affect the photophysics of AIE-active SCCs.

Stang and co-workers also synthesized a novel range of multi-TPE metallacycles via metal–ligand coordination self-assembly.[99] More specifically, a new 120° TPE-based dipyridyl ligand was synthesized, from which multi-TPE metallacycles were prepared by use of the directional-bonding approach via metal–ligand coordination-driven self-assembly. This strategy allows for precise control over the metallacycle size and shape, along with the distribution and total number of anchored TPE moieties. These metallacycles exhibited increased molar absorption coefficients ranging from 2.83 × 103 to 3.11 × 104 M−1 cm−1 after metal–ligand coordination, but relatively weak fluorescent emission due to the presence of freely rotating phenyl rings. Upon molecular aggregation, the multi-TPE metallacycles clearly displayed AIE activity, which was reflected by fluorescence enhancements as well as increased quantum yields. On account of their AIE characteristics in the condensed state, multi-TPE metallacycles 64, 65, and 68 were further explored for application in the detection of a model explosive, namely, picric acid, and high quenching constants were observed (Figure 11). These findings provide a comprehensive understanding of the influence of structural factors on the light-emitting properties and sensing applications of multi-TPE metallacycles, which paves a promising route to elaborate metal–organic materials based on SCC platforms by coordination-driven self-assembly.

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obtained, resulting from electrostatic interactions between the positively charged metallacycles and the negatively charged heparin. The positively charged metallacycle skeleton played a vital role during the aggregation process, which resulted in obvious changes in the emission intensity. As shown in Figure 12, an optical study indicated that metallacycle 70 could be regarded as a turn-on sensing probe for heparin, with a detection range of $0–28 \times 10^{-6}$ M, thereby covering the clinical dosage level. Moreover, metallacycle 70 could selectively bind with heparin instead of protamine sulfate, as demonstrated by competitive binding tests. The inherent merits of coordination-driven self-assembly, including intrinsic internal cavities that can respond to external stimulus therefore render coordination metallacycles good candidates for the detection of large biomolecules. The described study therefore not only replenishes the functional metallacycle library, but also furnishes a possible method to sense and bind biomolecules.

Zhang et al. used eight 90° Pt(II) acceptors, four dipyridyl ligands, and two sodium benzoate-decorated TPE units to prepare three emissive tetragonal prismatic metallacages, namely,
Cages 72a and 72b, bearing 4,4′-dipyridine and 1,2-dipyridylethene units as the pillars, respectively, showed good emission at 485–494 nm depending on the polarity of the solvent employed. However, the use of a 4,4-difluoro-4-bora-3a,4a-diaza-s-indacene (BODIPY) dipyridyl derivative (71c) as the pillar structure endowed cage 72c with two distinct emission bands at 462–475 and 540–545 nm, wherein the former represented the emission characteristics of the TPE units and the latter originated from the BODIPY fluorophores. Moreover, cage 72b can be employed as a turn-on fluorescent sensor for thiol-containing amino acids via a self-destructive reaction. Following its decomposition by thiol-containing amino acids, cage 72b can be regenerated via the flowing addition of Pt(II) acceptors. Thus, the thiol-containing amino acid sensing properties exhibited by cage 72b in methanol/water (1/1, v/v) were confirmed to take place through a self-destructive mechanism. These emissive metallacages not only provide new types of emissive materials with tunable emission properties, but also give insights into the stimuli-responsive destruction of these cages, rendering them potential candidates for light-emitting materials, chemo-sensors, and smart drug delivery systems (Figure 13).

4.3. Cell Imaging

Fluorescent supramolecular assemblies have been widely applied in cell imaging because of their improved brightness and inertness to the cell microenvironment, in addition to their good biocompatibility. Thus, Zhang et al. developed fluorescent assemblies through the covalent linkage of a TPE-based rhomboidal Pt(II) metallacycle 76. More specifically, an alkylamine and an N-hydroxysuccinimide-activated carboxylic acid were employed to crosslink the pendent amino functional groups of a rhomboidal metallacycle to prepare metallacycle-cored assemblies 77 and 78, which further produced nanoparticles at the low concentrations, and developed into network structures upon increasing the concentrations (Figure 14). Compounds 77 and 78 displayed brightly enhanced emissions and highly superior quantum yields in methanol/water (1/9, v/v) compared with their metallacycle precursors because of the fact that polymer formation induced aggregation of the TPE chromophores. The good fluorescent properties of 77 and 78 inspired the investigation of their potential applications in bioimaging and cancer therapy. Indeed, significant enrichments of 77 and 78 were observed in lung cells by confocal laser scanning microscopy (CLSM) imaging, thereby indicating that these fluorescent metallacycle-cored supramolecular assemblies could act as diagnostic and therapeutic agents for both cell imaging and tumor therapy.

NIR fluorescence imaging technology has become a hot topic in biomedical research because of its advantages of deeper tissue penetration and a higher spatial resolution. Furthermore, Zhang and co-workers prepared a cyanostilbene-based dipyridyl ligand exhibiting NIR emission by the introduction of D-π-A structures, and subsequently constructed platinum(II)
metallacycles 79–81 through metal–ligand coordination-driven self-assembly (Figure 15). These metallacycles exhibited NIR emission originating from their organic precursors, rendering them good contrast agents for cell imaging. Because of the antitumor activities of the platinum(II) ligands, these metallacycles were employed as therapeutic agents for NIR fluorescence imaging and cancer therapy. Among the various metallacycles, trigonal metallacyle 79 exhibited the best anticancer activity, which was even superior to that of the clinically used cisplatin. This study therefore offers a new type of NIR emissive theranostic agents for potential application in imaging-guided therapies, drug delivery, and cancer theranostics and therapy.

4.4. Cancer Therapy

AIEgens are almost nonemissive in the discrete state, but emit strong fluorescence in the aggregated state due to the restriction of their intramolecular motion. Supramolecular coordination was therefore employed to limit the intramolecular rotation of AIEgens, rendering them highly fluorescent in both the solution and aggregated states. These features result in AIEgen-based SCCs with improved photostabilities, making them hopeful candidates for cell imaging and cancer therapy. In this context, Yu et al. reported the multicomponent coordination-driven self-assembly of a tetragonal prism (Figure 16).
when two donor building blocks (83 and 84) were mixed with cis-(PEt3)2Pt(OTf)2.[108] Metallacage 85 was constructed by the combination of precursors 83, 84, and 26 acting as the edges, faces, and vertices, in a 4:2:8 ratio, respectively, under the principles of edge-directed and face-directed directional bonding. The tetragonal prismatic metallacage emitted strong emission even at very low concentrations, in which the free ligand was nonemissive, and this was attributed to the further restriction of intramolecular rotations in the metallacage. These results indicated that the metallacages were suitable for application in biological imaging. To form nanoparticles for application in biological environments, metallacage 85 was then embedded with mPEG-DSPE and biotin-PEG-DSPE, wherein the presence of PEG and biotin groups provided a means to stabilize the prisms within the hydrophobic pocket. These nanoparticles combined diagnostic and therapeutic functions and were found to actively target biotin receptor-positive cancer cells selectively over biotin receptor-negative cells. Both in vitro and in vivo research demonstrated that metallacage-loaded nanoparticles (MNPs) displayed low systemic activities, and strongly emissive properties suitable for fluorescence imaging. A further study also revealed that the MNPs possessed higher antitumor efficacies with lower toxicities compared to Pt(II) anticancer drugs such as oxaliplatin, carboplatin, and cisplatin. This pioneering example of a metallacage provides an excellent nanoplatform on which to combine theranostic anticancer agents with AIE imaging components, providing a promising potential theranostic platform for cancer therapy and a blueprint for the next generation of nanomedicines.

Stang and Yu also developed an amphiphilic polymer, Pt-PAZMB-b-POEGMA, containing metallacycle 87, in which the TPE derivative acted as an AIE fluorophore for cell imaging and Pt(II) imparted anticancer properties. Pt-PAZMB-b-POEGMA contained glutathione (GSH)-responsive copolymers as the arms and an AIE metallacycle as the core (Figure 17).[109] The amphiphilic polymer could further self-assemble into two vesicle-containing nanoparticles of different sizes. Because of their diverse morphology and size, these assemblies exhibited different endocytic pathways, and had different internalization rates and disparate cytotoxicities in HeLa cells. Notably, the assemblies were able to encapsulate neutral doxorubicin (DOX) and doxorubicin hydrochloride (DOX·HCl), respectively. The amphiphilicity of the Pt-PAZMB-b-POEGMA polymer was altered via a GSH-triggered cascade elimination of the hydrophobic protection groups, resulting in disassembly of the nanostructures and subsequent release of the loaded chemotherapeutic agent. These results indicated that the amphiphilic Pt-PAZMB-b-POEGMA polymer was able to successfully transport both the DOX anticancer drug and Pt(II), in addition to exhibiting synergistic cancer therapy behavior.
5. Conclusion and Challenges

Fluorescent supramolecular assemblies are of particular importance in the area of supramolecular chemistry due to their abundant applications. In this progress report, recent advances in metallacycle/metallacage-cored supramolecular assemblies exhibiting AIE properties are presented. The examples reviewed here strongly confirm that the combination of AIE with supramolecular coordination complexes prepared by coordination-driven self-assembly is an efficient approach for the production of fluorescent supramolecular assemblies with various well-defined discrete structures and desired functionalities. Due to their favorable characteristics, many of these systems have been proven to be useful as sensors, light-emitting nanomaterials, and antitumor agents. Nonetheless, some important aspects are yet underexplored: i) Water-soluble fluorescent supramolecular assemblies have not been well developed, despite having potential for application as new drug carriers and delivery agents. ii) Additional novel soft materials are required to rationally design and prepare unique combinations of robustness, stimuli-responsiveness, self-healing, adaptivity, and recyclability. iii) Stimuli-responsive and sophisticated fluorescent supramolecular assemblies should be explored to imitate the functions and properties of biological systems. Based on these points, the development of fluorescent supramolecular assemblies are expected to facilitate the evolution of novel fluorescent materials for applications in sensors, probes, and imaging agents in biological systems, in addition to their usage in light-emitting materials. In fact, although many efforts have been made in these areas, a number of challenges remain in terms of developing novel fluorescent supramolecular assemblies for practical applications. Through the introduction of traditional polymers into metallacycle/metallacage-cored supramolecular assemblies with AIE fluorophores, new structures are obtained, which often give rise to improved mechanical properties for the fluorescent supramolecular assemblies, thereby providing the possibility for their further application as functional materials. In addition, further attention should be paid to the intrinsic cavity in the metallacycle/metallacage of supramolecular assemblies, since functional guest molecules could be introduced into the cavity through host–guest interactions, thereby endowing or regulating the functionality of the fluorescent supramolecular assemblies. Furthermore, new functional elements or groups (such as metal ions, disulfide bonds, or metal coordination bonds) may be introduced into these fluorescent supramolecular assemblies to build complex supramolecular materials through hierarchical self-assembly. Finally, the development of fluorescent supramolecular assemblies exhibiting different topological structures (such as branched, hyperbranched, dendritic, star, and cross-linked structures) should be examined. Indeed, for the construction of such structures, coordination-driven self-assembly is an efficient and simple pathway, whereby the resulting structures can be regulated by changing the ligand angle or molar ratio and thus, overcoming the issues related to tedious multistep organic syntheses. In conclusion, we expect that past, ongoing, and future studies on fluorescent supramolecular assemblies will be of benefit to mankind and will contribute to promoting the development of society.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

aggregation-induced emission, coordination-driven self-assembly, supramolecular assemblies, supramolecular coordination complexes