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Application of aggregation-induced emission (AIE) in the urinary system disease

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Highlights:

- AIE materials have shown great potential in urinary system diseases, particularly in early diagnosis, precise treatment, and drug delivery.
- This review systematically summarizes the applications of AIE materials in urinary cancers, such as bladder cancer, renal cancer, prostate cancer, and upper urinary tract cancer, including fluorescence imaging, photodynamic therapy, and drug delivery techniques.
- The review explores the application of AIE materials in the diagnosis of urinary tract infections and renal lesions, as well as their advantages when combined with imaging technologies such as CT, MRI, and ultrasound.
- The article analyzes the challenges faced in the clinical translation of AIE materials, including biocompatibility, stability, and large-scale synthesis, while proposing future development directions such as customized molecular design and multifunctional applications combined with nanotechnology.

Abstract: AIE is a unique photophysical phenomenon, and its distinctive luminescence properties have demonstrated significant potential in the biomedical field. In urinary system diseases, AIE materials, with their high quantum yield, excellent optical properties, and environmental responsiveness, have been widely applied in the early diagnosis, precise treatment, and drug delivery of urinary system cancers. This review systematically summarizes the applications of AIE materials in urinary cancers, such as

bladder cancer, renal cancer, prostate cancer, and upper urinary tract cancer, including fluorescence imaging, photodynamic therapy, and drug delivery techniques. Additionally, the review explores the application of AIE materials in the diagnosis of urinary tract infections and renal lesions, as well as their advantages when combined with other imaging technologies (e.g., CT, MRI, and ultrasound). Furthermore, the article analyzes the challenges faced in clinical translation, such as biocompatibility, stability, and large-scale synthesis, while proposing future development directions, including customized molecular design and multifunctional applications combined with nanotechnology.

Keywords: aggregation-induced emission; urinary system diseases; bioimaging; photodynamic therapy; drug delivery; clinical applications

1. Introduction

1.1. Aggregation-induced emission (AIE) phenomenon and its basic principles

AIE is a distinct photophysical phenomenon in which certain organic molecules exhibit weak or negligible fluorescence in solution, but demonstrate significantly enhanced fluorescence upon aggregation [1]. In contrast to traditional fluorescent materials, which typically undergo fluorescence quenching, known as Aggregation-Caused Quenching (ACQ), due to intermolecular interactions during aggregation, AIE materials show increased photoluminescence (PL) in their aggregated or solid states (Figure 1) [2–3]. This unique feature greatly expands their potential applications across diverse fields.

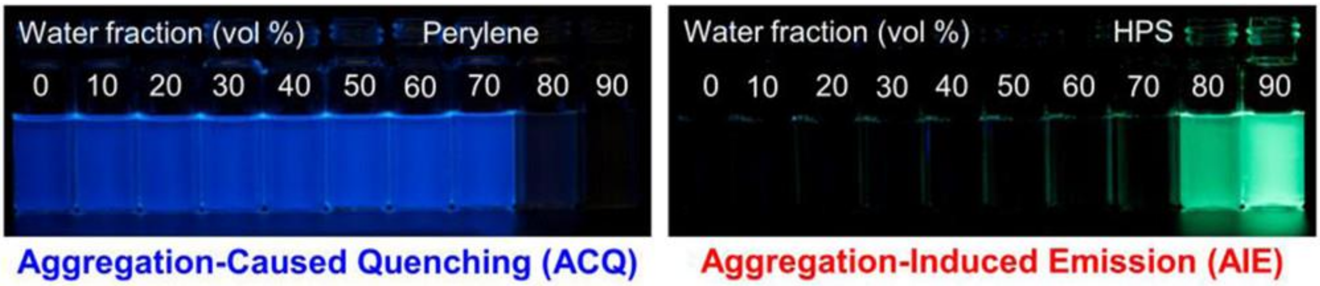

Figure 1. Fluorescence photographs of solutions or suspensions of (left) perylene (20 μM) and (right) hexaphenylsilole (HPS; 20 μM) in THF/water mixtures with different fractions of water (f_w), with perylene and HPS showing typical ACQ and AIE effects, respectively. Reprinted with permission [3]. Copyright 2025, ACS-CR.

The discovery of the AIE phenomenon has significantly altered our understanding of conventional fluorescent materials, propelling "aggregation-induced emission" to the forefront of research [4]. AIE-active molecules generally possess specific molecular structures that undergo rearrangement or self-assembly during aggregation [5]. This structural transformation reduces non-radiative energy loss between molecules, thereby enhancing fluorescence emission [6]. AIE molecules are increasingly utilized in a wide range of applications, including biosensing, optoelectronic devices, display technologies, and environmental monitoring [7]. Furthermore, due to their high quantum yield and tunable emission properties, AIE molecules hold great promise for use in photodynamic therapy and theranostics in the medical field [6,8–11]. As shown in Figure 2, the key AIE research focuses in the field of urology can be broadly categorized into four aspects: innovative therapeutic strategies for urological cancers, improvement of quality of life in benign diseases, precise diagnostics using fluorescence imaging probes, and the application of advanced drug delivery systems to minimize side effects.

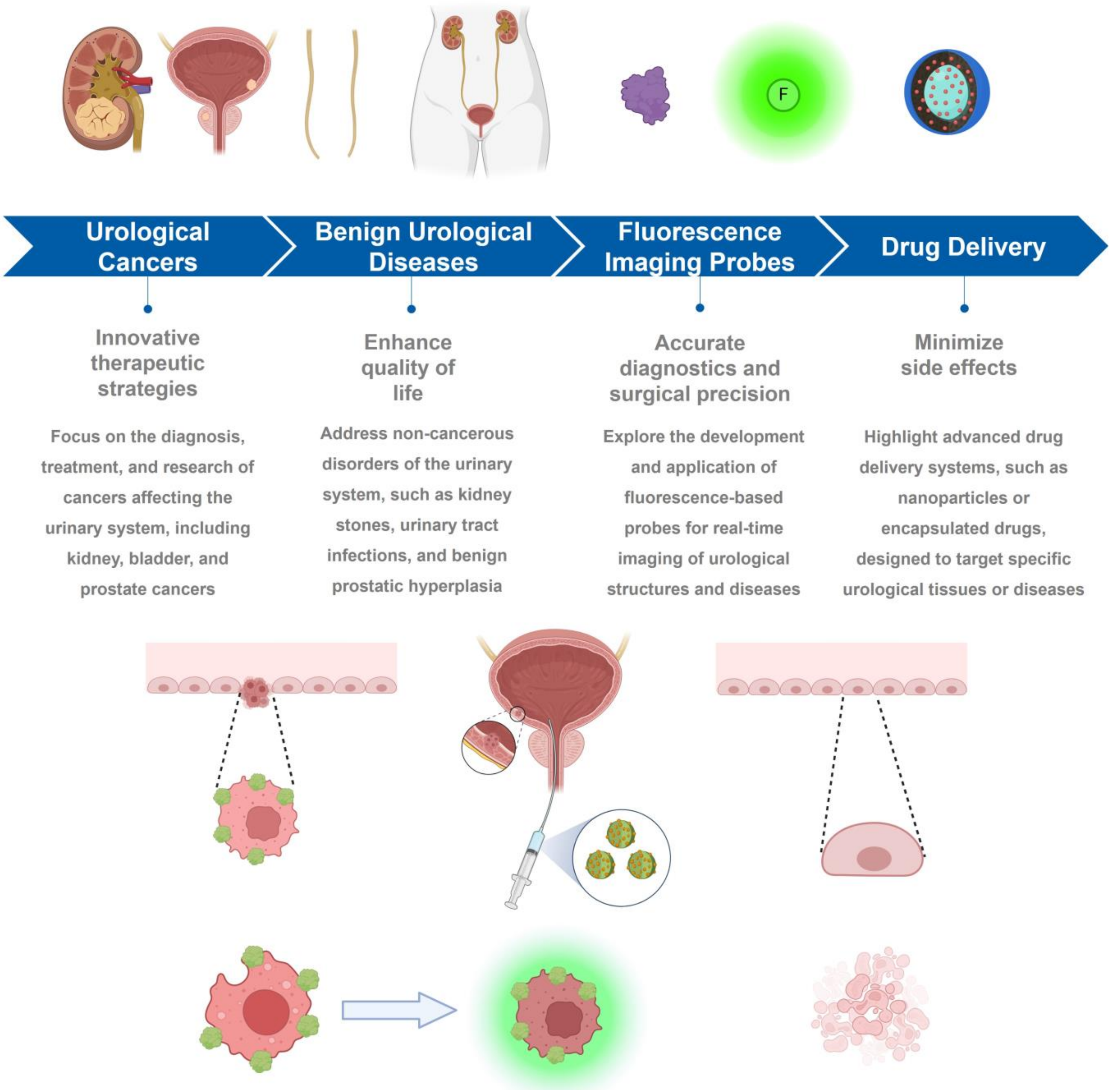

Figure 2. Overview of advancements in the diagnosis and treatment of urological diseases. The graphic highlights key areas of focus: (1) Urological Cancers—innovative therapeutic strategies targeting kidney, bladder, and prostate cancers; (2) Benign Urological Diseases—enhancing quality of life by addressing conditions like kidney stones, urinary tract infections, and benign prostatic hyperplasia; (3) Fluorescence Imaging Probes—enabling accurate diagnostics and surgical precision through real-time imaging of urological structures and diseases; (4) Drug Delivery—minimizing side effects with advanced drug delivery systems such as nanoparticles and encapsulated drugs, tailored for targeted therapy of urological conditions; and (5) The figure illustrates the specific imaging capabilities of AIE in both tumor and non-tumor sites.

1.2. Characteristics of AIE materials

1.2.1. High quantum yield

A key feature of AIE materials is their exceptionally high quantum yield, which serves as a crucial indicator of fluorescence efficiency. A high quantum yield typically signifies that the material can effectively convert absorbed light into fluorescence emission [12]. Unlike conventional fluorescent materials, AIE substances maintain high fluorescence efficiency in their aggregated state, allowing them to retain brightness even in complex environments, such as low concentrations or thin films [13].

In the biomedical domain, the high quantum yield of AIE materials makes them particularly suitable for bioimaging and sensing applications [13–15]. Their efficient light emission contributes to the generation of clearer *in vivo* images, thereby enhancing the sensitivity of detecting abnormal regions, especially in early-stage cancer diagnosis, where it significantly improves the efficacy of molecular imaging techniques [16–17].

1.2.2. Excellent optical properties

AIE materials not only feature high quantum yield but also exhibit a range of exceptional optical properties, including broad-spectrum emission, tunable emission wavelengths and colors, and impressive photostability [2,18–20]. Unlike conventional fluorescent materials, which are constrained by narrow emission spectra, AIE materials offer greater flexibility, with emission that can be tailored through molecular design to cover wavelengths from ultraviolet to visible, and even into the near-infrared range, thus catering to diverse application needs [3,21].

For instance, in biomedical imaging, the tunable emission properties of AIE materials allow the adjustment of emission wavelengths to match the specific characteristics of tissues or lesions, thus minimizing signal attenuation due to deep tissue absorption [22]. Additionally, AIE materials typically demonstrate strong photostability, maintaining consistent fluorescence even under extended excitation, which is essential for reliable *in vivo* imaging and long-term monitoring [23].

1.2.3. Responsiveness and environmental adaptability

AIE materials are highly responsive to external stimuli such as temperature, pH, and solvents [11]. As environmental conditions change, AIE materials can dynamically adjust their fluorescence properties in real time [24]. Owing to their excellent adaptability, AIE materials can be employed to monitor various physiological changes *in vivo*, including enzymatic activity, inflammatory responses, and alterations in the tumor microenvironment, making them ideal candidates for the development of biosensors [10].

In cancer diagnosis and therapy, AIE materials can detect specific alterations in the tumor microenvironment, such as changes in acidity or redox status, and report these pathological changes through fluorescence signals [25–26]. This high sensitivity makes AIE materials valuable tools for the early detection of cancer and other diseases.

1.2.4. Potential in biomedical applications

The excellent optical properties and responsiveness of AIE materials have given them enormous potential in the field of biomedicine (Figure 3).

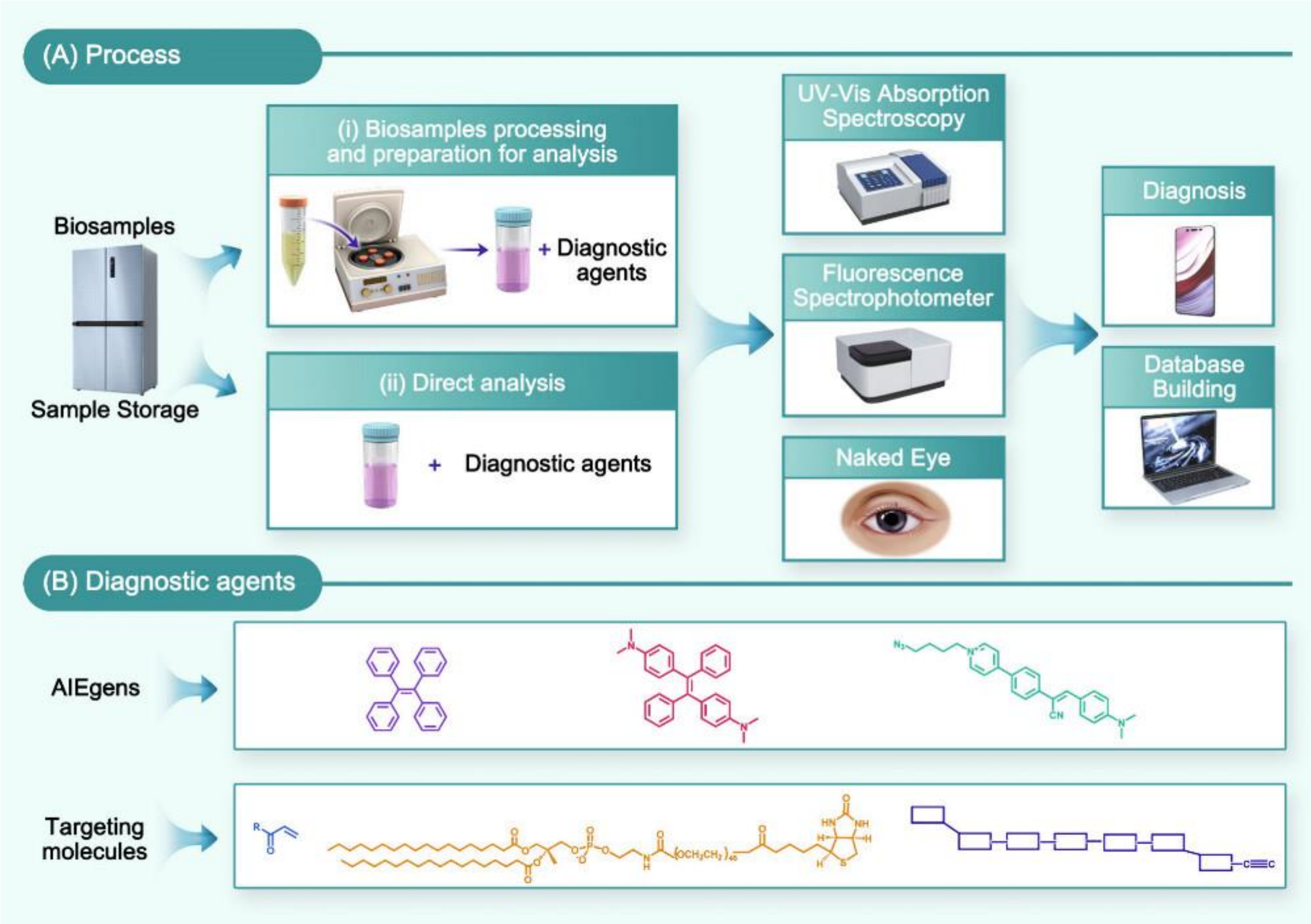

Figure 3. (A) Schematic of biosamples collection, storage, processing, and analysis, for biopsy. (B) The typical AIEgen fluorescent probes used for biopsy in biosamples. Reprinted with permission [58]. Copyright 2025, ACS-CR.

Bioimaging is one of the most extensively studied applications of AIE materials, especially in *ex vivo* and *in vivo* cellular imaging, organ imaging, and tumor imaging [13,27–28]. A key advantage of AIE materials is their ability to exhibit significantly enhanced fluorescence emission when aggregated, offering high-resolution and high-contrast imaging [29]. Unlike traditional fluorescent probes, AIE materials maintain high brightness even at low concentrations, effectively preventing the fluorescence quenching often associated with aggregation [30]. This characteristic enables them to deliver clear and reliable imaging signals, making them highly valuable for visualizing various biological systems. In particular, AIE materials are widely used in early cancer diagnosis, where they facilitate the precise identification of tumor location, size, and boundaries.

In cellular imaging, AIE materials can specifically label molecules on the cell surface or within cells, enabling real-time monitoring of cellular processes [31]. For instance, AIE molecules can target specific receptors on cancer cells and generate strong fluorescence signals during cell–cell interactions. This allows researchers to track cancer cell proliferation and migration with high sensitivity [32]. In organ imaging, AIE materials can be utilized for non-invasive imaging to monitor organ function and pathology, thereby facilitating real-time assessment of organ health and disease progression [33].

Biosensors represent another significant application of AIE materials. These materials exhibit distinct optical responses when interacting with specific biomolecules or pathological changes, providing high sensitivity for detecting disease biomarkers, pathogens, or physiological parameters [34]. By designing AIE molecules that selectively respond to specific biological targets, they can be applied to the detection of cancer cells, viruses, bacteria, and other biomarkers [35]. For instance, AIE materials can be used to identify specific molecular markers present on the surface or inside cancer cells [36]. Since cancer cells often express unique receptors or antigens, AIE probes can selectively bind to these markers, generating strong fluorescence signals [37]. This specificity enables AIE probes to detect cancer cells with high sensitivity, supporting early diagnosis and continuous monitoring [11]. Additionally, AIE materials can also be employed to detect pathogens such as viruses and bacteria, contributing to rapid and effective pathogen detection, which is crucial for accurate and timely clinical intervention [38]. In summary, the unique optical properties of AIE materials make them powerful tools for biosensing applications.

PDT is a treatment method that utilizes photosensitizers to generate reactive oxygen species upon light exposure, which can kill tumor cells [39]. AIE materials hold great promise in PDT due to their enhanced fluorescence in the aggregated state, enabling the production of singlet oxygen ($^1O_2$) and hydroxyl radicals ($\cdot OH$) upon excitation to target and destroy cancer cells [40]. Compared to traditional photosensitizers, AIE materials benefit from higher quantum yield in their aggregated form, enhancing the therapeutic effect of PDT [41]. Studies show that AIE materials accumulate in tumor sites, where they generate singlet oxygen to kill cancer cells and inhibit tumor growth [42]. Their strong targeting ability, low phototoxicity, and ability to reduce side effects make AIE materials safer and more effective for localized cancer treatment. Moreover, combining PDT with chemotherapy or immunotherapy could further improve cancer treatment outcomes [43].

AIE materials are widely applied in drug delivery systems, enabling the visualization of spatiotemporal drug release processes [44–45]. AIE materials offer two significant advantages: first, their high fluorescence quantum yield allows for real-time imaging of drug release [46]. Upon external stimuli, drugs loaded with AIE materials are released, and the AIE signals can serve as tracers to monitor this release process [47]. For instance, Chen *et al*. developed an AIE-based pH-sensitive material that exhibits strong red and blue emissions in acidic and basic compartments, respectively, thus achieving visualized drug delivery [48]. To date, AIE materials have been successfully applied in highly selective bioimaging of cancer cells [49]. In cancer therapy, AIE-active drug delivery systems enable the tracking and monitoring of drug release both *in vitro* and *in vivo*, offering valuable insights into therapeutic processes [50].

The strong fluorescence properties of AIE materials also make them valuable in antibacterial and antiviral applications. In antibacterial therapy, AIE materials can generate reactive oxygen species (such as singlet oxygen) upon light excitation, effectively killing bacteria [51]. They are particularly useful in imaging and detecting infection sites by enhancing light-induced fluorescence responses [52]. In antiviral applications, AIE materials can bind specifically to viral surface proteins, preventing viral entry and replication [53]. Additionally, the singlet oxygen produced under light excitation can directly target and kill viruses, offering promising potential for antiviral treatments [54]. AIE materials thus provide new avenues for the early detection and treatment of viral infections.

The fundamental AIE phenomenon and the key characteristics of AIE materials have been discussed. The following sections will focus on their specific applications in urinary system diseases, including their roles in diagnosing and treating urinary cancers, urinary tract infections (UTIs), and renal lesions, as well as their integration with advanced imaging and drug delivery technologies.

2. Applications of AIE in the diagnosis and treatment of common urinary system diseases

Early diagnosis and treatment of urinary system diseases and cancers remain a major challenge in medicine [55]. As the incidence of urinary system cancers (such as bladder cancer, kidney cancer, prostate cancer, *etc.*) increases, traditional diagnostic methods such as cystoscopy and CT scans, while accurate to some extent, have limitations such as invasiveness, high cost, and inconvenience. Therefore, developing non-invasive, highly sensitive detection methods and efficient, targeted treatment strategies has become a key focus of current research. As an emerging fluorescent material, AIE shows great promise in the diagnosis and treatment of urinary system diseases due to its significantly enhanced luminescent properties in the aggregated state (Figure 4) [56].

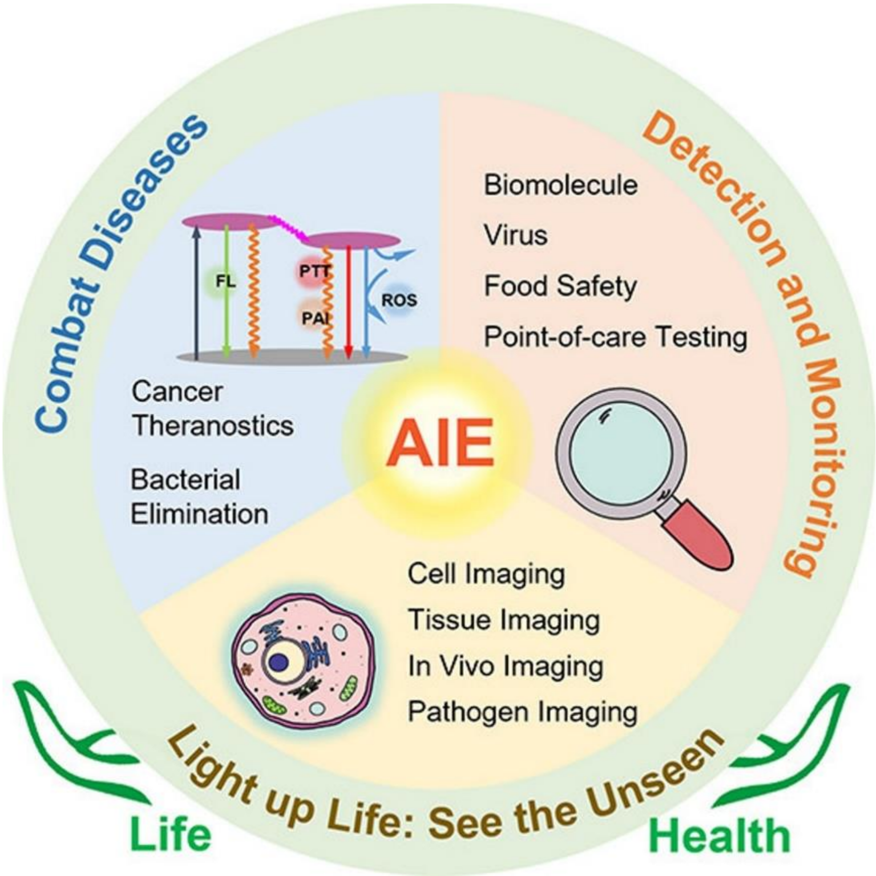

Figure 4. This schematic summarizes the versatile roles of AIE materials, emphasizing their contributions to combating diseases, detecting and monitoring biological targets, and improving health outcomes. Key applications include cancer theranostics, bacterial elimination, cell and tissue imaging, pathogen detection, and point-of-care testing. AIE materials' ability to "light up life" by visualizing the unseen is central to their impact on disease management and health monitoring. Reprinted with permission [56]. Copyright 2025, ACS-Nano.

2.1. Applications of AIE in the diagnosis of urinary system diseases

AIE materials, with their unique optical properties such as high quantum yield, environmental responsiveness, and significantly enhanced fluorescence in the aggregated state, have shown broad application prospects in the diagnosis of urinary system diseases. Traditional diagnostic methods, such as urine culture, imaging, and biochemical monitoring, have limitations such as long detection periods and low sensitivity [57]. AIE materials, by targeting specific biomarkers, offer non-invasive, highly sensitive, and specific diagnostic tools, aiding in the early detection and dynamic monitoring of diseases [58].

2.1.1. Targeted detection

AIE materials excel in targeted detection, particularly for biomarkers related to urinary system diseases, such as bacteria, inflammatory factors, metabolites, and abnormal proteins, enabling accurate and efficient diagnosis [59]. For example, acute kidney injury (AKI), a progressive renal dysfunction caused by infections, drug toxicity, or ischemia, can be detected using AIE-based probes. Zhang *et al.* developed a supramolecular fluorescent probe for ultrasensitive detection of ferricyanide, a marker for AKI, allowing cell imaging and early clinical identification [60]. Traditional markers like serum creatinine have a significant lag, delaying early diagnosis. In contrast, AIE materials can target early biomarkers of AKI, such as Kidney Injury Molecule-1 (KIM-1) and Neutrophil Gelatinase-Associated Lipocalin (NGAL), improving diagnostic sensitivity [61]. AIE probes also bind to enzymes released after tubular injury (e.g., lactate dehydrogenase), providing high-resolution fluorescence imaging to visualize renal pathology and support early intervention [62]. In addition, AIE probes are valuable for detecting kidney stones, which are composed of calcium oxalate, calcium phosphate, uric acid, and other compounds [63]. By designing probes that specifically bind to oxalate ions, calcium ions, or uric acid crystals, rapid detection of abnormal urine components is possible [59]. Upon binding to these targets, AIE probes aggregate and emit enhanced fluorescence, enabling doctors to identify stone composition and personalize treatment [64]. This approach also facilitates dynamic monitoring of urine composition, evaluation of treatment efficacy, and prevention of stone recurrence [65].

2.1.2. Non-invasive detection

Non-invasive detection using body fluids such as urine and blood can assist in disease diagnosis while effectively reducing the need for invasive procedures and radiation-based examinations, thus offering patients a safer and more comfortable diagnostic experience [66]. AIE probes, with their high sensitivity and specificity, are particularly well-suited for detecting disease biomarkers, including those related to urinary system disorders [67]. Urine, produced by the kidneys and excreted through the ureters and bladder, reflects the function and condition of these organs. AIE probes can selectively bind to specific molecules in urine, such as proteins, inflammatory factors, or abnormal metabolites, and generate strong fluorescence signals [68]. For example, Yang *et al.* developed an AIE probe capable of identifying 20 types of bacteria associated with urinary tract infections within 30 seconds, enabling quantitative detection of mixed bacterial populations and significantly improving diagnostic efficiency [69]. In addition, AIE probes can detect specific proteins and inflammatory markers in urine, making them suitable for the diagnosis and monitoring of chronic kidney disease and acute kidney injury [59].

Moreover, AIE probes can be applied to blood samples, where they detect specific proteins or inflammatory mediators indicative of kidney dysfunction [70]. In summary, AIE probes offer distinct advantages in non-invasive diagnostics and hold great promise for widespread application in the detection of urinary system diseases due to their excellent sensitivity and specificity.

2.1.3. Enhanced detection sensitivity

AIE materials, with their high quantum yield and fluorescence properties in the aggregated state, are particularly effective in detecting low concentrations of biomarkers, making them ideal for early screening and diagnosis of urinary system diseases [11]. In the early stages of disease, biomarker concentrations are often too low for traditional methods, which struggle with weak signals and background interference. AIE materials overcome these challenges by specifically binding to target molecules, aggregating, and generating intense, stable fluorescence signals that amplify detection and reduce false negatives [71]. For example, in urine tests, AIE probes can detect trace levels of inflammatory factors or proteins, providing highly sensitive disease detection through enhanced fluorescence signals [72]. Similarly, in blood samples, AIE probes can detect low-concentration biomarkers of kidney dysfunction, such as KIM-1 or β2-microglobulin, offering clear and reliable signal feedback [58]. This fluorescence enhancement compensates for the limitations of traditional methods, allowing AIE materials to detect subtle early-stage pathological changes, providing crucial support for timely diagnosis [73].

2.2. AIE in the treatment of urinary system diseases

AIE materials offer significant promise not only in diagnosing urinary system diseases but also in their therapeutic applications [40,65]. With their unique optical properties—such as high fluorescence intensity, excellent biocompatibility, and responsiveness to environmental changes—AIE materials are gaining attention in various therapeutic fields [10]. Their ability to precisely target lesions, minimize side effects, and enhance treatment efficacy makes them an attractive option for treating urinary system diseases [74].

2.2.1. Targeted drug delivery

AIE materials can be applied in the construction of self-indicating drug delivery systems, which exhibit fluorescence changes when the delivery system disassembles or undergoes specific reactions to release drugs under certain conditions. By monitoring these fluorescence changes, the spatiotemporal release of drugs can be visualized in real time [44,50,75]. In urinary system infectious diseases, AIE probes enable real-time bacterial detection and, when used in combination with antibiotics or antimicrobial peptides, can track and monitor the therapeutic effects of targeted drugs [76–77]. Furthermore, Tan *et al.* designed and synthesized AIE probes for monitoring the progression of drug-induced acute kidney injury and diabetic chronic kidney disease-related renal dysfunction, offering a novel strategy for disease assessment and monitoring [78].

2.2.2. Inflammation modulation

Inflammation is central to the progression of various urinary system diseases, including chronic kidney disease, acute kidney injury, and UTIs. AIE materials, with their ability to respond to environmental changes, can effectively modulate inflammation by targeting specific disease sites. By incorporating anti-inflammatory drugs into AIE materials, drugs can be released directly at the site of inflammation, reducing inflammation and promoting tissue repair [79]. For instance, AIE materials can be designed to release anti-inflammatory agents in response to biomarkers specific to UTIs or chronic kidney disease. This targeted release minimizes unnecessary drug activation, reduces side effects, and enhances treatment precision [80]. Additionally, AIE materials can regulate the release of cytokines or chemokines, helping suppress inflammation and preventing complications like fibrosis or permanent kidney damage [81].

2.2.3. Enhancing renal tissue regeneration

AIE materials hold promise for enhancing tissue regeneration, particularly in cases of AKI. These materials can stimulate kidney regeneration pathways, promoting cell proliferation and tissue repair at the injury site, while reducing scarring. By supporting tissue regeneration, AIE materials help restore kidney function and prevent long-term complications associated with AKI and chronic kidney disease. Their non-toxic, biocompatible nature ensures they do not cause additional harm to the kidneys or other organs during treatment [58–59,82].

2.3. Other potential applications of AIE in the treatment of urinary system diseases

As AIE materials continue to advance in the biomedical field, their potential for treating urinary system diseases is becoming more evident. This section explores the applications of AIE in biomarker monitoring, kidney disease management, and other emerging areas [83].

2.3.1. Biomarker monitoring

Biomarker monitoring is essential for diagnosing and managing urinary system diseases, particularly in chronic conditions and early diagnosis. AIE materials, with their high quantum yield and significant fluorescence enhancement in the aggregated state, are ideal for real-time monitoring of biomarkers related to kidney damage or UTIs, making them valuable for tracking disease progression and treatment efficacy. In cases of AKI or CKD, urine often contains biomarkers like KIM-1 and NGAL. Traditional methods struggle to detect these biomarkers, especially in the early stages when their concentrations are low and background interference is a concern. AIE materials, however, can specifically bind to these biomarkers, amplify the signals, and improve sensitivity, enabling early detection of kidney damage and continuous monitoring of disease progression [84]. Furthermore, AIE probes can track the effects of drug treatments in real time, helping clinicians adjust therapeutic strategies. For chronic kidney disease patients, AIE materials can monitor inflammatory factors or kidney function markers in urine, providing valuable insights into treatment outcomes and guiding personalized therapies [85].

2.3.2. Auxiliary treatment for kidney diseases

AIE materials, with their strong fluorescence properties, hold broad application prospects in early disease diagnosis and therapeutic monitoring. In urinary system diseases, AIE-based drug delivery systems can be visualized to monitor their distribution, enabling timely adjustments of dosage and administration schedules. Moreover, AIE probes can detect specific proteins, inflammatory factors, or molecular markers in blood or urine, providing critical information to assess renal function changes and therapeutic efficacy. For example, Tang *et al.* developed biomimetic AIE-active dextran particles for immune monitoring of solid organ transplantation, offering potential for monitoring rejection in kidney transplantation [86]. In summary, the application of AIE materials in the urinary system shows great promise in biomarker detection, *in vivo* and *in vitro* fluorescence imaging, as well as in combination therapies such as phototherapy and synergistic treatments [59].

2.3.3. Drug development and treatment optimization

The utilization of AIE materials in drug development and the optimization of therapeutic strategies remains to be further improved. As drug carriers or probes, they assist in developing new drugs, screening effective compounds, and evaluating efficacy and safety in kidney systems [87]. By combining AIE materials with specific drugs, researchers can track drug distribution, metabolism, and excretion, accelerating drug development and optimizing treatment plans. In kidney disease treatment, the non-invasive nature of AIE materials ensures targeted delivery, maximizing therapeutic effects while minimizing damage to healthy tissues [59].

2.3.4. Clinical prognosis monitoring and disease management

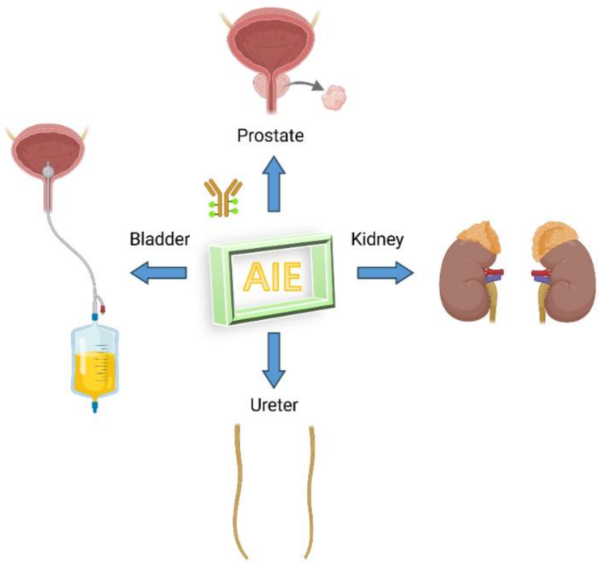

Figure 5. This illustration highlights the applications of AIE materials in the diagnosis and therapy of urinary system diseases, focusing on organs such as the kidneys, ureters, bladder, and prostate. Key advancements include tumor marker detection, renal fibrosis diagnosis, ureter imaging, and therapy for renal injury.

AIE materials hold significant potential for clinical prognosis monitoring and disease management. By tracking biomarkers and trends in renal function using AIE probes, clinicians can gain deeper insights into patients' responses to therapy and disease progression, thereby helping to optimize management strategies. For patients with chronic kidney disease, AIE materials can detect early signs of disease deterioration, enabling the development of targeted treatment plans to slow disease progression. Additionally, AIE materials play a crucial role in monitoring disease recurrence and guiding timely interventions [56].

Overall, Figure 5 illustrates the applications of AIE materials in the diagnosis and treatment of urinary system diseases, covering major organs such as the kidneys, ureters, bladder, and prostate. Key advances in this field include tumor marker detection, renal fibrosis diagnosis, ureter imaging, and kidney injury treatment. The superior performance of AIE materials in various urinary system disorders highlights their tremendous potential in early diagnosis, precise targeted therapy, and personalized treatment for urinary system diseases.

3. Applications of AIE in urological cancers

The application of AIE materials in urological cancers demonstrates their broad potential [88]. Due to their unique fluorescent properties and aggregation-induced emission enhancement, AIE materials have become effective diagnostic tools and therapeutic agents for various cancers, including bladder cancer, renal cancer, and prostate cancer. In terms of cancer diagnosis, AIE materials enable precise and non-invasive detection by targeting specific biomarkers in urine or blood samples, allowing for accurate visualization. In the field of cancer therapy, AIE materials contribute to photodynamic therapy and targeted drug delivery, enhancing therapeutic efficacy while minimizing damage to surrounding healthy tissues. In summary, AIE materials provide powerful support for the precise diagnosis and controlled treatment of urinary system cancers (Figure 6) [26,40].

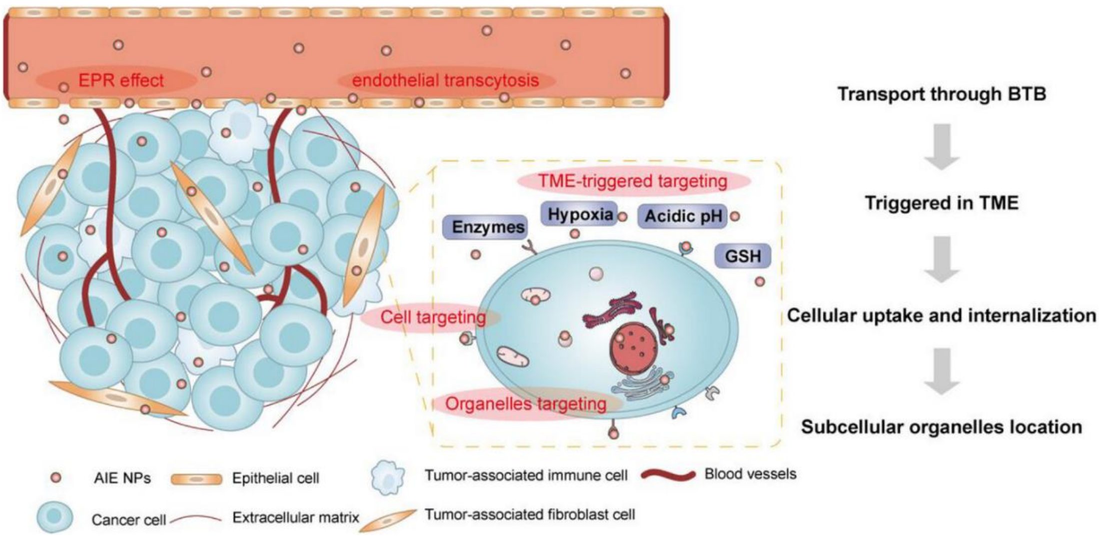

Figure 6. In vivo cancer-targeting strategies of AIEgen contain four parts: first, they pass through the blood–tumor barrier (BTB) to transport into tumors by enhanced permeability and retention (EPR) effect or endothelial transcytosis; then, they are activated in the tumor extracellular microenvironment; or they interact with the noncancer cells (stromal cells) or cancer cells and internalized by active targeting; finally, they are effectively localized on the subcellular organelles due to specific ligands. Reprinted with permission [26]. Copyright 2025, Aggregate.

3.1. Bladder cancer

AIE materials show significant potential in the diagnosis and treatment of bladder cancer [26]. Ding *et al.* developed a photo-enhanced cancer chemotherapy (PECC) strategy based on AIE molecules to address the dose-dependent toxic side effects of cisplatin-based neoadjuvant chemotherapy (NAC) in bladder cancer treatment. They designed BITT@BSA–DSP nanoparticles, which use albumin as a carrier, are functionalized with a cisplatin (IV) prodrug, and are loaded with the AIE molecule BITT. These nanoparticles exhibit near-infrared fluorescence imaging (NIR FLI) capabilities and support photodynamic and photothermal therapy. The nanoparticles can be efficiently taken up by bladder cancer cells, releasing Pt (II) in a reductive environment to enhance the chemotherapy effect, while the photo-enhancement synergistically improves the sensitivity of cisplatin chemotherapy and significantly reduces toxic side effects. In diagnostics, AIE materials, as fluorescent imaging probes, can target specific biomarkers on the surface of bladder cancer cells, significantly enhancing fluorescence signals, and improving the sensitivity and accuracy of early diagnosis [89–90]. Compared to traditional methods, AIE probes offer high sensitivity and selectivity, enabling rapid non-invasive screening through urine or cystoscopy and significantly reducing false positive and false negative results [67]. In therapy, AIE materials are widely used in PDT, where they generate reactive oxygen species under laser irradiation, effectively killing tumor cells and enhancing therapeutic outcomes. Zhang *et al.* developed a nano-vaccine (NM-7) based on a self-assembling organic small molecule with strong AIE properties, featuring a simple structure and well-defined functions. Acting as both an adjuvant and an antigen delivery carrier, NM-7 effectively induces robust antitumor $CD8^+$ T-cell immune responses and demonstrates significant synergistic therapeutic efficacy when combined with immune checkpoint blockade therapy [43]. Furthermore, AIE materials can assist in therapeutic fluorescence-guided procedures, enabling real-time fluorescence feedback that helps doctors precisely monitor tumor treatment progress, ensuring optimal therapeutic benefits [26]. These applications make AIE materials highly promising for the early diagnosis and precision treatment of bladder cancer.

3.2. Renal cancer

At the diagnostic level, AIE materials can target renal cancer cells by enhancing fluorescence signals, thereby improving the sensitivity and accuracy of early renal cancer detection. With their high brightness and excellent stability, AIE probes are well-suited for non-invasive detection using urine or blood samples, facilitating early screening of renal cancer and reducing both false-positive and false-negative results. At the therapeutic level, AIE materials can generate abundant singlet oxygen within tumor regions during photodynamic therapy, and the resulting reactive oxygen species effectively kill cancer cells, thus enhancing treatment efficacy. Moreover, AIE materials can serve as targeted drug delivery systems, increasing drug concentration specifically at tumor sites, minimizing damage to healthy tissues, and further improving therapeutic outcomes as well as patient compliance [91]. Therefore, AIE materials are widely applicable for the early diagnosis and precise treatment of renal cancer.

3.3. Prostate cancer

In the early diagnosis of prostate cancer, AIE materials enable the rapid detection of prostate-specific antigen (PSA), offering a novel paradigm for prostate cancer screening. Upon binding to PSA, AIE molecules enhance their fluorescence signals, thereby improving detection rates and facilitating early diagnosis of prostate cancer. Wang *et al.* reported a dual-function AIE-based strategy capable of simultaneously detecting prostate-specific membrane antigen (PSMA) and free PSA. This approach allows for the simultaneous evaluation of two biomarkers in living prostate cancer cells, providing a molecular-level tool for early screening and monitoring of prostate cancer [92]. Additionally, AIE materials can serve as contrast agents for magnetic resonance imaging (MRI) or ultrasound imaging, further improving imaging resolution and assisting clinicians in precisely localizing tumors and monitoring tumor growth [93]. In terms of prostate cancer therapy, photodynamic therapy (PDT) utilizing AIE molecules can induce strong green fluorescence signals and generate reactive oxygen species (ROS) upon aggregation within tumor cells, thereby enhancing treatment efficacy while precisely identifying cancer cells. Moreover, AIE-based materials have significant potential in drug delivery, enabling targeted release of chemotherapeutic agents, which ensures more precise dosing, minimizes drug uptake by healthy tissues, and improves the overall efficacy of chemotherapy [94]. In conclusion, AIE materials offer highly efficient and safer clinical solutions for the early diagnosis and precise treatment of prostate cancer.

3.4. Upper urinary tract cancer

AIE materials exhibit significant application potential in the diagnosis and treatment of upper urinary tract cancer. In diagnostics, AIE materials can be used for molecular imaging analysis of urine or tissue samples, where enhanced fluorescence signals help identify tumors at an early stage. AIE molecules target biomarkers specific to upper urinary tract cancer, providing high sensitivity and selectivity in imaging detection, thereby improving diagnostic accuracy, especially in the detection of early-stage and small lesions, where they show clear advantages. In therapy, AIE materials are widely applied in therapeutic imaging and combined with PDT. The aggregation-induced emission effect of AIE materials enhances the therapeutic effect of PDT by generating reactive oxygen species to accurately kill cancer cells. Additionally, AIE probes can detect small metastatic lesions in upper urinary tract cancer, assisting in assessing tumor spread, which improves the precision and effectiveness of clinical treatments [67]. Through these applications, AIE materials offer innovative solutions for the early diagnosis and precision treatment of upper urinary tract cancer.

4. Applications of AIE in other urological diseases

4.1. AIE in UTIs

As bacterial probes, AIE materials can utilize their aggregation-induced emission properties to real-time monitor infection sources, thereby improving diagnostic sensitivity and enhancing the accuracy of clinical assessments. Well-designed AIE molecules can specifically target bacterial surface biomarkers or antigens, and through selective binding to bacteria, generate strong fluorescence signals, providing an efficient and precise method for bacterial detection. Compared with traditional bacterial culture and conventional diagnostic methods, AIE materials offer higher speed and specificity in diagnosing UTIs, making them well-suited for rapid screening and early detection [69].

Moreover, AIE materials exhibit excellent biocompatibility, low toxicity, and *in vivo* stability, ensuring their safety in clinical diagnostics. These materials can be widely applied in urine sample analysis, and through fluorescence imaging, they enable rapid localization of infection sources, facilitating accurate diagnosis at the early stages of UTIs. This approach helps avoid false-negative or false-positive results that may occur with conventional methods. For dynamic monitoring of UTIs, AIE probes not only provide real-time feedback but also allow tracking of infection progression, assisting clinicians in evaluating treatment efficacy and adjusting therapeutic strategies. Therefore, AIE materials hold great potential as bacterial probes for UTIs diagnosis and monitoring, offering a promising application prospect in clinical practice [95].

4.2. AIE in renal pathology

AIE materials demonstrate remarkable potential in the diagnosis and monitoring of renal pathology, particularly in the early diagnosis of chronic kidney disease. As fluorescent probes, AIE molecules offer high-sensitivity detection methods. By targeting biomarkers related to kidney damage, AIE molecules can produce significant fluorescence signals at the early stages of renal pathology, assisting doctors in making accurate diagnoses at the disease’s onset and preventing further deterioration. Compared to traditional renal function tests, AIE probes are capable of effectively monitoring pathological changes at lower concentrations, offering higher sensitivity and selectivity [59].

Renal dysfunction can be detected using AIE-based markers. By measuring the fluorescence signals of AIE materials in urine samples, rapid and non-invasive assessment of renal function changes can be achieved. The presence and intensity of AIE-labeled markers in urine are closely correlated with the degree of kidney injury, serving as reliable indicators of renal health. This approach not only facilitates early detection of kidney pathology but also allows dynamic monitoring of renal function throughout the treatment process, enabling real-time evaluation of therapeutic outcomes. Therefore, the application of AIE materials in renal pathology provides groundbreaking and innovative support for the early diagnosis, disease monitoring, and efficacy evaluation of chronic kidney disease [96].

5. AIE in urological system imaging

AIE materials have shown significant potential in the imaging of the urological system, particularly in the early diagnosis and precise treatment of diseases. As fluorescence imaging probes, AIE materials, with their excellent fluorescence properties, provide high-sensitivity and high-resolution imaging support for detecting urological system diseases [97].

5.1. AIE materials as fluorescence imaging probes

5.1.1. High-sensitivity detection of urological system diseases using AIE fluorescence properties

AIE materials exhibit significantly enhanced fluorescence emission in their aggregated state, providing high sensitivity for detection in urine and tumor tissues. Through rational design, AIE materials can target specific biomarkers at the early stages of diseases such as UTIs, urinary system tumors, and kidney injuries.

Moreover, even at low concentrations, AIE materials are capable of generating strong fluorescence signals, making them an excellent tool for early disease screening. Compared to traditional fluorescent probes, AIE materials offer superior stability, showing great potential in biological imaging applications [71].

For future clinical applications, well-designed AIE materials may be used for the early detection of urinary system tumors, including urothelial carcinoma and bladder cancer. These probes can accurately localize tumor cells and micro-lesions, playing a crucial role in early diagnosis and timely treatment. Additionally, engineered AIE nanoprobes can reduce false-positive and false-negative results, thereby improving diagnostic accuracy and reducing misdiagnosis rates [67].

5.1.2. Enhancing imaging resolution of urine components and tumor microenvironment

AIE materials can effectively enhance imaging performance in target tissues and tumor regions. In urine analysis, AIE materials enable real-time detection of bacteria, proteins, and other biomarkers in urine, contributing to the early diagnosis of diseases such as UTIs and kidney injury [22]. For urinary system tumor imaging, AIE materials can target specific molecules on the surface of tumor cells, thereby improving clinicians' ability to accurately identify tumor regions and ultimately enhancing patients' quality of life [98].

The tunability of AIE materials allows them to perform excellently in various imaging modes (such as fluorescence imaging and confocal microscopy), further improving imaging resolution and contrast [11]. This makes early detection of lesions more precise. As fluorescence imaging probes, AIE materials offer significant advantages in the diagnosis of urological diseases. Their unique fluorescence properties and high selectivity enable high-sensitivity detection and significantly enhance the imaging resolution of urine components and tumor microenvironments, providing strong support for early detection and precise treatment of urological system diseases.

5.2. Combination of AIE with other imaging techniques

AIE materials, when combined with traditional diagnostic and therapeutic approaches, can complement conventional methods in urinary system imaging. In clinical practice, single-modality imaging techniques often have inherent limitations, such as insufficient imaging depth, low resolution, and inability to provide multidimensional diagnostic information. To overcome these challenges, integrating AIE materials with other imaging technologies can significantly enhance imaging performance and offer more comprehensive and precise diagnostic information [97].

5.2.1. AIE combined with computed tomography (CT)

CT is a widely used imaging technique in medical diagnostics; however, CT imaging often lacks molecular-level detail and cannot provide cellular or molecular-specific information. Combining AIE materials with CT imaging can overcome this limitation by adding molecular-level targeting capability, showing great promise for applications in urinary system diseases. AIE materials can selectively target specific cells or tissues *in vivo*, offering molecular-level labeling, while CT scanning provides comprehensive structural and anatomical information. CT offers high-resolution images, and Dai *et al.* have designed AIE probes that leverage their aggregation-induced optical properties for precise surgical navigation. This approach effectively addresses the shortcomings of traditional fluorescent probes, such as poor imaging quality, low targeting efficiency, and high false-positive rates. By integrating anatomical and molecular imaging modalities, this strategy offers a more comprehensive solution for the early detection and precise treatment of urinary system diseases [25].

5.2.2. AIE combined with magnetic resonance imaging (MRI)

MRI is an important imaging technique for the diagnosis of urinary system diseases, offering excellent soft tissue resolution and deep tissue imaging capabilities. However, MRI imaging may exhibit limited sensitivity in certain cases. Combining AIE materials with MRI can effectively overcome this limitation. When AIE materials are integrated with MRI, they enable simultaneous fluorescent labeling of tumors or target tissues during MRI-based assessment. Duo *et al.* successfully combined molecular-level fluorescence imaging provided by AIE probes with the high-resolution structural imaging of MRI, achieving more precise disease diagnosis and monitoring. This strategy holds great potential for the early screening and treatment of urinary system tumors, as well as for other clinical applications [58,99].

5.2.3. AIE combined with ultrasound

Ultrasound imaging is a non-invasive, easy-to-operate, and real-time imaging technique that is widely used in clinical practice. However, the resolution of ultrasound imaging is relatively limited, making it challenging to accurately detect small lesions or tumor regions. Combining AIE materials with ultrasound imaging can effectively enhance imaging quality. Shen *et al.* demonstrated that AIE materials can exhibit controllable fluorescence responses triggered by ultrasound, revealing the tunable properties of AIE materials under ultrasound stimulation and offering new insights for the design and application of novel soft materials. The real-time imaging capability of ultrasound, when combined with AIE materials, can significantly improve the detection rate of pathological lesions, showing great potential for early screening of UTIs and bladder cancer detection [100].

5.2.4. Application and prospects of multimodal imaging

Combining AIE materials with imaging techniques such as CT, MRI, and ultrasound can effectively overcome the limitations of single-modality imaging. Multimodal imaging approaches provide more comprehensive and efficient diagnostic strategies, significantly improving imaging quality and enabling multi-scale and all-around assessments of urinary system diseases. For example, in the diagnosis of renal diseases, the integration of AIE materials with MRI allows for the precise localization of renal lesions and reveals their molecular characteristics. Meanwhile, combining AIE materials with CT or ultrasound facilitates tumor visualization, enabling early detection and the development of personalized treatment plans. This multimodal imaging strategy offers strong support for early screening, precise diagnosis, and therapeutic evaluation of urinary system diseases, demonstrating the enormous potential of AIE materials in medical imaging. Thus, AIE-based multimodal imaging holds promising prospects for future medical diagnostics and personalized therapy.

6. AIE in drug delivery improvement for the urinary system

6.1. Potential of AIE materials in targeted drug delivery

AIE molecules, as drug carriers, are particularly important in the treatment of urinary system diseases. The enhanced fluorescence properties exhibited by AIE molecules in the aggregated state provide them with a unique advantage in drug delivery. By associating with drugs, AIE molecules can effectively deliver anticancer drugs, antibiotics, and other therapeutics to targeted sites, particularly in the treatment of urinary system cancers such as bladder cancer, kidney cancer, and prostate cancer. AIE materials can precisely target tumor cells, enhancing the therapeutic effect of the drug. This characteristic not only increases the concentration of drugs at the diseased site but also reduces the impact on normal tissues, thereby alleviating side effects [75].

AIE materials can visualize the spatiotemporal release of drugs by monitoring fluorescence changes [44]. This capability ensures the efficient release of therapeutic agents at tumor sites, thereby enhancing anticancer treatment efficacy and enabling real-time visualization of the therapeutic process. Such visualization offers direct feedback for clinical treatments, allowing physicians to adjust drug dosage and treatment strategies in a timely manner, ultimately ensuring both the efficacy and biosafety of drug delivery.

6.2. Drug release triggered by AIE molecules in response to physiological changes

AIE materials, when loaded onto responsive carriers, enable controlled drug release in response to specific physiological conditions [11]. This makes AIE materials ideal candidates for smart drug delivery systems. In the treatment of urinary system diseases, the local microenvironment at diseased sites often differs from that of normal tissues—for example, the acidic environment of tumor tissues or temperature changes at infection sites can alter local conditions. AIE materials can precisely trigger drug release in response to these environmental changes [101].

In cancer therapy, AIE materials can respond to pH variations in the tumor microenvironment, leading to structural disassembly and targeted drug release. Such AIE-based smart drug delivery systems not only enhance therapeutic efficacy but also significantly reduce side effects by ensuring that drugs are released only at specific sites, thus avoiding systemic distribution and unwanted adverse reactions [5]. These functional AIE drug carriers show great potential for targeted therapy of urinary system diseases, particularly in treating kidney diseases, UTIs, and urinary system tumors. This approach improves the precision of urinary system disease treatment, thereby enhancing therapeutic outcomes and patient quality of life.

7. Challenges and prospects of AIE materials

7.1. Stability and biocompatibility

Although AIE materials hold great potential in the diagnosis and treatment of urinary system diseases, challenges regarding their stability and biocompatibility remain to be addressed. The *in vivo* stability of AIE materials is crucial for maintaining their optimal performance over an extended period, especially in drug delivery and imaging applications, where sustained high-efficiency fluorescence emission and aggregation behavior are essential. However, many AIE materials may degrade or aggregate in complex physiological environments, leading to a reduction in fluorescence intensity and potentially compromising clinical therapeutic outcomes [102]. Therefore, enhancing the stability of AIE materials in biological systems and prolonging their retention time at tumor sites are key focuses of current research.

In addition, biocompatibility is another critical issue. While AIE materials generally exhibit good biocompatibility, their long-term presence in the body may still trigger immune responses or cytotoxic effects [10]. To ensure their safety, it is necessary to thoroughly investigate the metabolic pathways, potential immunogenicity, and *in vivo* cytotoxicity of AIE materials. Moreover, structural optimization of AIE materials is essential to improve their compatibility with biological systems and clinical applications. In summary, enhancing both the stability and biocompatibility of AIE materials is a crucial prerequisite for advancing their clinical translation.

7.2. Large-scale synthesis and clinical translation

One of the major obstacles to the clinical application of AIE materials is their high synthesis cost and difficulty in large-scale production. Currently, the synthesis of most AIE materials requires relatively complex reactions and expensive raw materials, which inevitably limits their widespread use in clinical settings. Given the growing demand for AIE materials in clinical diagnostics and therapeutics, the development of efficient and cost-effective synthetic processes is essential to meet the needs of large-scale production. In addition, to ensure stability and consistency during large-scale manufacturing, issues such as material purity, yield, and reproducibility must be properly addressed [103]. In recent years, progress has been made through structural modifications and surface functionalization of AIE materials, as well as the development of green synthesis methods, which not only improve biocompatibility but also enhance the potential for scalable production.

In terms of clinical translation, regulatory and safety issues related to AIE materials must be addressed. The use of AIE-based drug delivery systems and imaging probes must undergo rigorous drug approval processes and comply with the regulatory requirements of various national authorities. This includes toxicological evaluations, long-term safety studies, and the accumulation of extensive clinical trial data. As the clinical application of AIE materials is still in its early stages, standardized operational protocols remain underdeveloped. Therefore, it is essential for regulatory bodies to establish comprehensive clinical application standards specifically for AIE materials, in order to accelerate their clinical translation [104].

7.3. Future directions

The future development of AIE materials will focus on several key areas. First, the customized design of novel AIE molecules and innovative strategies will play a fundamental role in enhancing the specificity and targeting capabilities of AIE materials. By precisely engineering the chemical structures of AIE molecules, they can be tailored as probes for different diseases, thereby improving the accuracy of diagnosis and therapy. In addition, the exploration of targeted drug delivery systems for specific cells or tumors can be complementary to AIE materials, creating a synergistic effect that combines the strengths of both approaches. This integrated strategy will further advance the application of AIE materials in precision medicine.

Second, integrating nanotechnology and smart materials will further enhance the application of AIE materials in disease diagnosis and therapy. Nanotechnology can endow AIE materials with numerous new functionalities, such as improved tissue penetration, targeting capability, and *in vivo* metabolic behavior. Nano-carriers can encapsulate larger amounts of therapeutic agents and release them in response to specific external stimuli, thereby improving the efficiency of drug delivery and therapeutic outcomes. Moreover, when combined with controlled drug release, AIE materials can contribute to building more precise and personalized therapeutic systems, enabling the dynamic adjustment of drug release rates to optimize treatment processes. In the future, AIE materials are expected to become essential tools for medical imaging and precision therapy, offering strong support for the early screening, diagnosis, treatment, and personalized management of urinary system diseases.

8. Conclusion

In conclusion, AIE materials demonstrate tremendous potential in the diagnosis and treatment of urinary system diseases, yet they still face challenges related to stability, biocompatibility, synthesis cost, and clinical translation. Through customized molecular design, integration with nanotechnology, and advanced surface modification strategies, AIE materials are expected to achieve precise and visualized diagnosis and therapy for urinary system diseases in the future. These advancements will promote their widespread application in the medical field, provide strong support for targeted drug delivery and early disease detection, and offer critical contributions to precision medicine and personalized therapy.

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Conflicts of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors’ contribution

Conceptualization, Xiangqian Cao and Bing Shen; methodology, Xiangqian Cao and Yilin Yan; validation, Xiangqian Cao, Yilin Yan, and Xinyi Zhu; writing—original draft preparation, Xinyi Zhu; writing—review and editing, Xiangqian Cao, Xiaodong Zhu, and Bing Shen; resources, Weiguang Zhao; data curation, Haoyuan Wang; visualization, Haoyuan Wang; supervision, Bing Shen; project administration, Xiangqian Cao; funding acquisition, Xiaodong Zhu and Bing Shen. All authors have read and agreed to the published version of the manuscript.

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