

Review

Atomically Precise Gold Nanoclusters in Electrochemiluminescence: Fundamentals, Modulation Strategies, and Applications

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Abstract: Atomically Precise Gold Nanoclusters (AP-AuNCs) have emerged as cutting-edge nanomaterials in the electrochemiluminescence (ECL) realm due to their atomically precise structures, quantum confinement effect, and superior biocompatibility. This review systematically summarizes the recent advancements of AP-AuNCs in ECL. First, the fundamental ECL mechanisms are elucidated from a molecular orbital perspective, rooted in the “core-ligand shell” hierarchical structure and superatomic electronic nature of AP-AuNCs. Subsequently, precision modulation strategies for tuning their ECL performances, such as gold core structural regulation, bimetallic doping, ligand engineering, valence state engineering, aggregation-induced ECL, and system energy level matching, are comprehensively presented. Furthermore, the current application landscape in biomedicine, environmental monitoring, and food safety is evaluated. Finally, the future challenges and developmental prospects of this field are also discussed. This review aims to provide a systematic theoretical reference and innovative insights for the atomic-level design of high-performance AP-AuNCs-based ECL systems, facilitating their transitions toward practical application scenarios.

Keywords: atomically precise gold nanoclusters; electrochemiluminescence; modulation strategies; superatomic orbital theory

1. Introduction

Electrochemiluminescence (ECL) is a light emission phenomenon triggered by electrochemical reactions at an electrode surface [1]. Since 1929, it has evolved into a cornerstone of analytical chemistry, indispensable for biosensing, clinical diagnostics, and environmental monitoring because of near-zero background interference, exceptional sensitivity, and high spatiotemporal resolution [2,3]. For example, Hong et al. [4] reported a sensitive ECL-incorporated lateral flow immunosensor based on Ru(bpy)₃²⁺-labeled gold nanoparticles for biomarker C-reactive protein (CRP) levels in clinical serum samples. Wang’s group [5] developed a novel dual-potential ratiometric ECL sensor based on luminol and palladium nanoclusters for highly sensitive detection of carcinoembryonic antigen (CEA) in early cancer diagnosis. Cai et al. [6] constructed a dual-potential ECL biosensor based on Au@luminol and CdSe quantum dots (QDs) for simultaneous monitoring of Mn²⁺ and Cd²⁺ in PM_{2.5}. However, conventional ECL luminophore systems face intrinsic limitations that hinder further performance breakthroughs [7,8]. The classic Ru(bpy)₃²⁺ complex is constrained by its rigid molecular structure, which lacks emission wavelength tunability to limit its utility in multicolor and multiplexing assays; Luminol-based systems rely heavily on harsh co-reactants (e.g., H₂O₂), compromising their biocompatibility and resulting in transient, short-lived luminescence. Meanwhile, semiconductor QDs suffer from low ECL efficiency and biotoxicity risks



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posed by potential heavy metals [9]. The core challenge underlying these limitations is that traditional luminophores cannot be precisely engineered or systematically manipulated at the atomic level to optimize their electronic structures and excited-state properties.

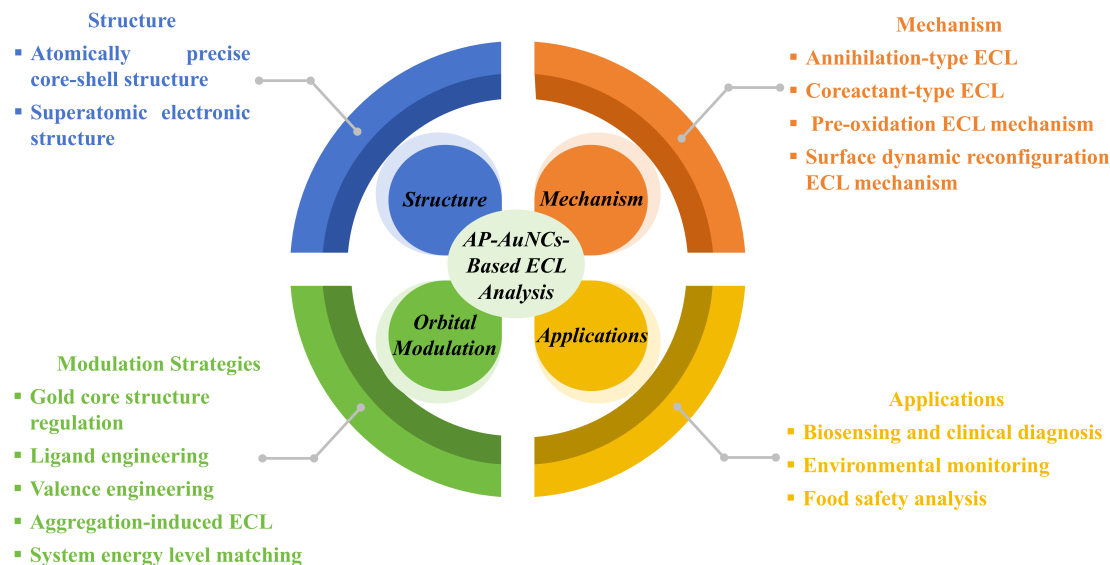
Atomically precise gold nanoclusters (AP-AuNCs) have emerged as a highly promising class of alternative nanoluminophores due to molecular-like nanostructures, atomic precision, robust optoelectronic properties, and excellent biocompatibility, which offers a paradigm shift for overcoming intrinsic bottlenecks of traditional ECL systems [10,11]. It should be noted that not all ultrasmall gold clusters can be classified as AP-AuNCs. In this review, AP-AuNCs specifically refer to gold clusters with atomically resolved compositions, well-defined molecular structures, and precisely determined ligand arrangements, typically including thiolate-protected clusters such as $\text{Au}_{25}(\text{SR})_{18}$, $\text{Au}_{38}(\text{SR})_{24}$, and related systems [11,12]. Although some molecular gold clusters with discrete electronic states may exhibit unique optical or ECL behaviors, they are not regarded as AP-AuNCs unless their atomic compositions and structures are unambiguously determined [11,13]. Such non-atomically precise gold clusters are therefore only discussed when they provide essential mechanistic insights into ECL processes and are clearly distinguished from AP-AuNC-based systems. Typically under 2 nm, AP-AuNCs represent a critical transitional regime between single-atom species and plasmonic gold nanoparticles [14]. In contrast to traditional, highly polydisperse gold nanomaterials with ill-defined configurations, AP-AuNCs possess well-defined chemical formulas, atomically sharp crystal structures, and discrete, quantized electronic energy levels [15]. Governed by the superatom orbital theory, their electronic structures display atom-like shell-filling configurations and exceptional chemical stability [16]. This intrinsic combination of atomic homogeneity and precisely tunable energy levels renders AP-AuNCs ideal model platforms for elucidating and manipulating ECL mechanisms at the molecular orbital level [17].

The study of AP-AuNCs-based ECL has become a vibrant frontier in nanoanalysis. In 2011, Zhu's group [18] first reported ECL emission from BSA-stabilized Au_{25} clusters, representing an early demonstration of gold cluster-based ECL sensing. Subsequently, Ding's group pioneered spooling ECL spectroscopy to map the size- and valence-dependent pathways of AP-AuNCs (e.g., Au_{25} , Au_{38} , and Au_{144}), proving that near-infrared (NIR) ECL originates from intra-cluster molecular excited-state transitions, providing a theoretical framework for regulating performance at the atomic level [19]. Concurrently, Wang et al. [20] proposed a covalent modification strategy that covalently attached the co-reactant to AuNCs' surface, enabling them to generate efficient NIR-ECL in aqueous systems and effectively addressing the incompatibility of organic-phase systems with biological applications. However, the intrinsically low ECL quantum yields remained a major obstacle. To address this issue, a variety of strategies (e.g., aggregation-induced emission (AIE), ligand engineering, etc.) have been developed [21,22]. Specifically, Guo's group [23] proposed a Zn^{2+} -mediated aggregation strategy that realized a 9-fold ECL enhancement in Zn^{2+} -DPA/MUA-capped AuNCs relative to their Zn-free counterparts. Nie et al. [24] reported a ligand-based shielding effect in β -cyclodextrin-protected AuNCs that stabilized co-reactant radicals and shortened the charge transfer pathway, thereby boosting near-infrared ECL efficiency by up to a 321-fold enhancement over conventional Au NCs, enabling highly sensitive detection of noradrenaline. These advances in ultrabright AP-AuNC emitters have recently promoted their applications from conventional sensing toward high-resolution ECL imaging. In 2025, Zhou et al. [25] pioneered the engineering of ultra-bright dual-ligand-capped AuNCs with intra-cluster hydrogen bonding, which enabled a near-zero-thickness ECL imaging of high-definition subcellular structures in single cells with a lateral resolution of 170 nm, successfully breaking the spatial resolution constraints of traditional ECL matrices.

Despite these remarkable advances, several challenges still limit the further translation of AP-AuNC-based ECL systems toward practical applications. Although substantial progress has been achieved in enhancing ECL efficiency, the quantum yields of most AP-AuNCs remain inferior to those of conventional ECL luminophores [7,26], highlighting the need for more effective regulation of excited-state processes. In addition, the atomically precise synthesis of AP-AuNCs requires stringent control over ligand coordination, metal precursor ratios, and reaction conditions, making reproducibility and large-scale preparation challenging [9,11]. Variations in cluster structures, surface states, and ligand environments can further influence their ECL properties [16,22]. Therefore, the development of facile, scalable, and highly reproducible synthesis approaches, together with deeper mechanistic understanding of excited-state regulation, is crucial for advancing AP-AuNC-based ECL systems toward real-world applications.

Over the past decade, significant progress has been made in AP-AuNC-based ECL research [27,28]. However, there remains a distinct gap in fundamental mechanistic understanding. Since most studies rely on steady-state measurements, the dynamic nature of excited-state relaxation and charge transfer remains ambiguous, which inherently limits molecular orbital modulation to empirical trials rather than rational design based on quantitative structure-activity relationships. In this review (Scheme 1), we focus on AP-AuNC systems with clear mechanisms, summarizing their precise ECL modulation strategies by interpreting the essence of their excited states from the

perspective of superatomic orbital theory. Additionally, representative applications across biomedicine, environmental monitoring, and food safety are also outlined. We hope this review could give profound theoretical guidance to future research on developing highly efficient AP-AuNCs-based ECL systems, ultimately overcoming current practical hurdles and broadening their advanced applications in the future.



Scheme 1. Schematic illustration of fundamentals, modulation strategies, and applications of AP-AuNCs-based ECL analysis.

2. Structures and Characteristics of AP-AuNCs

In contrast to plasmonic gold nanoparticles larger than 2 nm, AP-AuNCs consist of an exact number of ligand-protected gold atoms. Characterized by explicit atomic formulas, definitive crystal structures, and discrete electronic energy levels, AP-AuNCs effectively bridge the transition regime between single atoms and conventional nanomaterials [14]. These distinct molecule-like optoelectronic properties position them as pristine model platforms for unraveling the intrinsic nature of ECL processes at the molecular orbital scale.

2.1. Atomically Precise Core-Shell Structure of AP-AuNCs

Thiol-protected AP-AuNCs feature a characteristic hierarchical “core-ligand shell” architecture. The composition, valence states, and bonding characteristics of their structural units govern electron orbital distribution, which in turn dictates their ECL performance [29]. As a prototypical example, the highly stable $\text{Au}_{25}(\text{SR})_{18}^-$ NCs consists of a 13-atom icosahedral Au(0) core, encapsulated by six V-shaped “-S-Au-S-Au-S-” staple motifs. Each staple unit comprises two Au(+1) atoms and three thiol ligands, tethered to the core via terminal Au-Au metallic bonds. This hierarchy establishes a distinct valence gradient: the Au(0) core is maintained by metallic interactions, while the Au(+1) atoms in the staples form robust covalent Au-S bonds with the ligands. Beyond providing structural stability, these surface ligands modulate the electronic structure through both electronic and steric effects. The inherent modifiability of this core-shell framework offers versatile strategies for performance tuning. By manipulating the core atom count, tailoring the staple motifs, substituting ligands, or introducing heteroatom doping, the electronic orbitals can be precisely engineered at the atomic level, enabling the customization of ECL emission wavelengths and quantum yields [30].

2.2. Superatomic Electronic Structure of AP-AuNCs

When the dimensions of a metal cluster shrink below the Fermi wavelength of the bulk metal, valence electrons become confined within a restricted space. This triggers the quantum confinement effect, which causes the quasi-continuous energy bands to split into discrete, molecular-like energy levels. On this basis, the superatom theory elucidates the fundamental electronic structure of AP-AuNCs: valence electrons are no longer localized to individual atomic nuclei but instead populate delocalized, atom-like shell orbitals encompassing the entire cluster. According to this theory, when the total valence electron count reaches specific “magic numbers” (e.g., 2, 8, 18...), the NCs achieve a closed-shell electronic configuration, which confers exceptional chemical stability and unique photoelectric properties. A quintessential example is the $\text{Au}_{25}(\text{SR})_{18}^-$ NCs, which possesses 8 valence electrons.

This count is derived from the 13 core Au atoms ($13 e^-$) and 12 staple Au atoms ($12 e^-$), minus the electrons localized by the 18 thiol ligands ($18 e^-$), plus the single negative charge ($1 e^-$), which perfectly fill the $1S^21P^6$ superatomic shells, accounting for its status as one of the most robust AP-AuNCs identified to date [31].

2.3. Regulation Law of AP-AuNCs Structure on ECL Performance

Owing to their well-defined atomic compositions and precise structures, AP-AuNCs exhibit a rigorous quantitative structure-activity relationship between their electronic configurations and ECL performance. To date, a broad spectrum of AP-AuNCs, ranging from Au_{18} to Au_{144} , has been systematically investigated. These studies have elucidated fundamental regulatory mechanisms, revealing how the core atom count, structural isomerism, and interfacial alloying collectively dictate and optimize ECL properties.

2.3.1. Core Atomic Number

Generally, as the number of core atoms in a NCs increases, the energy level spacing of the superatomic orbitals gradually decreases, which results in an overall narrowing of the HOMO-LUMO gap to subsequently trigger a progressive red-shift of the ECL emission wavelength toward the near-infrared region [26]. Conversely, smaller NCs typically exhibit superior ECL efficiency. For instance, atomically precise $Au_{38}(SR)_{24}$ achieves a relative ECL quantum yield of up to 3.5 (relative to $Ru(bpy)_3^{2+}$) in the TPrA system, underscoring the exceptional luminescence performance inherent to these small-scale NCs [32].

2.3.2. Isomer Effect

Beyond atomic composition, the spatial arrangement of atoms (structural isomerism) exerts a profound influence on the electronic configurations and ECL performance of AP-AuNCs. Chen et al. [33] reported a pair of Au_{20} isomers. Despite sharing the same total number of gold atoms, their different core structures lead to distinct ECL performances, confirming that the gold core structure determines ECL properties of AP-AuNCs.

2.3.3. Alloying Effect

Doping heteroatoms (e.g., Ag, Sc, etc.) into the gold core to construct alloy NCs is another effective strategy for regulating electronic structures and ECL activities [34,35]. By perturbing the electron cloud distribution, shifting superatomic energy levels, and intensifying spin-orbit coupling, heteroatom incorporation can simultaneously optimize the emission wavelength and significantly enhance the ECL quantum yield. These synergistic effects allow for the precise atomic-level tuning of the NCs' radiative transition pathways.

In short, the hierarchical correlation among the core-shell structure, superatomic electronic configuration, and ECL parameters provides a rational pathway for atomic-level modulation of ECL performance. The number of core atoms determines the superatomic electron count and energy gap, enabling tunable ECL emission from the visible to near-infrared region [16,36,37]. Atomically precise clusters with closed-shell superatomic configurations and magic electron numbers exhibit well-defined electronic structures and enhanced stability, making them attractive ECL emitters [16,38]. Furthermore, ligand rigidification, surface defect passivation, and interfacial charge-transfer regulation can suppress nonradiative decay and improve ECL quantum efficiency [22].

3. ECL Mechanism of AP-AuNCs

The essence of electrochemiluminescence is an electron transfer process driven by electrochemical excitation. In this process, redox reactions at the electrode surface generate reactive intermediates, which subsequently undergo intermolecular electron transfer to form excited-state species and then relax back to the ground state via radiative transition [39]. Different from traditional semiconductor quantum dots and organic luminophores, the ECL process of AP-AuNCs originates from electron transfer between discrete molecular orbitals. Each electron transfer step can be precisely mapped to a specific structural unit and orbital energy level. This unique molecular-like nature establishes AP-AuNCs as a premier model system for elucidating the fundamental mechanisms of ECL at the atomic level. At present, the ECL mechanisms of AP-AuNCs are mainly categorized into the classic annihilation-type ECL and coreactant-type ECL, alongside recently discovered mechanisms such as pre-oxidation and aggregation-induced ECL.

3.1. Annihilation-Type ECL

Annihilation-type ECL involves the electrochemical generation of reactive species from AP-AuNCs through alternating potentials. By applying successive oxidation and reduction steps at the electrode surface, both cation and anion radicals are produced. These radicals then collide and undergo electron transfer (annihilation) to reach an excited state and relax to the ground state by emitting light. During the oxidation process, AP-AuNCs lose electrons from the surface staple orbitals (HOMO) to generate cation radicals (AP-AuNCs^{•+}). During the reduction process, AP-AuNCs gain electrons to fill the core superatomic orbitals (LUMO) to generate anion radicals (AP-AuNCs^{•-}). In the subsequent annihilation process, the HOMO holes of the cation radicals recombine with the LUMO electrons of the anion radicals to form excited states (AP-AuNCs*). Finally, the excited states return to the ground state through radiative transition, generating an ECL signal. The luminescence pathway is detailed in Equations (1)–(4):



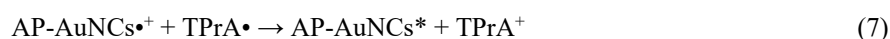
In 2012, Swanick et al. [40] first observed the annihilation-type ECL phenomenon in Au₂₅(SR)₁₈⁻ NCs, confirming that the resulting luminescence originates from the intrinsic molecular orbital transition of NCs. Annihilation-type ECL offers a “pure” signal, free from the complications of coreactants. This makes it an essential tool for both theoretical calculations and experimental validation, as it can be used to directly determine the redox potential, electron affinity, and orbital energy levels (HOMO-LUMO gap) of NCs. Although it has these advantages, its practical application is still limited. Due to the high overpotentials required and inherently low luminescence efficiency, annihilation-type ECL is currently utilized primarily for fundamental mechanistic research rather than analytical sensing.

3.2. Coreactant-Type ECL

Coreactant-type ECL involves the introduction of an auxiliary species (the coreactant) into the system. Upon applying a potential, the coreactant undergoes a redox reaction at the electrode surface to generate highly reactive, short-lived oxidizing or reducing intermediates. These intermediates subsequently engage in electron transfer with AP-AuNCs, producing an excited state that relaxes via light emission. According to the type of co-reactant, it can be divided into an anodic oxidation-reduction pathway and a cathodic reduction-oxidation pathway, and the electron transfer processes of both strictly follow the orbital law of “hole injection into HOMO and electron injection into LUMO”.

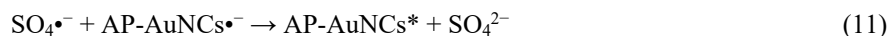
3.2.1. Anodic Oxidation-Reduction Pathway

Amine co-reactants represented by tripropylamine (TPrA) are oxidized at anodic potential to generate strong reducing intermediate TPrA[•], which undergoes electron transfer with oxidized AP-AuNCs to form excited states. This is the most mainstream pathway in the current research of AP-AuNCs ECL. The luminescence process is illustrated in Equations (5)–(8):



3.2.2. Cathodic Reduction-Oxidation Pathway

Peroxide co-reactants represented by potassium persulfate (K₂S₂O₈) are reduced at cathodic potential to generate a strong oxidizing intermediate SO₄^{•-}, which undergoes electron transfer with reduced AP-AuNCs to form excited states. The luminescence process is presented in Equations (9)–(12):



In 2014, Hesari et al. [32] first observed efficient co-reactant-type ECL in the $\text{Au}_{38}(\text{SR})_{24}/\text{TPrA}$ system, and found that its efficiency was more than 100 times that of annihilation-type ECL. Subsequently, this mechanism was proved to be universal in all AP-AuNCs systems, and became the basis for subsequent performance optimization and application development.

3.3. Pre-Oxidation ECL Mechanism

Pre-oxidation ECL is currently the most effective strategy for achieving high quantum yield in AP-AuNCs, a concept pioneered by Peng's team [41]. This mechanism involves the preliminary oxidation of AP-AuNCs into stable cations through chemical or electrochemical methods to effectively pre-inject "holes" into the HOMO orbitals. Consequently, the subsequent ECL process requires only a single-step electron injection into the LUMO orbitals to reach the excited state. By bypassing the need for simultaneous or alternating radical generation, this approach greatly improves electron transfer efficiency and minimizes energy loss. The pre-oxidation ECL process is shown in Equations (13)–(16):



Compared with traditional co-reactant-type ECL, pre-oxidation ECL avoids the repeated redox process of NCs on the electrode surface and reduces non-radiative transition channels, enabling an absolute ECL quantum yield of 66% for AP-AuNCs that surpasses the efficiency limits of conventional systems [41].

3.4. Surface Dynamic Reconfiguration-Mediated ECL Regulation

During the electrochemical reactions, the ligand shells of ligand-protected gold clusters may undergo dynamic rearrangement and ligand exchange, resulting in surface dynamic reconstruction processes. Such structural evolution can modify the atomic arrangement, oxidation states, and electronic distribution of surface Au-S motifs, thereby regulating HOMO energy levels, electron density, and charge injection efficiency. Recent studies have revealed that surface dynamic reconstruction can significantly influence ECL behavior by altering interfacial electron-transfer pathways. For example, Lei et al. reported that triethylamine (TEA) radicals induced reversible rearrangement of surface Au(I)-S bridging structures in molecular gold clusters without atomically resolved structures, enabling tunable ECL emission from the visible to near-infrared regions. Although this system is not classified as an AP-AuNCs, it provides valuable mechanistic insights into the influence of dynamic surface reconstruction on ECL processes [42]. For AP-AuNC-based ECL systems, understanding and controlling surface reconstruction processes remain highly valuable, as subtle changes in ligand arrangement and surface states may strongly affect ECL stability, reproducibility, and efficiency.

3.5. Correlation between Structural Features and Dominant ECL Pathways

Structural features of AP-AuNCs, including gold core size, ligand environment, and heteroatom alloying, play critical roles in determining their ECL pathways and ECL overall performance [11,26]. The gold core size governs the superatomic electron configuration and energy-level distribution, thereby influencing excited state generation and relaxation processes during ECL reactions [11,14]. Generally, small clusters with larger HOMO-LUMO gaps tend to exhibit ligand-centered or ligand-to-metal charge-transfer (LMCT) transitions, whereas larger clusters with narrower energy gaps are more favorable for metal-centered transitions and near-infrared ECL

emission [14,22]. Therefore, precise control of core size provides an effective strategy for regulating the dominant ECL pathway, emission wavelength, and ECL efficiency. The ligand environment also exerts a dual influence on ECL behavior. The electronic characteristics of ligands can modulate interfacial charge-transfer processes between AP-AuNCs and co-reactants, while ligand rigidity, hydrogen bonding interactions, and surface packing can restrict intramolecular motion and suppress nonradiative relaxation, thereby promoting radiative transitions and enhancing ECL efficiency [11,17,19]. Consequently, rational ligand engineering enables regulation of excited-state pathways, including ligand-centered, LMCT, and metal-centered transitions. In addition, heteroatom alloying provides another powerful approach for tuning the electronic structures and ECL properties of AP-AuNCs. Incorporation of heteroatoms (e.g., Ag, Cu, Pt) into the gold core can modify superatomic electron configurations, redistribute frontier molecular orbitals, and regulate redox potentials and charge-transfer kinetics [35,43,44]. These electronic modifications alter excited-state populations and ECL pathways, often leading to improved emission efficiency compared with their monometallic counterparts.

Overall, the ECL behavior of AP-AuNCs is intrinsically governed by the interplay between structural characteristics and electronic states. The gold core primarily determines the superatomic electronic configuration and excited-state energy landscape, the ligand environment regulates charge-transfer and relaxation processes, and heteroatom alloying fine-tunes orbital distributions and redox properties [11,43]. Together, these structural factors dictate the dominant ECL pathways and ultimately determine key performance parameters, including emission wavelength, intensity, and quantum yield. Establishing the structure-mechanism-performance relationship therefore provides an important theoretical framework for the rational design of high-performance AP-AuNC-based ECL systems.

3.6. Dynamic Mechanistic Understanding of AP-AuNC-Based ECL Revealed by In-Situ Characterization

Before elucidating the dynamic evolution of ECL processes, comprehensive characterization of AP-AuNCs is essential for establishing their intrinsic structural and electronic properties. Conventional static characterization techniques, including TEM/HRTEM, XRD, UV-Vis spectroscopy, FTIR, XPS, and electrochemical measurements (e.g., CV and EIS), provide fundamental information regarding cluster morphology, atomic arrangement, ligand coordination, surface electronic states, and interfacial charge-transfer properties. These structural and electronic parameters serve as the foundation for understanding the subsequent dynamic ECL behaviors of AP-AuNC-based systems (Table 1).

Table 1. Summary of characterization methods for correlating AP-AuNCs structures with ECL performance.

Category	Technique	Key Information Obtained	Structural/Electronic Insights for AP-AuNCs
Static characterization	TEM/HRTEM	Particle size, morphology, dispersion, lattice structure	Reveals ultrasmall cluster size, aggregation state, and structural integrity of AP-AuNCs; HRTEM provides direct evidence of nanocluster formation and crystallinity
	XRD	Crystal phase, lattice characteristics, crystallinity	Provides information on atomic packing, crystalline features, and structural stability of AP-AuNCs
	UV-Vis spectroscopy	Electronic transitions, absorption bands, energy-level information	Identifies molecular-like electronic structures, ligand-to-metal charge transfer (LMCT), metal-centered transitions, and superatomic states
	FTIR	Functional groups, ligand coordination, intermolecular interactions	Confirms surface functionalization and interactions that suppress nonradiative decay
	XPS	Elemental composition, oxidation states, electronic environment	Elucidates charge redistribution, metal-ligand interactions, and electron-transfer pathways
	CV/EIS	Redox behavior, electron-transfer kinetics, interfacial charge-transfer resistance	Reveals the efficiency of electron injection, co-reactant activation, and electrochemical processes governing ECL emission
Dynamic characterization	Time-resolved ECL	Excited-state lifetime, transient emission behavior	Reveals short-lived intermediates, excited-state evolution, and dynamic electron-transfer processes in ECL emission
	<i>In-Situ</i> XPS	Real-time electronic structure evolution during electrochemical reactions	Monitors surface reconstruction, oxidation-state changes, and charge redistribution under ECL conditions
	ECL imaging	Spatial emission distribution, local ECL activity	Visualizes ECL emission uniformity, electrode interface behavior, and nanoscale luminescence distribution

Notes: XRD: X-ray diffraction; FTIR: Fourier-transform infrared spectroscopy; XPS: X-ray photoelectron spectroscopy; CV: Cyclic voltammetry; EIS: Electrochemical impedance spectroscopy.

Conventional ECL investigations of AP-AuNCs have predominantly relied on steady-state electrochemical and spectroscopic measurements, which provide valuable information on emission intensity, wavelength, and overall electrochemical behavior. However, these approaches are insufficient for directly resolving transient excited-state evolution, short-lived charge-transfer intermediates, and dynamic reconstruction of surface structural dynamics during ECL reactions. Recent advances in *in-situ* and time-resolved characterization techniques (such as time-resolved ECL, spooling ECL spectroscopy, *in-situ* XPS) have therefore opened new avenues for deciphering the dynamic mechanisms underlying AP-AuNC-based ECL processes. For example, Ding and co-workers developed spooling ECL spectroscopy to directly correlate ECL emission dynamics with the electronic structures of AP-AuNCs (e.g., Au₂₅(SR)₁₈, Au₃₈(SR)₂₄, Au₁₄₄(SR)₆₀, Au₂₁(SR)₁₅), which revealed size-dependent excited-state pathways and demonstrated that NIR-ECL originates from intra-cluster excited-state transitions [26,45,46]. In addition, time-resolved ECL studies have demonstrated that transient intermediates generated during electrochemical excitation play critical roles in determining excited-state formation and emission efficiency [33,35,54]. Peng et al. [41] employed time-resolved ECL measurements to investigate the dynamic evolution of Met-AuNC-based ECL during electrochemical oxidation. They found that repeated potential cycling induced accumulation of oxidized Au species, which modulated the electronic structure of clusters and facilitated interfacial charge injection, thereby promoting excited-state generation. Based on this mechanistic understanding, an electrochemical pre-oxidation strategy was developed to construct Ox-Met-AuNCs, resulting in a 25-fold enhancement in ECL intensity compared with pristine Met-AuNCs and achieving an ECL efficiency of 66% relative to the annihilation-type Ru(bpy)₃²⁺ system. Furthermore, complementary *in-situ* XPS and other surface-sensitive spectroscopic techniques have provided unprecedented insights into the real-time evolution of metal oxidation states, metal-ligand coordination environments, and surface electronic structures under electrochemical stimulation [8,47]. These dynamic analyses enable direct observation of interfacial electronic reconstruction and reaction intermediates that are inaccessible through conventional ex situ characterization. Collectively, the integration of static structural characterization with advanced dynamic characterization strategies establishes a comprehensive structure-property-mechanism relationship, providing deeper mechanistic understanding and guiding the rational design of high-performance AP-AuNC-based ECL systems.

4. Orbital Modulation Mechanisms and Strategies for AP-AuNCs ECL

Preceding mechanistic insights reveal that precise atomic-level modulation of molecular orbitals significantly enhances charge injection, electron-transfer kinetics, and excited-state dynamics in the ECL process, while simultaneously quenching non-radiative pathways. This orbital engineering represents a definitive approach to circumventing existing limitations in ECL efficiency, emission wavelength, and stability of AP-AuNCs, paving the way for the rational design of superior luminescent systems [48,49]. Accordingly, this chapter outlines the theoretical underpinnings of orbital modulation in AP-AuNCs. We systematically review multidimensional regulation strategies, unpacking their mechanisms and structure-activity relationships, and highlight the optimization pathways achieved through multi-strategy synergy.

4.1. Core Theoretical Basis of Orbital Modulation

4.1.1. Superatomic Orbital Theory and Orbital Selectivity Rules of ECL

Based on the correspondence between structure and electronic state, the orbital system of AP-AuNCs can be classified into three distinct hierarchical levels, each serving specific functions in the ECL process and representing core targets for precise orbital modulation. First, nuclear superatomic orbitals, arising from the delocalization of 6s valence electrons of core Au(0) atoms, primarily contribute to the lowest unoccupied molecular orbital (LUMO). As core sites for electron injection during the ECL process, they dictate the upper limit of excited state energy and the intrinsic emission wavelength range. Second, surface state orbitals, formed via the hybridization of outer “staple” Au(+1) 6s orbitals and sulfur ligand 3p orbitals, mainly constitute the highest occupied molecular orbital (HOMO). These orbitals act as the essential sites for hole injection, determining both the hole injection energy barrier and the redox stability of NCs. Third, ligand orbitals, comprising the molecular orbitals of surface-protecting ligands, participate in the ligand-to-metal (LMCT) and metal-to-ligand charge transfer (MLCT) processes, thereby being crucial for regulating the excited state relaxation pathways and non-radiative transition probabilities [50].

Importantly, the ECL process of AP-AuNCs exhibits stringent orbital selectivity. During the oxidation process, holes are preferentially injected into the HOMO to form cation radicals, whereas during reduction, electrons are selectively injected into the LUMO to generate anion radicals. Subsequent electron transfer between these radicals yields excited states, which ultimately produce luminescence via radiative transition back to the

ground state. Consequently, all orbital modulation strategies must strictly adhere to this selectivity rule, enabling the precise optimization of ECL performance through the directional modification of these three orbital categories.

4.1.2. Regulation Principle of Electron Transfer Kinetics Based on Marcus Theory

Marcus electron transfer theory provides the core quantitative framework for describing charge transfer kinetics in the ECL process of AP-AuNCs [51]. According to this theory, the electron transfer rate (k_{et}) in electrochemical reactions is jointly determined by the driving force (ΔG), reorganization energy (λ), electronic coupling matrix element (H_{AB}) and temperature (T). The core expression is defined as [52]:

$$k_{\text{et}} = \frac{2\pi}{h} H_{\text{AB}}^2 \frac{1}{\sqrt{4\pi\lambda k_{\text{B}}T}} \exp\left(-\frac{(\Delta G + \lambda)^2}{4\lambda k_{\text{B}}T}\right) \quad (17)$$

Guided by this theory, orbital modulation of AP-AuNCs for ECL optimization must follow three core kinetic criteria: (1) Energy Level Matching Criterion: Efficient electron transfer occurs exclusively when the redox potential of the co-reactant intermediate matches the target orbital energy level of NCs. Any energy level mismatch significantly elevates the activation barrier, thereby compromising the efficiency of excited state generation. (2) Reorganization Energy Minimization Criterion: The electron transfer reorganization energy of AP-AuNCs originates predominantly from the vibrational relaxation of the ligand shell (internal reorganization energy). Consequently, suppressing ligand dynamic distortion to minimize this internal reorganization energy is a pivotal pathway for improving ECL radiative transition efficiency. (3) Inverted Region Avoidance Criterion: When the driving force exceeds a critical threshold ($-\Delta G > \lambda$), the reaction enters the Marcus inverted region, where the electron transfer rate counterintuitively decreases as the driving force increases. Orbital modulation must therefore avoid the efficiency losses induced by excessive energy gaps, aiming for an optimal balance between the driving force and reorganization energy.

4.2. Modulation Strategy

Precise modulation of the intrinsic “core-ligand shell” geometric structure of AP-AuNCs serves as the cornerstone for tailoring their ECL performances with atomic-level accuracy. To achieve this, modulation strategies are categorized into six interconnected dimensions. Further, the ECL enhancement efficiency, wavelength shift, merits, and limitations of each of the modulation strategies are summarized in Table 2.

4.2.1. Gold Core Structure Regulation

The gold core serves as the primary carrier of nuclear superatomic orbitals. Precise manipulation of its atomicity, atomic arrangement, and magic-number electronic structure allows for the directional tuning of the LUMO energy level, HOMO-LUMO gap, and excited-state stability, which is the most direct pathway to achieve precise regulation of ECL emission wavelength.

According to superatomic shell theory, when the number of valence electrons of the gold core reaches magic numbers (e.g., 2, 8, 18), the AuNCs adopt a closed-shell electronic configuration. This configuration significantly improved the stability of the superatomic orbitals and drastically suppressed non-radiative transitions. By precisely controlling the number of gold core atoms through synthesis, continuous linear regulation of the HOMO-LUMO gap can be achieved. Ding's group [26] systematically verified that the number of gold core atoms in AP-AuNCs dictates the HOMO-LUMO energy gap, which further regulates the ECL wavelength, intensity, and efficiency. Specifically, Au₂₅ possesses the largest energy gap (1.31–1.44 eV), generating emission peaks at 872–950 nm; Au₃₈ exhibits a moderate energy gap (~0.95 eV) with stable emission at 930 nm; whereas Au₁₄₄ features a very narrow bandgap and emits in the near-infrared region, albeit with a remarkably low ECL efficiency. Notably, closed-shell magic-number NCs exhibits substantially higher ECL stability and quantum yields than their non-magic-number neighbors of adjacent sizes. This closed-shell framework stabilizes the superatomic orbitals, minimizes the internal reorganization energy, and inhibits non-radiative relaxation of excited states.

Even at an identical total atomicity, discrepancies in the spatial arrangement of core atoms can drastically alter the energy level distribution and electron cloud density of nuclear superatomic orbitals, thereby yielding vastly distinct ECL behaviors. Chen et al. [33] demonstrated this by comparing two Au₂₀ isomers (Au₂₀-AC[−] and Au₂₀(TBBT)₁₆), which possess Au₇ and Au₁₃ cores, respectively. Their different core structures result in a 0.18 eV difference in the HOMO-LUMO energy gap. Ultimately, Au₂₀-AC[−] delivers an NIR ECL intensity seven times that of the standard Ru(bpy)₃²⁺/TPPrA system, while its isomer Au₂₀(TBBT)₁₆ shows negligible self-quenching ECL in solution, demonstrating that the spatial structure of the gold core is key to regulating ECL performance of AP-AuNCs.

4.2.2. Bimetallic Doping Regulation

The surface “staple” motif represents a defining feature of thiol-protected AuNCs [53]. Site-specific heteroatom doping within this staple structure can directionally tune the HOMO level, lower the hole-injection energy barrier, and modulate metal-to-ligand/ligand-to-metal charge transfer (MLCT/LMCT) processes. This approach significantly enhances the oxidative stability of the nanoclusters, serving as a pivotal strategy for designing high-performance ECL systems. Specifically, single-atom doping at the staple sites optimizes frontier orbital distributions and strengthens spin-orbit coupling (SOC) without disrupting the closed-shell electronic configuration, thereby synergistically boosting both ECL intensity and stability. Tang et al. [54] demonstrated that the Ag-doped GSH-Ag/Au bimetallic nanoclusters maintained a stable cluster structure and exhibited significantly enhanced ECL intensity, with the emission peak red-shifting from 630 nm to 710 nm. Their ECL efficiency was much higher than that of pure AuNCs, demonstrating superior electrochemical activity and luminescence performance.

4.2.3. Ligand Engineering

Ligands are the key modulators of the surface state and ligand orbitals of AP-AuNCs [55]. Without altering the underlying gold core structure, this strategy enables the directional optimization of the NCs' HOMO/LUMO levels, inner-sphere reorganization energy, charge transfer efficiency, and environmental adaptability. This is achieved by systematically tailoring the electronic effects, rigidity, packing density, and functional groups of the ligand shell, making it the most versatile and widely adopted strategy for ECL performance regulation.

Electronic Effects

The electron donating/withdrawing profiles of ligands directly modulate the energy positions of surface state orbitals. Generally, electron-donating ligands elevate the HOMO level, whereas electron-withdrawing counterparts lower the LUMO level, thereby precisely tailoring the HOMO-LUMO gap and the energy alignment between NCs and co-reactants. Zhu et al. [56] proposed the surface charge redistribution-induced ECL enhancement mechanism and designed and synthesized Agm/ATT-Au NCs. By utilizing the positively charged electron donor ligand Agm to regulate the surface charge distribution and HOMO-LUMO energy levels of the clusters, the electron transfer kinetics were significantly accelerated, resulting in an annihilation ECL efficiency of 26.29% and a signal enhancement of approximately 110 times compared to the single ligand system (Figure 1A).

Ligand Rigidification

The intramolecular vibration and rotation of flexible ligands represent the primary source of inner-sphere reorganization energy in AP-AuNCs, serving as major pathways for the non-radiative decay of excited states. Restricting ligand flexibility can significantly suppress dynamic structural distortions via rigid conjugated backbones, intramolecular hydrogen-bonding networks, or host-guest molecular recognition [57–59]. This rigidification minimizes the inner-sphere reorganization energy, curtails non-radiative relaxation, and inhibits detrimental surface restructuring during electrochemical reactions, thereby enhancing ECL signal stability. For instance, Zou's group [60] utilized *L*-arginine (Arg) as a host to anchor surface ligands of ATT-AuNCs via host-guest recognition, which blocked non-radiative energy channels to realize a 70-fold enhancement in oxidative-reduction ECL at +0.78 V. Nie et al. [61] confined GSH-AuNCs within ZIF-8 MOFs via a coordination-assisted self-assembly strategy. This confinement effectively suppressed energy dissipation caused by ligand rotation and mitigated the self-quenching effect arising from the spatial distribution of NCs, ultimately leading to a 10-fold enhancement in ECL efficiency relative to densely aggregated GSH-AuNCs (Figure 1B). Zhou et al. [25] engineered an intramolecular hydrogen-bonding network using CR₄/ATT dual ligands to rigidify the surface configuration of AuNCs. This strategy drastically curtails non-radiative decay and simultaneously activates a brand-new reduction-oxidation ECL pathway, driving the ECL quantum efficiency to a record 13.0%, which is 4.2 times that of the Ru(bpy)₃²⁺ system.

Ligand Density

The ligand packing density on gold cores directly influences surface state orbital integrity, co-reactant adsorption, and interfacial charge transfer [62]. While a low ligand density increases unsaturated coordination sites to form defect-state non-radiative recombination centers, an excessively high density creates an insulating layer that blocks charge transport between the nanoclusters, electrode, and co-reactants. Through *in-situ* ECL monitoring of dynamic ligand exchange, Lu's group [63] observed that the ECL signal increased initially and then declined with changes in ligand coverage, establishing a clear volcanic relationship (Figure 1C). They verified that optimal

ligand replacement passivates surface defects and enhances electron injection. In contrast, insufficient coverage exacerbates non-radiative recombination via unsaturated sites, and over-saturation inhibits charge transfer via encapsulation. Ultimately, this study confirms that the strongest and most stable ECL in gold nanoclusters is achievable only by balancing surface defect passivation with efficient interfacial charge transfer.

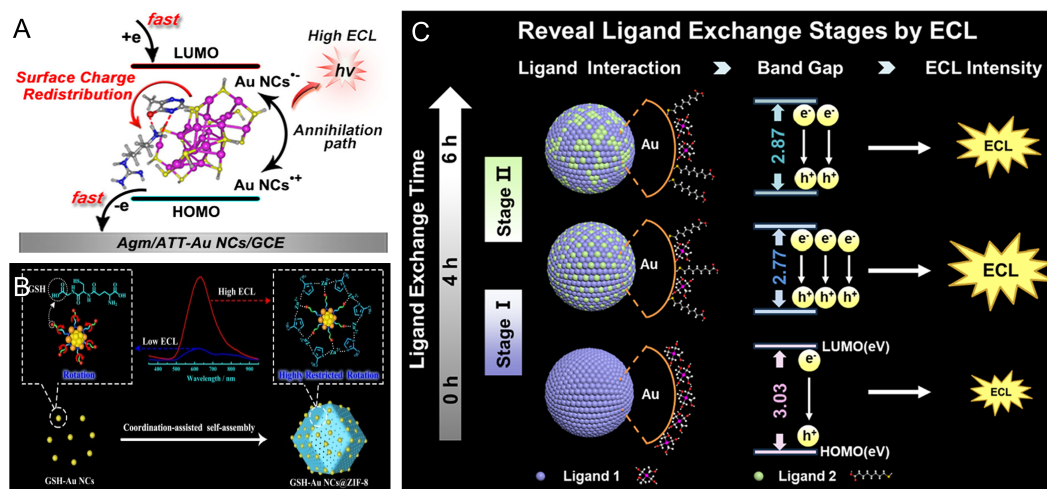


Figure 1. Key factors of ligand engineering governing the ECL performance of AP-AuNCs: (A) Electronic Effect [56], (B) ligand rigidification [61], and (C) ligand density [63].

4.2.4. Valence Engineering

Valence engineering of AuNCs involves the strategic manipulation of the Au(0)/Au(I) ratio to directionally tailor their electronic structures, surface defects, and energy level distributions, thereby enabling precise control over ECL pathways, emission wavelengths, and turn-on potentials [64]. Wang et al. [17] precisely modulated the Au(0)/Au(I) ratio by tuning the synthetic aging time, achieving directional regulation of ECL performance. As the Au(0) content increased, the ECL mechanistic pathway shifted systematically from a bandgap-regulated regime to a surface-defect-dominated process. Concurrently, three potential-resolved ECL peaks emerged, the lowest turn-on potential was lowered to 0.37 V, and the emission wavelength red-shifted from 660 nm to 740 nm. This study underscores that Au(0) species are pivotal for achieving low-potential, high-intensity ECL, thereby offering a novel paradigm for elucidating ECL mechanisms, as well as developing multi-channel emissions and low-potential biosensing platforms based on AuNCs.

4.2.5. Aggregation-Induced ECL

Contrary to the conventional aggregation-induced quenching effect of traditional organic materials, AP-AuNCs typically exhibit an aggregation-induced ECL (AIECL) phenomenon, characterized by a significantly enhanced ECL intensity in the aggregated state [65,66]. The fundamental mechanism underlying this behavior extends beyond mere “restriction of intramolecular motion” (RIM), being driven instead by the synergistic effect of three interconnected factors: (1) ligand rigidification, wherein aggregation restricts the vibration and rotation of surface ligands to suppress motion-induced non-radiative transitions; (2) surface defect passivation, where the unsaturated coordination sites on the nanocluster surfaces are passivated by the ligands or metal ions of adjacent nanoclusters during aggregation, thereby minimizing non-radiative relaxation channels of the excited state; (3) weak inter-cluster electronic coupling, which forms between adjacent nanoclusters to promote charge separation and significantly boost the generation efficiency of excited states. Zou’s group [67] proposed a Zn^{2+} -induced aggregation strategy to realize a 1690-fold ECL enhancement in D-penicillamine (DPA)-capped AuNCs (Zn^{2+} -AuNCs), driven by a multiplicative dual-factor mechanism. Zn^{2+} coordination effectively restricted ligand vibration and rotation, thereby suppressing non-radiative decay to yield a ~ 17 -fold enhancement in photoluminescence. Moreover, the formed Zn^{2+} -DPA bonds facilitated electron transfer and accelerated charge annihilation by aligning the energy levels between AuNCs and the bonds, which further amplified the ECL signal by another ~ 100 -fold.

4.2.6. System Energy Level Matching

Based on the Marcus electron-transfer theory, this strategy optimizes the extra-cluster environment to regulate the orbital coupling and energy level alignment between the nanoclusters, functional materials, and co-reactants [49]. Therefore, a substantial enhancement in ECL performance is achieved without altering the intrinsic structure of the nanoclusters, making this approach highly compatible with complex practical applications. The co-reactant is a core component of the ECL system, where the alignment between its redox potential and the nanocluster orbital energy levels directly determines electron transfer efficiency. Based on Marcus theory, meticulous co-reactant screening and composite system optimization enable precise energy level matching. This minimizes the electron transfer barrier, avoids the Marcus inverted region effect, and simultaneously improves the system's biocompatibility. Peng et al. [68] proposed a molecular orbital theory-based energy level engineering strategy to regulate the ECL performance of different ligand-protected AuNCs. Aligning their energy levels with the co-reactant DIPEA improved electron transfer efficiency and reduced the ECL onset potential, while narrowing the HOMO-LUMO gap enhanced emission efficiency (Figure 2). Among them, the resulting β -CD-protected AuNCs/DIPEA system exhibited a solid-state ECL efficiency 145 times that of the conventional $\text{Ru}(\text{bpy})_3^{2+}$ reference, with an onset potential as low as 0.48 V, ultimately enabling the first-ever visualization of near-infrared ECL via an infrared camera.

Table 2. Summary of the ECL enhancement efficiency, ECL wavelength shift, advantages and limitations of various modulation strategies.

Modulation Strategies	System	ECL Enhancement Efficiency	ECL Wavelength Shift	Advantages	Limitations	Ref.
Gold core structure regulation	Atomic-accurate Au NCs (Au_{25} , Au_{38} , Au_{144})	3.5-fold ECL enhancement efficiency for Au_{38} relative to the standard $\text{Ru}(\text{bpy})_3^{2+}/\text{TPrA}$ system	Red-shift of emission wavelength with increasing nuclear size	Directional performance control; High stability;	Limited palette of high-performance sizes; strict synthetic precision requirement;	[26]
Gold core structure regulation	Au_{20} -AC/isomer $\text{Au}_{20}(\text{TBBT})_{16}$	769% (Au_{20} -AC/4.7% ($\text{Au}_{20}(\text{TBBT})_{16}$) relative to the $\text{Ru}(\text{bpy})_3^{2+}/\text{TPrA}$ system	15 nm redshift for Au_{20} -AC and 20 nm blueshift for $\text{Au}_{20}(\text{TBBT})_{16}$ relative to PL	suppressed non-radiative decay; dual-dimensional regulation	high structural sensitivity	[33]
Bimetallic doping regulation	GSH-Ag/Au NCs	-	80-nm red-shift of ECL emission peak after silver doping	Simultaneous enhancement of luminescence and electrochemical performance with retained structural stability	High difficulty in synthesis control; performance boundaries in doping amount	[54]
	Sc@AuNCs	35.19% relative to the annihilation-type $\text{Ru}(\text{bpy})_3^{2+}$ system	20-nm red-shift of ECL emission peak after scandium doping			[35]
	$\text{Au}_{12}\text{Ag}_{13}$ NCs	400-fold ECL enhancement efficiency relative to the standard $\text{Ru}(\text{bpy})_3^{2+}/\text{TPrA}$ system	10 nm redshift relative to the PL			[48]
Ligand engineering	CR4/ATT-AuNCs	4.2-fold ECL enhancement efficiency relative to the standard $\text{Ru}(\text{bpy})_3^{2+}/\text{TPrA}$ system	No ECL wavelength shift	Strong universality; rich regulatory dimensions; significant performance improvement	Difficulty in decoupling multi-factor coupling; existence boundary of environmental adaptability	[25]
	Arg/ATT-AuNCs	-				[60]
Valence engineering	BSA-AuNCs	-	band gap-regulated ECL at 660 nm; surface defect ECL red-shift to 740 nm with prolonged incubation	Selective potential-resolved ECL; low trigger potential	Strict requirements for synthesis, purification and long incubation period	[17]
Aggregation-induced ECL	$\text{Zn}^{2+}/\text{DPA}$ -AuNCs	-		Multiple-collaboration mechanism; high-concentration scenario adaptability	Poor controllability of aggregation process, insufficient long-term stability of homogeneous system	[67]
	SS-ATT-AuNCs	78% relative to the annihilation-type $\text{Ru}(\text{bpy})_3^{2+}$ system	Negligible ECL wavelength shift			[22]
System energy level matching	β -CD-AuNCs	145-fold enhancement in ECL efficiency compared with the classic $\text{Ru}(\text{bpy})_3^{2+}/\text{TBAP}$ system	Negligible ECL wavelength shift	No change in intrinsic structure; strong compatibility	Solid-state environment-dependent performance; requirement for further anti-interference validation	[68]

Notes: $\text{Au}_{20}(\text{SAdm})_{12}(\text{CHT})_4$: Au_{20} -AC for short; SAdm = 1-adamantanethiolate; CHT = cyclohexanethiol; TBBT = 4-tert-butylthiophenol; TBAP = Tetra-n-butylammonium perchlorate; TPrA = Tripropylamine.

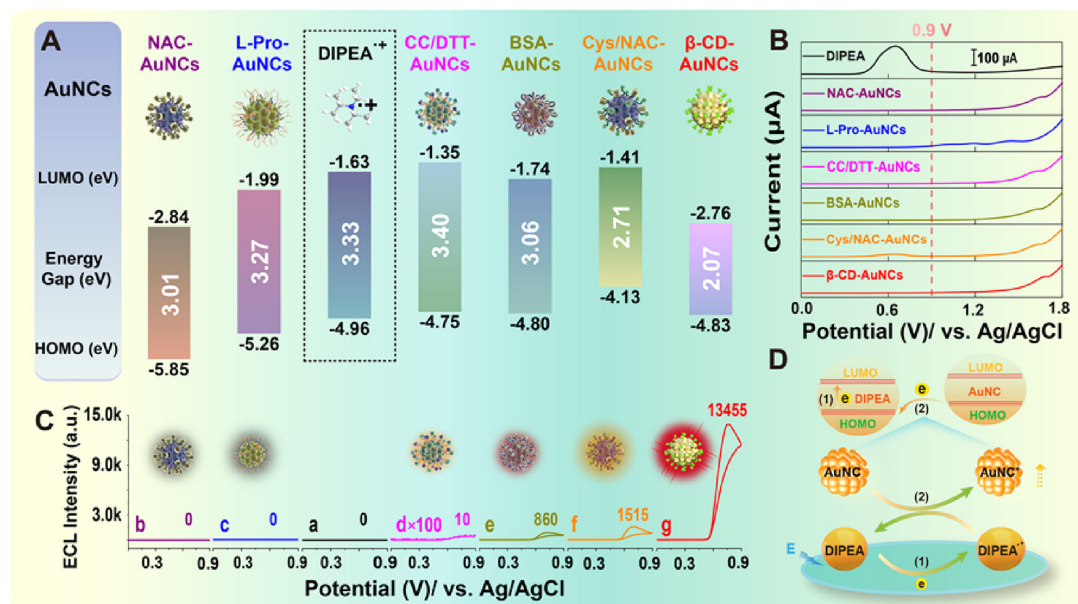


Figure 2. (A) Energy level positions of different ligand (NAC, L-Pro, β -CD, Cys/NAC, BSA, and CC/DTT)-protected AuNCs and DIPEA⁺. (B) Anodic DPV and (C) ECL intensities of different ligand-protected AuNCs. (D) Energy level-related electron transfer reactions between AuNCs and DIPEA. Reprinted with permission from Ref. [68]. Copyright 2023, American Chemical Society.

5. Applications of AP-AuNCs-Based ECL Systems

Leveraging these directional orbital optimization strategies, AP-AuNCs-based ECL systems have demonstrated distinct advantages across the biomedical, environmental, and food safety sectors [69–71]. Compared to conventional luminophores ($\text{Ru}(\text{bpy})_3^{2+}$, QDs), AP-AuNCs offered unique advantages in structural tunability, biocompatibility, and analytical performance. Although $\text{Ru}(\text{bpy})_3^{2+}$ remained the benchmark ECL emitter due to its mature mechanism and high stability, its limited tunability and susceptibility to matrix interference constrained ultrasensitive detection; QDs provided tunable emission and high luminescence efficiency but suffered from heavy metal toxicity and poor stability under complex conditions. In sharp contrast, atomically precise structures and tailorable ligand environments of AP-AuNCs enable effective regulation of electronic states and ECL properties, resulting in excellent biocompatibility, matrix tolerance, and ultrasensitive sensing performance. Accordingly, this review summarizes recent advances in AP-AuNCs-based ECL systems, with emphasis on their applications in biomedicine, environmental monitoring, and food safety (Table 3).

5.1. Biosensing and Clinical Diagnosis

The rigorous requirements of biosensing and clinical diagnosis necessitated an expansive linear range, an ultra-low detection limit, excellent biocompatibility, and high anti-interference capacity in complex biological matrices. To meet these demands, researchers have implemented multi-dimensional strategies to precisely modulate the ECL performances of AP-AuNCs, which effectively overcame the sensitivity bottlenecks inherent in traditional systems to achieve the high-precision detection of low-abundance biomarkers [72–74]. For example, Zhu et al. [75] developed an ultrasensitive biosensor based on a AuNCs@3D porous ZrO_2 hollow nanosphere composites (AuNCs@ ZrO_2) with spatial confinement-enhanced ECL activity for detecting insulin-like growth factor 1 (IGF-1), a critical biomarker for acute myocardial infarction. The AuNCs@ ZrO_2 composite was fabricated by electrostatically confining negatively charged Au NCs within the positively charged 3D microenvironment of ZrO_2 HNs. The resulting spatial confinement suppressed ligand vibration and accelerated electron-hole recombination, thereby promoting the radiative transitions of the excited AuNCs and achieving a 5.1-fold enhancement in ECL efficiency compared to pristine AuNCs. By further integrating the ordered localization catalytic hairpin assembly (OL-CHA) strategy, a “signal on-off” ECL biosensor for IGF-1 detection was constructed, exhibiting a wide linear range from 1 fg/mL to 10 ng/mL and an exceptional LOD of 0.36 fg/mL and favorable selectivity over three interfering proteins, which surpassed the analytical performance of commercial ELISA kits in human serum analysis (Figure 3). Ahmad et al. [76] constructed a double-shell rigidified $\text{Zn}^{2+}/\text{Au}_{22}(\text{SG})_{18}/\text{PDA}$ NCs-based ECL sensing platform for sensitive detection of Cu^{2+} and histidine in actual serum samples through an architectural modulation strategy. By leveraging the synergistic effects of Zn^{2+} coordination and covalent cross-linking of PDA,

the surface ligands of Au₂₂(SG)₁₈ were effectively rigidified to suppress non-radiative transitions via an AIE-to-AIEE mechanism for markedly enhancing its ECL efficiency, thereby enabling highly sensitive “quenching-recovery” detection of Cu²⁺ and histidine with LODs of 0.705 and 1.928 μM, respectively. Additionally, this ECL sensor showed high selectivity for Cu²⁺ and histidine, readily distinguishing them from common interfering substances.

Table 3. Summary of representative applications of AuNCs-based ECL sensing platforms in environmental, food safety, and biomedical sectors.

Materials	Targets	Linear Ranges	LOD	Samples	Ref.
Zn ²⁺ -d-DPA/MUA@AuNCs	PSA	5–800 ng/mL	1 ng/mL	-	[23]
β-CD-Au NCs	noradrenalin	1 nM–1 mM	0.91 nM	-	[24]
AuAgBNCs	diuron	0.5 ng/mL–5 μg/mL	1.68 pg/mL	river water	[34]
Sc@AuNC	AD7c-NTP	0.001–100 ng/mL	0.45 pg/mL	human urine	[35]
AuNCs/CaFe ₂ O ₄	AFB1	10 fg/mL–100 pg/mL	2.45 fg/mL	rice	[49]
GSH-Ag/Au NCs	DA	10 nM–1 mM	2.3 nM	human serum	[54]
Agm/ATT-Au NCs	GFAP	100 ag/mL–100 pg/mL	27.5 ag/mL	human glioma U87 cells	[56]
CB[7]/L-Phe/MPA-AuNCs	d-dimer	50 fg/mL–100 ng/mL	29.2 fg/mL	human plasma	[58]
Arg/ATT-AuNCs	<i>S. aureus</i>	10–10 ⁹ CFU/mL	1.16 CFU/mL	scallop, fish, shrimp	[59]
GSH-Au NCs@ZIF-8	rutin	0.05–100 μM	10 nM	-	[61]
SS-ATT-AuNCs	PSA	10 fg/mL–200 ng/mL	2.2 fg/mL	human serum	[65]
Gba/ATT-AuNCs	suPAR	10 fg/mL–10 ng/mL	3.15 fg/mL	patient serum	[72]
MUA-AuNCs	CA125	0.5 mU/mL–1 U/mL	0.1 mU/mL	serum	[73]
Ft-AuNCs	Aβ40	0.001–100 ng/mL	0.18 pg/mL	clinical plasma	[74]
Au NCs@ZrO ₂	IGF-1	1 fg/mL–10 ng/mL	0.36 fg/mL	acute myocardial infarction patients	[75]
Zn ²⁺ /Au ₂₂ (SG) ₁₈ /PDA	Cu ²⁺ , histidine	0.1–40 μM; 1–85 μM	0.705 μM, 1.928 μM	human serum	[76]
GSH-AuNCs@Fe-MIL-88A	CA15-3	0.1 pM–100 nM	0.02 pM	serum	[77]
AuNCs@COFs	Pb ²⁺	10 pM–5 μM (ECL), 1 nM–5 μM (colorimetric)	7.9 pM (ECL), 0.56 nM (colorimetric)	soil	[78]
OM-AuNCs	Cu ²⁺	1 aM–10 fM	0.023 aM	human serum	[79]
AuNCs	Pb ²⁺	0.1 nM–100 μM	24 pM	farmland soil, soil near chemical plant, contaminated soil	[80]
AuNCs	Pb ²⁺	0.05 pM–10 nM	0.05 pM	soil	[81]
AuNCs@A-SIM	CN ⁻	0.01–1.0 μM	1.2 nM	river water	[82]
AuNCs	As ³⁺	1 pM–5 nM	0.019 pM	soil	[83]
cucurbit[7]uril@Try-MPA-AuNCs	KAN	50 fg/mL–50 ng/mL	32.9 fg/mL	milk, honey	[84]
Met-AuNCs	VP	10–10 ⁷ CFU/mL	1.23 CFU/mL	scallop, fish, shrimp, seawater, river water	[85]
AuNCs@Ti ₃ C ₂ TxNR	estradiol	0.001–1000 ng/mL	77.6 fg/mL	river water, human urine, animal serum	[86]
AuNCs	bleomycin	0–3.5 μM	35.27 nM	serum	[87]
AuNCs@MSX	OTA	0.001–100 ng/mL	0.31 pg/mL	corn, millet	[88]
AuNCs@CS	AFB1	31.6 fg/mL–3.16 pg/mL	9.3 fg/mL	leech	[89]
Glu/TG-AuNCs	TC	100 fM–1 μM (PL), 5 fM–1 μM (ECL)	73 fM (PL), 2.3 fM (ECL)	milk	[90]
AuNCs@CuS@COF	ZEN	0.1 pg/mL–100 ng/mL	0.052 pg/mL	wheat, oat, corn	[91]
CR-AuNCs	KAN	10 pM–33 μM	1.5 pM	milk	[92]
NAC/Cys-AuNCs	NSE	0.1–5 ng/mL	0.033 fg/mL	serum	[93]
NAC-AuNCs	HBV	0.01–5 nM	5 pM	-	[94]
MSA/Cit@AuNCs	CEA	2–20,000 fg/mL	0.33 fg/mL	human serum	[95]
DNF@AuNCs	AFB1	0.01–200 ng/mL	7 pg/mL	peanut, corn flour	[96]
AuAgNCs	PSA	0.5–1000 pg/mL	0.1 pg/mL	human serum	[97]

“-” Not mentioned.

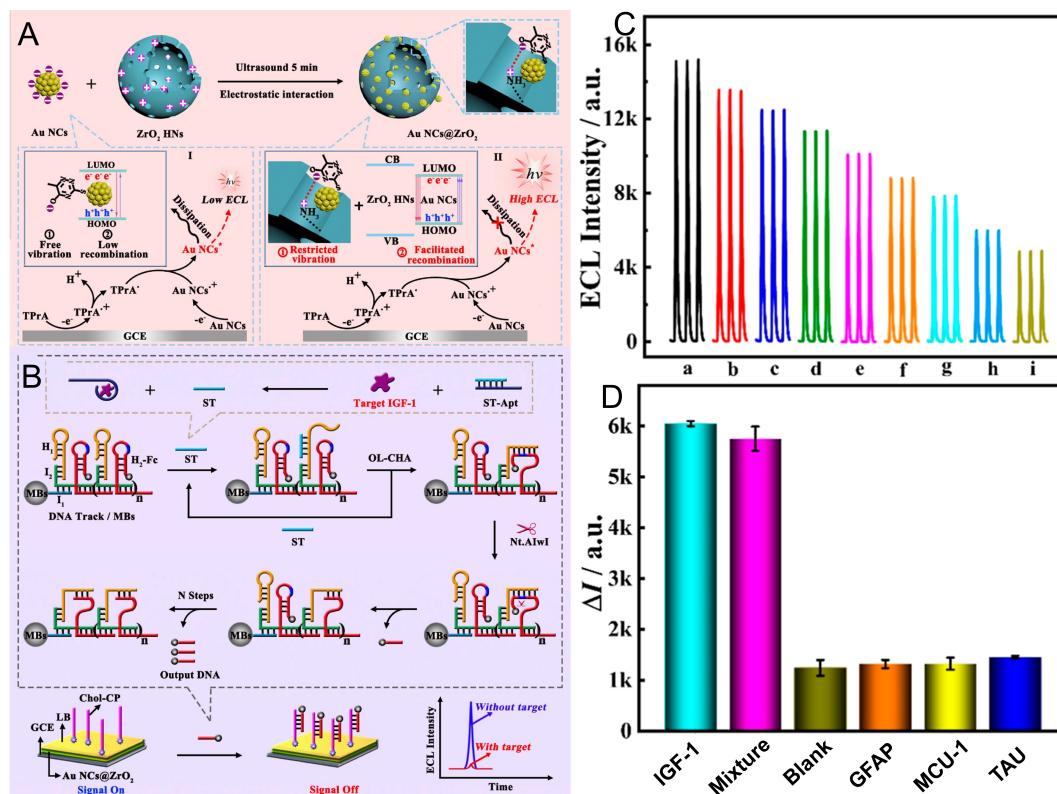


Figure 3. (A) Preparation of Au NCs@ZrO₂ and the ECL mechanism of the Au NCs/TPra system. (B) Schematic illustration of a sensitive Au NCs@ZrO₂-based ECL biosensor combined with OL-CHA signal amplification for IGF-1 detection. (C) ECL response to IGF-1 at different concentrations (a–i: 0 fg/mL–10 ng/mL). (D) Selectivity study for the ECL platform with GFAP, MCU-1, and TAU as interferences. Reprinted with permission from Ref. [75]. Copyright 2025, American Chemical Society.

In addition, Du's group [58] utilized the host-guest recognition between cucurbiturils [7] and L-phenylalanine to rigidify the surface of AuNCs (CB [7]/L-Phe/MPA-AuNCs), which significantly improved their ECL intensity and stability with an ECL efficiency of 3.4%. By integrating aminated TiO₂ as a co-reaction accelerator with oriented immobilized polypeptides, an ultrasensitive ECL biosensor for D-dimer detection in human plasma samples was engineered, with a linear range of 50 fg/mL–100 ng/mL and a LOD as low as 29.20 fg/mL. To further improve the electron transport efficiency, Li et al. [77] developed a novel ECL immuosensing platform for quantitatively detecting breast cancer biomarker CA15-3 in serum samples using the glutathione-capped AuNCs assembled on an etched Fe-MIL-88A framework (GSH-AuNCs@Fe-MIL-88A) as the ECL probe and Co-doped CdO (Co-CdO) as a co-reaction accelerator. In this system, the GSH-AuNCs@Fe-MIL-88A nanocomposite inhibited energy dissipation arising from ligand motion and facilitated charge transfer, thereby significantly amplifying ECL emission. Meanwhile, the Co-CdO accelerator promoted the catalytic oxidation of DIPEA to generate abundant radical intermediates, further amplifying the ECL signal. As a result, the ECL intensity increased with increasing CA15-3 concentration over a linear range of 0.1 pM to 100 nM, achieving a lower LOD of 0.02 pM with excellent selectivity (Figure 4). Similarly, Su et al. [35] reported a sandwich-type ECL immunoassay (ECLIA) platform for highly sensitive detection of Alzheimer's disease biomarker AD7c-NTP in human urine based on scandium-doped AuNCs (Sc@AuNC) as the ECL emitter and DIPEA as the low-oxidation-potential co-reactant. The introduction of Sc doping and DIPEA promoted accelerated electron transfer and the generation of coreactant-derived free radicals, leading to a 40.89-fold increase in ECL intensity and an ECL efficiency of 35.19% at a low operating potential of only 0.75 V. Benefiting from the superior ECL performance of Sc@AuNCs/DIPEA system, the proposed ECLIA exhibited a wide linear detection range of 0.001 to 100 ng/mL and a LOD of 0.45 pg/mL for AD7c-NTP, along with excellent selectivity and repetitiveness. Furthermore, the analytical results showed excellent agreement with a commercial ELISA kit, demonstrating the reliability and potential clinical applicability of the constructed ECLIA method (Figure 5).

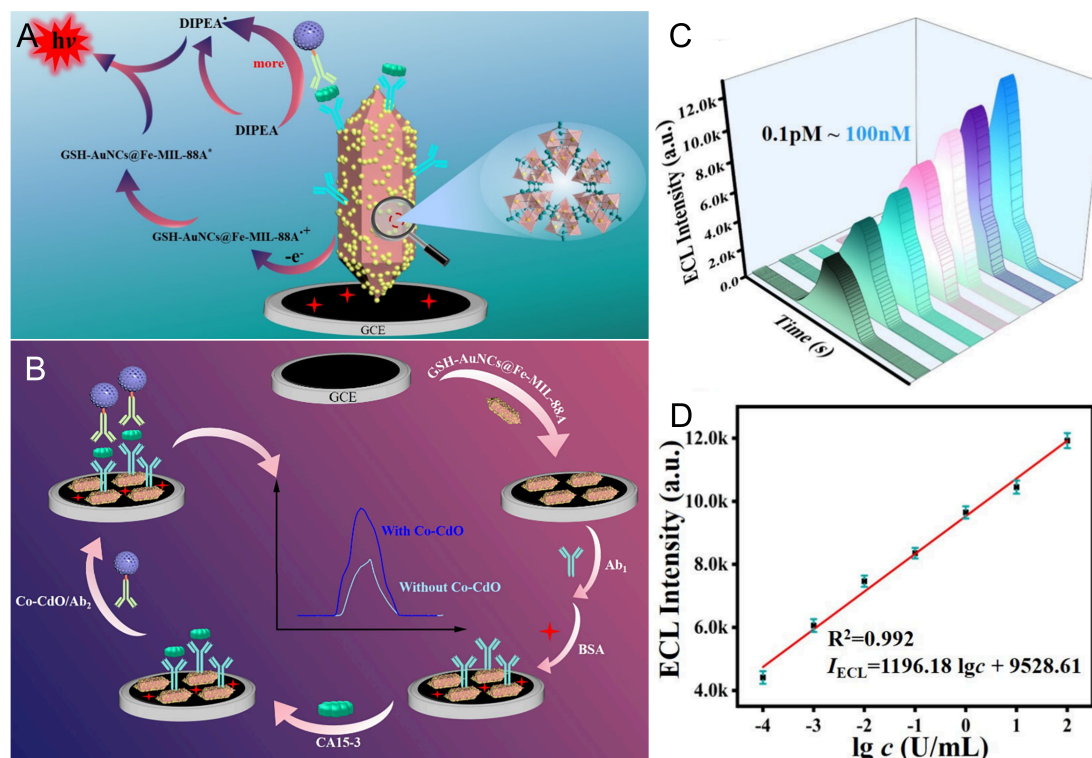


Figure 4. Illustration of (A) ECL mechanism of GSH-AuNCs@Fe-MIL-88A composites and (B) a sensitive ECL immunosensor for CA15-3 detection. (C) ECL signal response to different concentrations of CA15-3 (0.1 pM–100 nM) and (D) corresponding linear curve. Reprinted with permission from Ref. [77]. Copyright 2025, American Chemical Society.

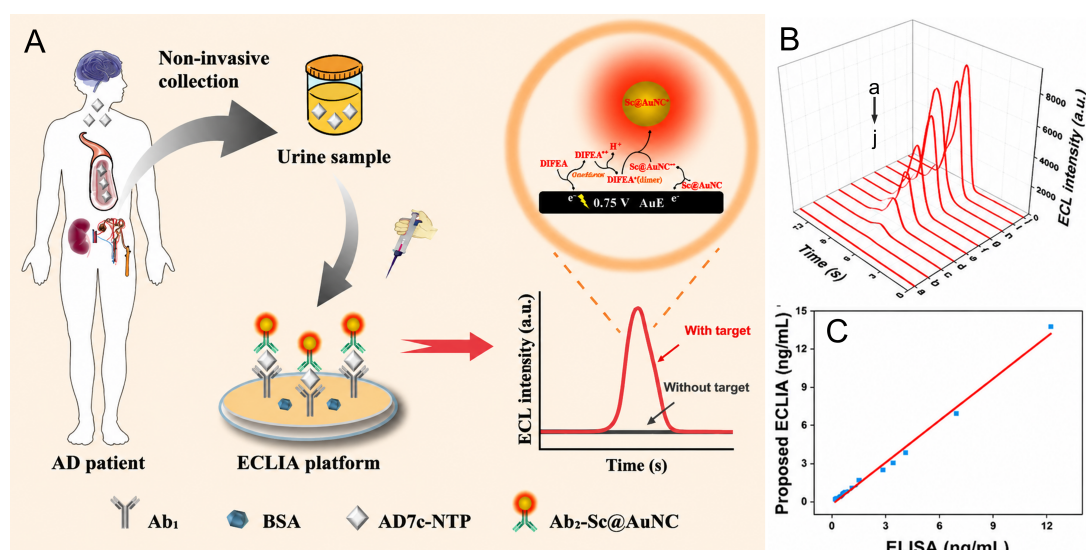


Figure 5. (A) Schematic diagram of a sandwich-type Sc@AuNC-based ECL immunosensor for AD7c-NTP assay. (B) ECL curves for various levels of AD7c-NTP. (a–j: 0–10,000 ng/mL). (C) Pearson's correlations between the commercial ELISA and the proposed ECL sensor for AD7c-NTP detection. Reprinted with permission from Ref. [35]. Copyright 2025, American Chemical Society.

5.2. Environmental Monitoring

Driven by rapid technological advancements and an increasing public focus on ecological health, the development of highly sensitive and efficient environmental monitoring technologies has become an urgent priority. To address the latent threats posed by toxic inorganic pollutants (e.g., Pb^{2+} , As^{3+} , CN^-) in water and soil, many researchers have utilized AIE enhancement strategy to precisely improve ECL performances of AP-AuNCs for constructing a series of multidimensional, high-stability ECL sensing platforms, which overcame the bottlenecks of trace analysis in complex environmental samples and provided robust, high-performance solutions

for the ultra-trace monitoring of environmental pollutants [78,79]. Li's group [80] reported a novel “on-off-on” ECL aptasensor with a dual-signal amplification strategy of AIE of AuNCs and RhB-based RET for ultrasensitive Pb^{2+} determination in soil. The Pb^{2+} -induced aptamer binding triggered RhB detachment and restored ECL signal, thereby achieving the ultrasensitive detection of Pb^{2+} , featuring a lower LOD of 24 pM and excellent selectivity. Later, this group [81] constructed a potential-resolved ratiometric ECL aptasensing platform based on AIE-active AuNCs and PTC-NH₂ as both ECL emitters and the ECL resonance energy transfer strategy (ECL-RET) donor-acceptor pair for monitoring Pb^{2+} in soil samples (Figure 6). In this study, the ECL-RET process led to a dramatic quenching of the anodic ECL signal of AuNCs while simultaneously generating a cathodic ECL signal from PTC-NH₂ in the absence of Pb^{2+} . Upon introduction of target Pb^{2+} , the ECL-RET process was disrupted, resulting in the recovery of the anodic ECL signal and a concurrent decrease in the cathodic ECL signal. By monitoring the variation in the ECL intensity ratio between AuNCs and PTC-NH₂ as a function of Pb^{2+} concentration (0.05 pM–10 nM), the developed ECL aptasensor realized a low LOD as low as 50 fM and exhibited satisfactory selectivity against a panel of 15 common interfering ions.

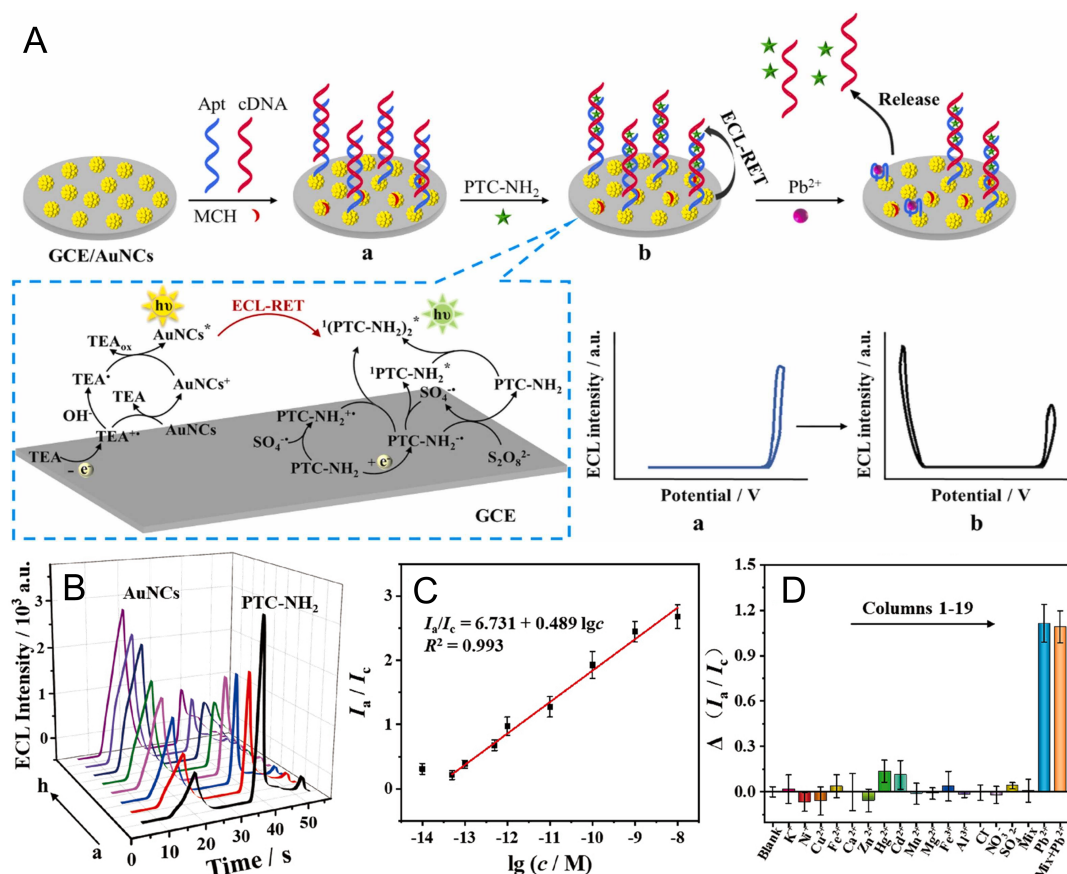


Figure 6. (A) Diagram of a ratiometric ECL aptasensor based on AuNCs and PTC-NH₂ for sensitive detection of Pb^{2+} . (B) ECL intensity response to various concentrations of Pb^{2+} (a–h: 0.05 pM–10 nM). (C) Calibration curve between the value of I_a/I_c and the logarithmic concentration of Pb^{2+} . (D) Selectivity of the proposed Pb^{2+} detection method. Reprinted with permission from Ref. [81]. Copyright 2023, Elsevier.

For other toxic inorganic pollutants in water and soil, Yao et al. [82] fabricated a unique ECL sensor based on electrophoretically encapsulated AuNCs within a silica isoporous membrane (AuNCs@A-SIM) for highly sensitive detection of CN^- in river water. The AuNCs were effectively confined within A-SIM's nanochannels to cause a significant AIECL effect with an ECL efficiency of 17.89%. As the CN^- concentration increased from 10 to 1000 ng/mL, the specific etching of AuNCs progressively attenuated the ECL intensity, thereby enabling highly sensitive detection of CN^- with a LOD of 1.2 nM, while also delivering outstanding selectivity and robust anti-interference performance (Figure 7). Xu et al. [83] proposed an innovative ECL aptasensor based on a “luminophore-coreaction accelerator” synergistic catalytic TEA oxidation strategy for As^{3+} assay. In this system, PdNCs as a coreaction accelerator formed a heterostructure with AuNCs to greatly amplify ECL intensity, which was attributed to the electron trap effect and increased electrochemically active surface area to accelerate the TEA free radical generation. Upon binding with the target As^{3+} , the aptamer underwent a specific conformational

transition to quench the ECL signal. With increasing As^{3+} concentration (1 pM–5 nM), the developed ECL aptasensor exhibited a gradual decrease in ECL intensity, accompanied by a good linear relationship between the ECL intensity and the logarithm of As^{3+} concentration. This proposed aptasensor not only achieved an ultralow LOD of 19 fM but also showed high selectivity for As^{3+} , effectively differentiating it from 7 common interfering ions (Figure 8).

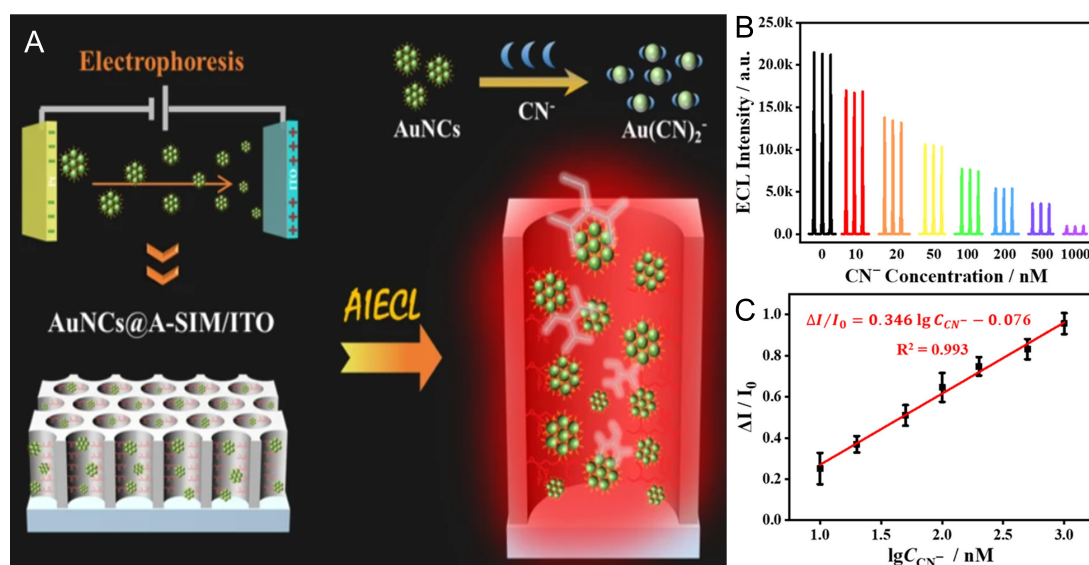


Figure 7. (A) Illustration of a novel AuNCs@A-SIM/ITO-based AIECL platform for CN^- detection. (B) ECL responses toward CN^- at varying concentrations (0–1000 nM). (C) Linear relationship between relative ECL intensity and logarithm of CN^- concentration (from 0.01 to 1 μM). Reprinted with permission from Ref. [82]. Copyright 2025, Springer.

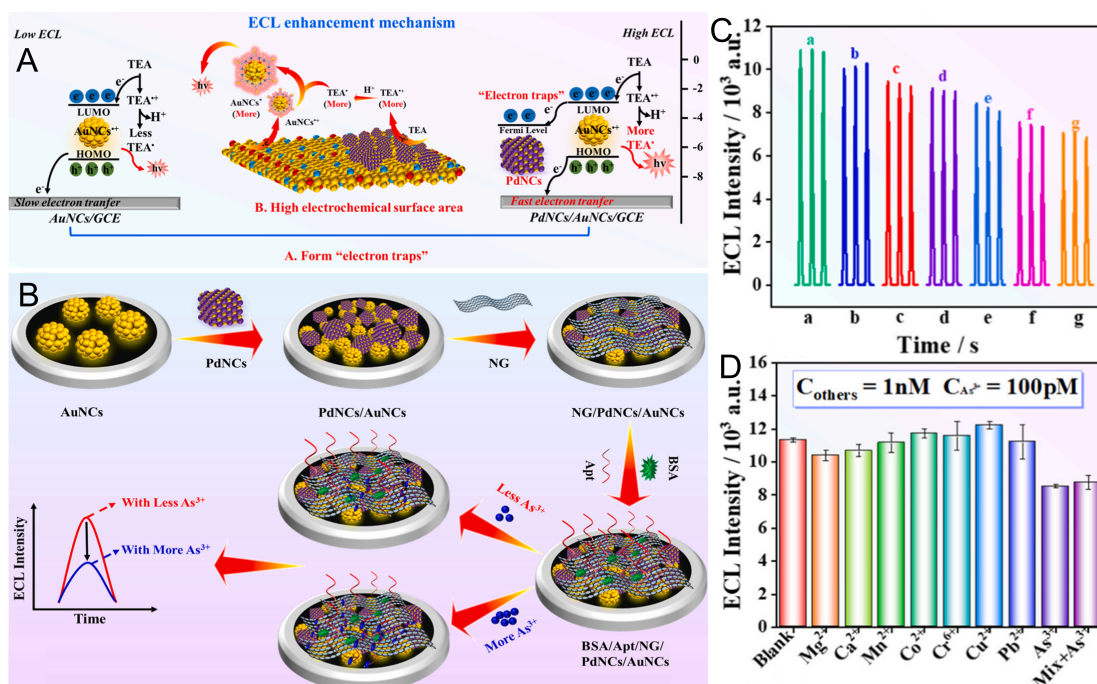


Figure 8. (A) Synergistic catalytic mechanism diagram of PdNCs and AuNCs in facilitating TEA oxidation. (B) Schematic illustration of a sensitive ECL aptasensor for detecting As^{3+} . (C) ECL response to As^{3+} at different concentrations (a–g: 1 pM–5 nM) and (D) Selectivity investigation. Reprinted with permission from Ref. [83]. Copyright 2026, Elsevier.

5.3. Food Safety Analysis

The AP-AuNCs-based ECL technology has demonstrated significant application potential in the field of food quality and safety monitoring. By employing optimization strategies like confined assembly and valence state engineering, researchers have successfully bolstered the ECL responses of AP-AuNCs, constructing high-

performance sensing platforms tailored for specific detection needs [84–86]. Spatial confinement serves as a universal strategy to enhance the luminescence efficiency of AP-AuNCs by restricting intramolecular motion and minimizing non-radiative transitions [87]. Wei's group [88] leveraged the spatial confinement and dispersion regulation of mesoporous silica xerogels to uniformly encapsulate AuNCs within a porous framework (AuNCs@MSX). This architecture effectively inhibited non-radiative ligand relaxation and self-quenching, resulting in a 2.32-fold increase in ECL efficiency compared to pristine AuNCs with a quantum yield of 16.98%. By combining this enhanced system with DNA walker-based cyclic amplification and an ECL-RET mechanism, a novel “on-off” biosensor was developed for the highly sensitive detection of ochratoxin (OTA) in corn and millet samples. The sensor achieved excellent performance over a broad linear range from 1 pg/mL–100 ng/mL, achieving an ultralow LOD of 0.31 pg/mL and satisfactory selectivity against potential interfering substances (Figure 9). Wang et al. [89] *in-situ* regulated the Au(0)/Au(I) valence ratio of AuNCs and prolonged the excited-state lifetime through the soft confinement effect of chitosan nanogel, which increased the ECL intensity by 2.4 times. The label-free ECL immunosensor was constructed for aflatoxin B1 (AFB1) assay in traditional Chinese medicine and food with a LOD as low as 9.3 fg/mL and high selectivity against other potential interfering toxins. Zhou et al. [90] established a portable and convenient point-of-care testing platform based on Glu/TG-Au NCs as the FL and ECL dual-signal probes for on-site detection of tetracycline (TC) in Eppendorf (EP) tubes. The platform employed an aptamer-antibody (Ap-Ab) chimera to capture TC, producing distinct visual FL signals through the combination of green-emitting (Glu/TG-AuNCs-S1) and red-emitting (BSA-AuNCs-S2) components for rapid screening. The mechanism involved the thermal dissociation of the S1–S2 duplex, which released S1 to initiate an ECL response with high sensitivity. This FL-ECL dual-signal biosensor demonstrated superior sensitivity and satisfactory selectivity, with LODs reaching 73 fM (visual FL) and 2.3 fM (ECL) (Figure 10).

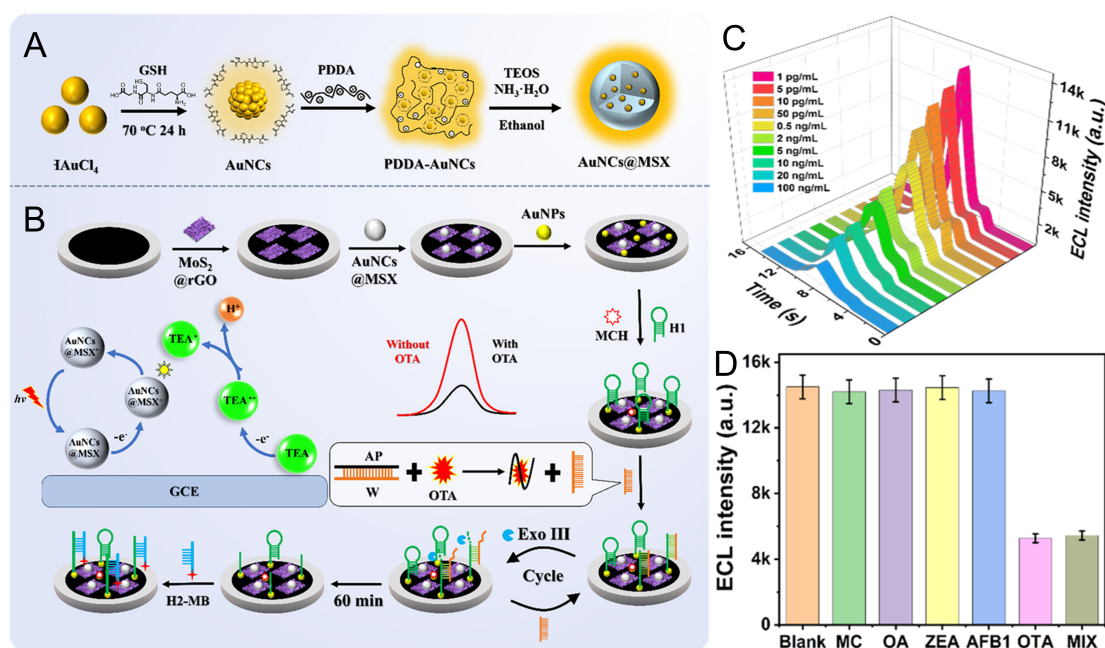


Figure 9. Schematic diagram of (A) the preparation of AuNCs@MSX and (B) a highly sensitive ECL biosensor based on AuNCs@MSX and DNA walker for detecting OTA. (C) ECL signal response to OTA at different concentrations (1 pg/mL–100 ng/mL). (D) Selectivity of the biosensor toward OTA (5 ng/mL) against interfering substances (50 ng/mL). Reprinted with permission from Ref. [88]. Copyright 2025, American Chemical Society.

Synergistic catalysis offers a robust approach to surmount the inherent bottlenecks of luminescence efficiency of AP-AuNCs. For instance, Xu et al. [91] constructed a sensitive “off-on” ECL biosensing system for accurate detection of ZEN by integrating the nanoconfinement effect of COFs, the co-reaction acceleration of CuS and a DNAzyme walker strategy. In this work, a high-performance AuNCs@CuS@COF emitter was formed by encapsulating CuS NPs within the COFs and then *in-situ* growing AuNCs within the COF pores, which prominently boosted its ECL emission due to enhanced electron transfer and radiative transition efficiency. In the presence of ZEN, the Cu^{2+} -activated DNAzyme walker cleaved the quencher MB-labeled substrate strands to restore the ECL signal. Consequently, the ECL intensity exhibited a progressive increase with increasing ZEN concentrations, yielding a broad linear range from 0.0001 to 100 ng/mL and an ultralow LOD of 52 fg/mL. This sensor demonstrated excellent performance, featuring excellent reproducibility, good stability, and satisfactory selectivity against

interfering mycotoxins (Figure 11). At the same time, Valence state regulation provides a streamlined sensing paradigm that bypasses the complexities of signal amplification and aptamer modification. Huang et al. [92] developed an ultrasensitive ECL biosensor for kanamycin (KAN) detection by modulating the valence states of AuNCs. In this system, KAN facilitated the oxidation of Au(0) in CR-AuNCs to Au(I) in the presence of H_2O_2 , leading to a significant quenching of the ECL signal. This direct-readout strategy achieved exceptional sensitivity without an auxiliary amplification process, which delivered a broad linear range from 10 pM to 33 μM and a lower LOD of 1.5 pM. Moreover, it exhibited excellent selectivity over other potential interferences (Figure 12).

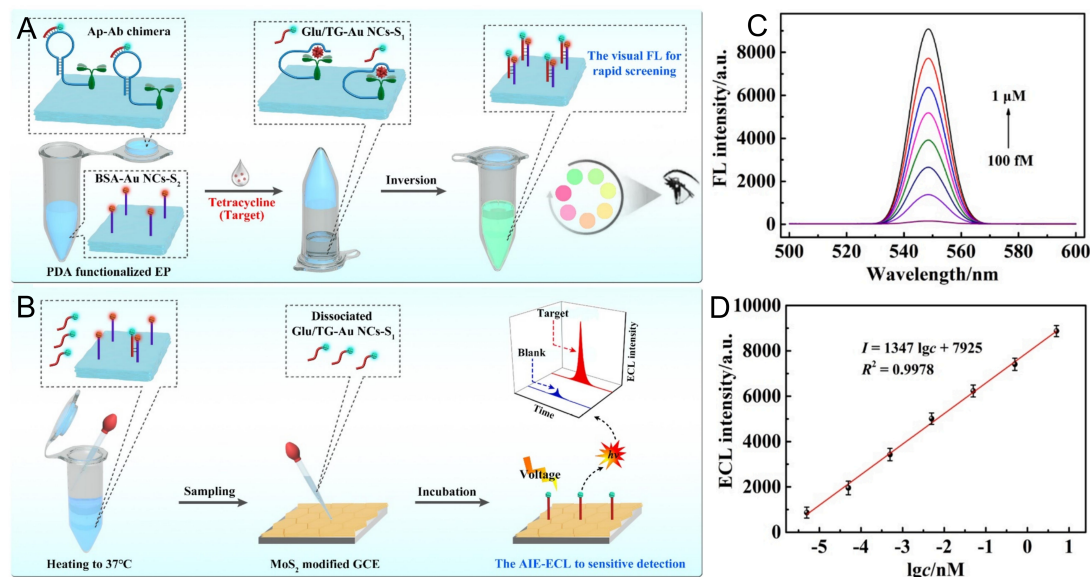


Figure 10. (A,B) Diagram of a portable Glu/TG-Au NCs-based FL-ECL dual-signal biosensor for TC detection. (C) FL responses of POCT with various TC concentrations. (D) The calibration linear curve for TC detection. Reprinted with permission from Ref. [90]. Copyright 2025, Elsevier.

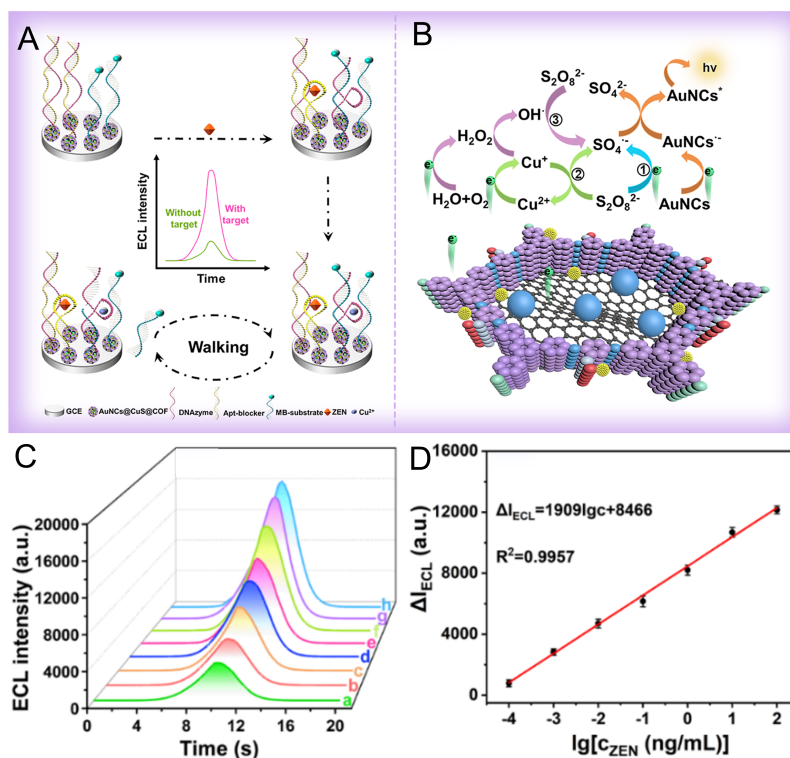


Figure 11. Schematic illustration of (A) fabrication process of ECL sensing Platform for ZEN detection and (B) ECL amplification mechanism by nanoconfinement-induced active radical enrichment and a co-reaction accelerator. (C) ECL response to ZEN at different concentrations (a–h: 0–100 ng/mL) and (D) Calibration curve for ZEN (from 0.1 pg/mL to 100 ng/mL). Reprinted with permission from Ref. [91]. Copyright 2025, American Chemical Society.

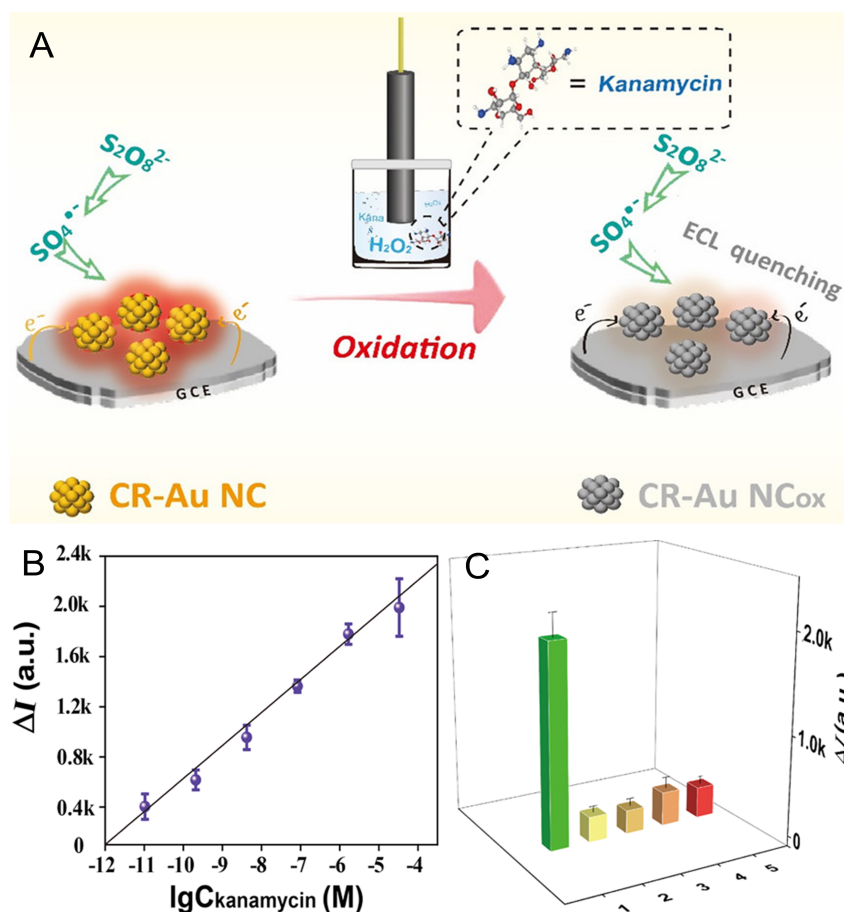


Figure 12. (A) Illustration of a sensitive ECL sensor based on AuNCs by direct valence regulation for accurately detecting KAN. (B) Linear relationship between relative ECL intensity and logarithm of KAN concentration. (C) Selectivity of the proposed KAN detection method (1–5: KAN, neomycin, spectinomycin, tobramycin, and streptomycin). Reprinted with permission from Ref. [92]. Copyright 2021, American Chemical Society.

6. Conclusions and Outlook

In summary, this review has systematically elucidated the research progress of AP-AuNCs in ECL, spanning from fundamental theories to practical applications. Despite significant breakthroughs, there are still several critical challenges to be addressed urgently. Future research may focus on the following directions:

(1) Elucidating the fundamental mechanisms of excited-state dynamics. Existing studies rely predominantly on steady-state electrochemical measurements, leaving the dynamic processes of charge-transfer kinetics, spin relaxation, and non-radiative decay channels insufficiently understood. Therefore, the synergistic integration of high-precision theoretical calculations and advanced characterization techniques (such as *in-situ* time-resolved spectroscopy and single-molecule ECL imaging) is poised to decipher the full kinetic chain of excited-state evolution at ultrafast timescales, thereby deconstructing the fundamental physical determinants of ECL efficiency to provide essential design criteria for next-generation high-performance systems.

(2) Establishing quantitative structure-activity relationships and enabling “on-demand design”. Current orbital modulation strategies remain largely empirical, and quantitative structure-activity relationships linking HOMO/LUMO energy levels, spin-orbit coupling, and charge separation efficiency to ECL performance have yet to be established. Future efforts should integrate high-throughput synthesis, machine learning, and quantum chemical calculations to construct predictive models and databases of “structure-orbital-ECL performance”, thereby enabling atomically precise “on-demand design” of high-performance ECL luminophores to overcome the inherent limitations of empirical optimization.

(3) Scaling up synthesis and optimizing biocompatibility for clinical translation. Atomically precise synthesis is currently confined to small-batch laboratory preparation, suffering from low yields and poor batch-to-batch consistency. Meanwhile, *in vivo* circulation stability, targeting specificity, and metabolic safety remain suboptimal, constituting the core bottleneck for clinical translation. Future research should develop efficient, controllable, and scalable precision synthesis methods, and optimize *in vivo* stability and biocompatibility through multifunctional

surface modification, thereby accelerating the translation of AP-AuNCs ECL technology toward clinical scenarios such as bedside diagnostics and *-in vivo* imaging.

(4) Synergizing multiple strategies to push performance limits and expand industrial applications. Individual modulation strategies inevitably face inherent performance boundaries. Future research can synergistically combine ligand engineering, alloying, and heterojunction engineering to achieve coordinated optimization of orbital energy levels, electron-transfer kinetics, and non-radiative decay suppression, while coupling with high-efficiency luminescence mechanisms such as pre-oxidation and aggregation-induced emission to break through the performance limits of quantum yield, stability, and emission wavelength tunability. Furthermore, integrating microfluidic chips and portable electrochemical workstations to develop miniaturized ECL detection platforms will promote the industrial application of this technology in on-site environmental monitoring, rapid food safety screening, and point-of-care diagnostics.

Author Contributions

T.H.: Conceptualization, data curation, investigation, writing—original draft preparation, writing—reviewing and editing, funding acquisition; J.Z.: Investigation, data curation, writing—reviewing and editing; E.Z.: Formal analysis; P.L.: Writing—reviewing and editing; G.S.: Writing—reviewing and editing, funding acquisition; J.X.: Conceptualization, writing—reviewing and editing, supervision, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

No data was used for the research described in the article.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

List of Abbreviations

Abbreviation	Full Name
AP-AuNCs	Atomically precise gold nanoclusters
AuNCs	Gold nanoclusters
Au(0)	Zero-valent gold
Au(I)	Monovalent gold
SR	Thiolate ligand
MOFs	Metal-organic frameworks
COFs	Covalent organic frameworks
QDs	Quantum dots
ECL	Electrochemiluminescence
AIECL	Aggregation-induced electrochemiluminescence
AIE	Aggregation-induced emission
RET	Resonance energy transfer
HOMO	Highest occupied molecular orbital
LUMO	Lowest unoccupied molecular orbital
LMCT	Ligand-to-metal charge transfer
MLCT	Metal-to-ligand charge transfer
NIR	Near-infrared
TPrA	Tripropylamine
TEA	Triethylamine
DIPEA	N,N-Diisopropylethylamine
LOD	Limit of detection

ELISA	Enzyme-linked immunosorbent assay
FL	Fluorescence
ZEN	Zearalenone
OTA	Ochratoxin
AFB1	Aflatoxin B1
<i>S. aureus</i>	<i>Staphylococcus aureus</i>
PSA	Prostate-specific antigen
<i>VP</i>	<i>Vibrio Parahaemolyticus</i>
A β 40	β amyloid protein 40
CRP	C-reactive protein
NSE	Neuron-specific enolase
suPAR	Soluble urokinase-type plasminogen activator receptor
CA15-3	Carbohydrate antigen 15-3
IGF-1	Insulin-like growth factor 1
AD7c-NTP	Alzheimer's disease-associated neuronal thread protein
GFAP	Glial fibrillary acidic protein
MCU-1	Mitochondrial calcium uptake 1
TAU	Microtubule-associated protein
DA	Dopamine
HBV	Hepatitis B virus
CEA	Carcinoembryonic antigen
TC	Tetracycline

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