REVIEW ARTICLE
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Photo/electrocatalysis and photosensitization using metal nanoclusters for green energy and medical applications
Photo/electrocatalysis and photosensitization using metal nanoclusters for green energy and medical applications

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Owing to the rapidly increasing demand for sustainable technologies in fields such as energy, environmental science, and medicine, nanomaterial-based photo/electrocatalysis has received increasing attention. Recently, synthetic innovations have allowed the fabrication of atomically precise metal nanoclusters (NCs). These NCs show potential for green energy and medical applications. The present article primarily focuses on evaluation of the recent developments in the photo/electrocatalytic and photosensitizing characteristics of metal and alloy NCs. The review comprises two sections: (i) photo/electrocatalysis for green energy and (ii) photosensitization for biomedical therapy applications. Finally, the challenges associated with the use of metal NCs are presented on the basis of current developments.

1. Introduction

During the past few decades, photocatalysis and electrocatalysis have received significant attention as a result of the increasing demand for sustainable technologies in the fields of energy, environmental science, and medicine. Photo/electrocatalytic approaches rely on electronic excitation, and their performance depends on the ability to create electron (e−)–hole (h+) pairs that successively undergo chemical reactions with other compounds via oxidative (e.g., \( \text{2H}_2\text{O}(l) \rightarrow \text{O}_2(g) + 4\text{H}^+(aq) + 4e^- \)) and reductive reactions (e.g., \( 2\text{H}^+(aq) + 2e^- \rightarrow \text{H}_2(g) \)). Many advanced nanomaterial-based photo/electrocatalysts have been synthesized and reported, and their advantages include large surface-to-volume effects, numerous catalytic active sites, quantum size effects and high stability. These catalysts are considered to be promising for energy and environmental applications, such as photo/electro water splitting to generate hydrogen (H₂) and conversion of carbon dioxide (CO₂). Furthermore, they are used in the fuel industry and in water treatment and disinfection, air purification, and self-cleaning surfaces. Usually, the term “photo/electrocatalysis” refers to photo/electrochemical reactions, which involve an electron transfer. Conversely, when energy transfer occurs in
a photochemical reaction, the process is often called “photosensitization”. Triplet photosensitizers are used not only for triple junction energy transfer, but are also utilized in photodynamic therapy (PDT) for medical applications.\(^7\)

One drawback of these nanomaterial-based photo/electrocatalysts is that they are generally poly-dispersed in size, morphology, and chemical composition. The heterogeneity of photo/electrocatalysts with multiple active sites often results in different catalytic activities and varying catalytic selectivity. Therefore, it is important to fabricate nanomaterial-based photo/electrocatalysts that can be controlled well at the atomic level.

Recent synthetic innovations have allowed the fabrication of atomically precise metal nanoclusters (NCs).\(^8\)–\(^18\) These metal NCs contain a few to hundreds of metal atoms that are protected by organic ligands (e.g., thiolate, phosphine, small molecules, synthetic polymers, and biomolecules). Particularly, thiolate-protected metal NCs and their alloy NCs can be prepared with atomic precision as \(\text{M}_n\text{(SR)}_m\) (M = gold (Au), silver (Ag), copper (Cu), platinum (Pt), palladium (Pd), or other element; SR = thiolate ligand) in a wide range of sizes by varying the \(n\) and \(m\) values. As mentioned previously, such NCs have potential applications in the fields of energy, environmental science, medicine, and other.\(^8\)–\(^13\) The \(\text{M}_n\text{(SR)}_m\) NCs have discrete energy levels due to the quantum size effect, making them significantly different from the larger (>3 nm) plasmonic metal (Au or Ag) nanoparticles (NPs) with continuous energy levels. By adjusting \(n\) and \(m\), one can control the discrete electronic/geometrical structure of \(\text{M}_n\text{(SR)}_m\) NCs and thereby their photosensitizing and photo/electrocatalytic capability. Recently, several excellent reviews have discussed the syntheses of metal NCs,\(^14\) photoluminescence,\(^14\) and their biomedical\(^15\)–\(^17\) and catalytic applications.\(^18\) However, to the best of our knowledge, there are no publications focusing on the photo/electrocatalytic and photosensitizing characteristics of metal NCs for applications in the green energy and medical fields. Therefore, a survey of recent progress, with a view to improving the photo/electrocatalytic and photosensitizing capability of metal NCs is needed.

In this review, we discuss recent achievements and evaluate the photo/electrocatalytic and photosensitizing characteristics of metal NCs and their alloy NCs. The review comprises two sections: (i) photo/electrocatalysis and photosensitization for green energy applications (specifically solar cell), and (ii) photosensitization for medical therapeutic applications (Fig. 1). We hope to provide a clear picture on how the photo/electrocatalytic and photosensitizing capability of metal NCs can improve their performance and promote the development of new green energy and medical applications.

### 2. Photo/electrocatalysis of metal NCs for green energy applications

In this section, we discuss recent progress of the photo/electrocatalytic (specifically reaction of water splitting and fuel cells) and photosensitizing applications (specifically solar cell) of metal NCs (Pd, Ag, Pt, or Au) and their alloy NCs. We summarized references used in this section in Table 1.

#### 2.1. Electrocatalytic applications for water splitting

Water electrolysis is one of the cleanest energy-producing processes, generating \(\text{H}_2\) using only water and electricity, which is regarded as the next-generation energy source or raw material for chemicals. Water electrolysis comprises two half-reactions, which are the \(\text{H}_2\) evolution reaction (HER) and the \(\text{O}_2\) evolution reaction (OER). When supplying electricity to metal electrodes, a reduction reaction occurs on the cathode and an oxidation reaction on the anode, and thereby water molecules are split into \(\text{H}_2\) and \(\text{O}_2\). However, the reaction does not proceed if the voltage supplied to the electrodes is higher than the redox potential of each reaction (HER: 0 V vs. SHE, OER: 1.23 V vs. SHE) due to the high activation energy. Therefore, investigations have been conducted to enhance the reactions using metal catalysts, such as precious metal NPs. An increased specific surface area of the active sites in the metal...
Table 1 Chemical reaction and summarized references in Section 2

| Section | Reaction                                      | Clusters | References |
|---------|-----------------------------------------------|----------|------------|
| 2.1.1   | \( \text{H}_2 \) evolution reaction           | Pt       | 24 and 25  |
| 2.1.1   | \( \text{H}_2 \) evolution reaction           | Pd       | 26 and 34  |
| 2.1.1   | \( \text{H}_2 \) evolution reaction           | Au       | 27–34      |
| 2.1.2   | \( \text{O}_2 \) evolution reaction           | Pd       | 26         |
| 2.1.2   | \( \text{O}_2 \) evolution reaction           | Au       | 40 and 41  |
| 2.2     | Electrochemical reaction for fuel cells       | Pt       | 45–48 and 55 |
| 2.2     | Electrochemical reaction for fuel cells       | Au       | 49–54 and 56 |
| 2.3     | Photocatalytic water splitting reaction       | Pt       | 58 and 59  |
| 2.3     | Photocatalytic water splitting reaction       | Au       | 60–64, 67 and 68 |
| 2.4     | Redox reaction for solar cell                 | Ag       | 65 and 66  |
| 2.4     | Redox reaction for solar cell                 | Au       | 69, 71 and 73–78 |
| 2.4     | Redox reaction for solar cell                 | Ag       | 70 and 72–74 |
| 2.4     | Redox reaction for solar cell                 | Pt       | 71         |
| 2.4     | Redox reaction for solar cell                 | Pd       | 71         |

On the other hand, under alkaline conditions, the following reaction sequence occurs:

Volmer reaction:
\[
\text{H}_2\text{O} + \text{e}^- \leftrightarrow \text{H}_{\text{ads}} + \text{OH}^-
\]

Heyrovsky reaction:
\[
\text{H}_{\text{ads}} + \text{H}_2\text{O} + \text{e}^- \leftrightarrow \text{H}_2 + \text{OH}^-
\]

Tafel reaction:
\[
2\text{H}_{\text{ads}} \rightarrow \text{H}_2
\]

Here, the “ads” subscript denotes a reaction site on the catalyst surface. So far, noble metals, such as Pt, have been known for their high activity in HER, and attempts have been made to increase this activity further via miniaturization of the metals, and to predict their activity using density functional theory (DFT) calculations. For example, Sun et al. studied the HER characteristics by preparing single Pt atoms and Pt NCs supported on nitrogen-doped graphene nanosheets (NGNs) using the atomic layer deposition technique. The results revealed that the HER activity of Pt atoms on Pt NCs (ALD50P) was 10.1 A mg\(^{-1}\), which is 37.4 times higher than the activity of the commercial carbon-supported Pt NP (Pt/C) catalyst (0.27 A mg\(^{-1}\)) (Fig. 2A and B). Furthermore, Chen et al. demonstrated that Pt NCs confined in a calixarene-based Ni\(_{24}\) coordination cage (Fig. 2C) show much higher activity in HER than the commercial Pt/C catalyst (Fig. 2D and E). The same group also reported that the activated carbon-supported Pd\(_6\) (Pd\(_6\)/AC-V; the ligands were removed in this case) shows the current density at 10.22 times higher than the commercial Pt/C catalyst at \(-0.423\) V.

In contrast, bulk Au, which belongs to group 11, shows almost no HER activity. Reduction of the size to the cluster region, however, results in changes in the electronic structure, and thereby Au NCs exhibit HER activity. Based on the recent studies, Au NCs can now be synthesized using a very simple and easy approach. Moreover, the sizes can be controlled at atomic precision and their functions can be modulated via ligand exchange and heteroatom doping. In recent years, a number of studies have been conducted on the HER activity of Au NCs. For example, Teraishi and Sakamoto et al. studied the effect of the ligand structure on the HER activity using porphyrin-coordinated Au NCs (Fig. 3). In their study, the distance between the porphyrin-ring and the surface sulfur (S) directly bonded to Au NCs was controlled by varying the number of methylene groups between those moieties (Fig. 3A and C). They found that the HER activity increases with decreasing distance between the porphyrin-ring and the Au NC surface (Fig. 3G and H). In addition, it was demonstrated that tetakis-5\(a\),10\(a\),15\(a\),20\(a\)-(2-acetylthiomethylphenyl) porphyrin (SC\(_1\)P)-protected Au NCs, with a 3.4 Å distance between the porphyrin-ring and the Au NC surface, show a high current density of 460% at 0.4 V vs. RHE, in comparison with Au NCs protected by ordinary phenylethanethiolate (PET). The study also demonstrates that the ligand structure strongly affects the HER activity and that the smaller Au\(_{6}\)(SR)\(_{3}\)m NCs exhibit the higher HER activity.
On the other hand, Lee and Jiang et al. investigated the effect of heteroatom doping of Au\textsubscript{n}(SR)\textsubscript{m} NCs on the HER activity. They examined the HER activity of hexanethiolate (C\textsubscript{6})-protected Au\textsubscript{25} and PtAu\textsubscript{24} NCs in a tetrahydrofuran (THF) electrolyte containing 1.0 M trifluoroacetic acid (TFA) (Fig. 4A–C). The obtained results demonstrated that PtAu\textsubscript{24} NC has better catalytic activity with a higher starting potential (E\textsubscript{0} = 0.89 V) than Au\textsubscript{25} NC (E\textsubscript{0} = 1.10 V). The same research group showed that the improved catalyst current and turnover frequency can be obtained even with Pd as the central atom, instead of Pt (PtAu\textsubscript{24} > PdAu\textsubscript{24} > Au\textsubscript{25}). The same tendency can be observed for the other-sized C\textsubscript{6}-protected Au\textsubscript{38} NCs (Pt\textsubscript{2}Au\textsubscript{36} > Pd\textsubscript{2}Au\textsubscript{36} > Au\textsubscript{38}). These results are in good agreement with those obtained from DFT calculations, which predicted that the HER activity significantly varies depending on the doping elements. Hence, the control of the electronic structure by alloying at the atomic level greatly affects the HER activity in the cluster size range.

In addition to these studies, Jin et al. investigated the HER activity of the composite comprising PET-protected Au\textsubscript{25} NCs and molybdenum disulfide (Mo\textsubscript{S\textsubscript{2}}) nanosheet (Mo\textsubscript{S\textsubscript{2}} nanosheet carrying PET-protected Au\textsubscript{25}; Au\textsubscript{25}/Mo\textsubscript{S\textsubscript{2}}; Fig. 4D and E). The Au\textsubscript{25}/Mo\textsubscript{S\textsubscript{2}} showed a current density 1.79 times higher than that of Mo\textsubscript{S\textsubscript{2}} at ~0.4 V, indicating that the improvement of HER activity of Mo\textsubscript{S\textsubscript{2}} nanosheet was caused by loading Au\textsubscript{25} NCs. X-ray photoelectron spectroscopy analysis showed that a negative shift of ~0.4 eV in the Mo 3d orbital energy was induced by loading Au\textsubscript{25} NCs. This implies that the partial charge transfer occurs from Au\textsubscript{25} NCs to Mo\textsubscript{S\textsubscript{2}}, leading to the increased HER activity. The HER activity of the composite is, therefore, considerably improved by the electronic interaction between the materials. Regarding the HER activity of the composite comprising Mo\textsubscript{S\textsubscript{2}}, Zhu et al. also evaluated Au\textsubscript{2}Pd\textsubscript{6}/Mo\textsubscript{S\textsubscript{2}}.

2.1.2. \textit{O}_2 evolution reaction. OER is a multi-step four-electron reaction dependent on the binding energy of the OER intermediate (OH, O\textsubscript{ads}, OO\textsubscript{ads}, etc.). Under acidic conditions, the reaction proceeds as follows:

\[
\text{H}_2\text{O} \rightarrow \text{OH}_{\text{ads}} + \text{H}^+ + e^- \\
\text{OH}_{\text{ads}} \rightarrow \text{O}_{\text{ads}} + \text{H}^+ + e^- \\
\text{O}_{\text{ads}} + \text{H}_2\text{O} \rightarrow \text{OOH}_{\text{ads}} + \text{H}^+ + e^- \\
\text{OOH}_{\text{ads}} \rightarrow 2\text{O}_{\text{ads}} + \text{H}^+ + e^- 
\]
On the other hand, under alkaline conditions, the following reaction sequence takes place:

\[
\begin{align*}
\text{OH}^- & \rightarrow \text{OH}_{\text{ads}} + e^- \\
\text{OH}_{\text{ads}} + \text{OH}^- & \rightarrow \text{O}_{\text{ads}} + \text{H}_2\text{O} + e^- \\
\text{O}_{\text{ads}} + \text{OH}^- & \rightarrow \text{OOH}_{\text{ads}} + e^- \\
\text{OOH}_{\text{ads}} + \text{OH}^- & \rightarrow 2\text{O}_{\text{ads}} + \text{H}_2\text{O} + e^- \\
2\text{O}_{\text{ads}} & \rightarrow \text{O}_2
\end{align*}
\]

According to this reaction pathway, the OER activity of the catalyst generally depends on the binding energy of the OER intermediates on the surface (O, OH, OOH, etc.). An appropriate binding energy of the oxygen species (neither too high nor too low) enables the catalyst suitable for OER. For this reason, the metal oxides, such as iridium oxide (IrO$_2$), ruthenium oxide (RuO$_2$), exhibit high activity. Therefore, extensive efforts have been made on their miniaturization, the theoretical prediction of the activity and the mechanism.$^{15-18}$

Moreover, research regarding cluster-sized particles is progressing. Chen and Gao reported that dodecanethiolate (C12)-protected Pd$_6$/AC exhibits a current density 37 times higher than that of commercially available Pt/C at an applied voltage of 1.83 V (Fig. 5A and B).$^{26}$ Although ligands were considered to be disadvantageous for electrode reactions, this study revealed that the higher electron density of C12-protected Pd$_6$/AC enhances the desorption process of oxygen atoms or molecules and is favorable for OER. In addition, there are several reports describing the suitability of Mn(SR)$_m$ NCs for OER. For example, Hussain and Joya et al. reported that the OER activity of Ni$_4$(PET)$_8$ NC is equal to that of a RuO$_2$ electrocatalyst.$^{39}$

As with HER activity, OER activity has also been studied for the composites including Au NCs. Jin et al. investigated the OER activity of the composite comprising PET-protected Au$_{25}$ NCs and cobalt diselenide (CoSe$_2$) nanosheet (CoSe$_2$) nanosheet carrying PET-protected Au$_{25}$; Au$_{25}$/CoSe$_2$ and revealed that Au$_{25}$/CoSe$_2$ shows a current density of 10 mA cm$^{-2}$ with a small overvoltage of approximately 0.43 V (≈0.52 V with CoSe$_2$ alone) (Fig. 6).$^{40}$ The group also investigated the effect of Au NC size on OER activity using a series of Au$_n$(SR)$_m$ NCs (Au$_{10}$, Au$_{25}$, Au$_{144}$, and Au$_{333}$). It was revealed that OER activity increases with increasing the Au NC size. Furthermore, Peng and Zeng demonstrated that Au NC/CoSe$_2$ is superior for increasing the OER activity compared to commercially available Ir/C.$^{41}$

### 2.2. Electrocatalytic application for fuel cells

The ultimate energy-conversion systems used for power generation are fuel cells utilizing materials such as H$_2$ and methanol obtained from natural energy sources. Such methods involve circulating energy systems that do not use any fossil fuels and only release water as the waste product.

Fuel cells are roughly classified into those using alcohol and those using H$_2$. The latter involves the H$_2$ oxidation reaction (HOR) and O$_2$ reduction reaction (ORR), which are the reverse reactions of HER and OER, respectively. HOR is a one-electron reaction system where the catalysts displaying HER-activity can be useful. In contrast, ORR is a four-electron reaction system, and since it proceeds through a complex reaction pathway, its reactivity is different from that of OER.

![Fig. 4](image-url)  
Fig. 4 (A) Geometrical structures of C6-protected Au$_{25}$ and PtAu$_{24}$ NCs (golden, gold atoms of the core; olive, gold atoms of the shell; grey, sulfur). (B) The square-wave voltammogram. (C) HER polarization curves of C6-protected Au$_{25}$ and PtAu$_{24}$ NCs. (D) High angle annular dark-field SEM (HAADF-STEM) images. (E) HER polarization curves of the C6-protected Au$_{25}$/MoS$_2$ composite. Panels (a)–(c) are reproduced with permission from ref. 29. Copyright 2017 Springer Nature. Panels (d) and (e) are reproduced with permission from ref. 33. Copyright 2017 Wiley-VCH.

![Fig. 5](image-url)  
Fig. 5 (A) OER polarization curves. (B) Mass OER activity of Pd$_6$/AC, Pd$_6$/AC-V and Pt/C at each overpotential. Panels (a) and (b) are reproduced with permission from ref. 26. Copyright 2017 Royal Society of Chemistry.
reduction side is slower than on the oxidation side, the former is the rate-limiting step in the fuel cell. Hence, understanding the factors controlling ORR and thereby the creation of high-performance ORR catalysts are essential for the development of efficient fuel cells.

Since Pt exhibits high ORR activity as well as high OER activity, the development of the miniaturization techniques, prediction of the activity by theoretical calculations, and the mechanism for Pt NCs have been studied extensively.42–44 For example, Yamamoto et al. examined the ORR activity of fine Pt NCs (PtX, NC, n = 12–24) using dendrimer-encapsulated atomically-controlled PtX NCs (Fig. 7).45 The results demonstrated that Pt19 NC exhibits the highest ORR activity (Fig. 7E). The edge site of Pt19 has an ideal oxygen binding energy, which indicates that in addition to the electronic structure, the geometrical structure affects the ORR activity.46–48

Moreover, the use of AuX(SR)m NCs as catalysts for ORR has also attracted significant attention as an alternative to expensive Pt catalysts and to evaluate the catalytic reaction mechanism. Chen et al. reported that the ORR activity increases with a decrease of Au NC size (Au25(PET)18 > Au30(PET)24 > Au144(PET)60).49–51 This increase is suggested to be due to the enhancement of the oxygen adsorption caused by increasing the proportion of surface atoms and shifting the d-band center associated with a decrease of Au NC size. Chakraborty and Dass et al. synthesized a series of 4-tert-butylbenzenethiolate (TBBT)-protected Au NCs and analyzed the ORR activity of Au NCs supported on single-walled carbon nanotubes.52 The study on the reaction rate revealed that the ORR activity increases in the order of Au36(TBBT)24 > Au133(TBBT)32 > Au279(TBBT)84 > Au32(tBBT)20 (Fig. 8C and D). The same research group also used tert-butylthiolate (S-tBu) as a ligand and showed that the ORR activity increases in the order of Au46(S-tBu)24 > Au30(S-tBu)18 > Au36(S-tBu)16 in the case of S-tBu-protected Au NCs.53

In addition to the NC size, the control of charge state of NCs is also a crucial factor for obtaining high activity. For example, the negatively charged Au25(PET)18 NC shows higher activity in the production of H2O2, which is a two-electron reduction reaction, than the neutral Au25(PET)18 NC (Fig. 8E and F).54 Since H2O2 is a useful raw material for a variety of chemical products, the development of a highly selective H2O2 production method is of importance. Likewise, the interaction with the substrate also requires consideration. Pt or Au NCs supported on various substrates, such as indium tin oxide (ITO)55 and reduced graphene oxide (rGO) sheets56 show outstanding electrocatalytic performance in ORR, which was found to be originated in the interaction between metal NC and the substrate.

2.3. Photocatalytic application for water splitting

Artificial photosynthesis, which has attracted significant attention in recent years, is an ultimate energy production technique involving conversion of light into chemical energy. In 1972, Honda and Fujishima et al. discovered that water can be split into H2 and O2 by irradiating the titanium dioxide (TiO2) photocatalyst with ultraviolet light.57 Utilizing this method allows
efficient generation of H₂ as an energy source using abundant water, without the production of carbon dioxide. In the photocatalytic water splitting reaction, the catalyst comprises a photocatalyst, which absorbs light, and a cocatalyst whose role is to reduce the overpotential of HER and OER. Moreover, the photocatalyst uses light energy instead of electric energy as the driving force for HER or OER. Therefore, the position of the conduction and valence bands and the width of the bandgap are essential factors when considering the photocatalyst.

Highly active metal NCs in electrochemical HER and OER are effective cocatalysts in photocatalytic systems. The photocatalytic reaction involves several key steps: (1) generation of the e⁻/h⁺ pair in the photocatalyst, (2) transfer of the e⁻ and h⁺ to the active sites, and (3) generation of H₂ and O₂ at the active sites. Here the cocatalyst greatly affects processes (2) and (3). The photodeposition and impregnation methods are typical approaches for loading cocatalysts on photocatalysts. They offer several advantages, such as the formation of fine metal particles directly on the photocatalyst. However, the disadvantages of these methods include large size dispersibility.

It is possible to load the controlled NC on photocatalyst and thereby to deepen the understanding on the effect of cocatalyst size on the photocatalytic activity when using an ultra-high vacuum apparatus. Heiz, Feldmann, and Jäckel et al. loaded a series of atomically precise Pt NCs (Pt₁₃, Pt₁₇, and Pt₁₉ NCs) on cadmium sulfide (CdS) nanorod utilizing an ultra-high vacuum apparatus (Fig. 9A and B).³⁸,⁵⁹ They investigated the water-splitting activity of the resulting photocatalysts (Pt NC/CdS) and consequently revealed that Pt₄₆/CdS exhibits the highest activity (Fig. 9C). In the NC region, the bandgap increases with a decrease of the NC size due to the quantum size effect. It was also reported that the control of the lowest unoccupied molecular orbital (LUMO) position of the cocatalyst by controlling the NC size is of great importance for the effective electron transfer from the photocatalyst to the cocatalysts. Furthermore, the group demonstrated that the LUMO position must be lower than the conduction band of the semiconductor photocatalysts and higher than the reduction potential of HER (Fig. 9D).

As well as investigation into electrochemical properties of HER and OER, research on photocatalytic water splitting is rapidly progressing also for Auₙ(SR)ₘ NCs. Negishi and Kudo et al. developed a photocatalytic system comprising atomically precise Au₃₅ NC and the BaLa₄Ti₄O₁₅ photocatalyst (Fig. 10).⁶⁰ In this study, the atomically precise Au₃₅ NC was loaded on the...
on BaLa₄Ti₄O₁₅ and subsequently eliminating the SG ligands by calcination. TEM analysis of the products confirmed that NC-size change barely occurred during the calcination. The resulting Au₂₅/BaLa₄Ti₄O₁₅ composite generates both H₂ and O₂ in a stoichiometric ratio upon light irradiation and the catalytic activity is 2.6 times higher than that of Au NP loaded-BaLa₄Ti₄O₁₅ (Fig. 10A). The same group also revealed that the smaller the particle size, the higher the activity (Fig. 10B). In their more recent study, it was described that the ORR, which is a reverse reaction, can be suppressed by coating the Au₂₅ NC with Cr₂O₃, and thereby the activity was improved by 19-fold compared to the non-coated Au₂₅/BaLa₄Ti₄O₁₅ (Fig. 10C–E). The cocatalysts with high HER and OER activities typically display good activity in HOR and ORR. Overall, as shown in this study, the control of the reverse reaction is an important factor for improving the activity.

The photocatalytic activity could also be modulated by heteroatom doping on the cocatalysts. Negishi and Yamazoe et al. demonstrated that Pd doping on Au₁₃₅ NC reduces the water-splitting activity, whereas Pt doping on Au₁₃₅ NC enhances it (Fig. 11A–F). Yang et al. also examined the effect of heteroatom doping on the photocatalytic activity of PtAg₂₄-loaded graphitic carbon nitride (PtAg₂₄/g-C₃N₄). They revealed that PtAg₂₄/g-C₃N₄ shows higher activity for photocatalytic H₂ production than Ag₂₅/g-C₃N₄ (Fig. 11G and H). In addition to the above studies, there are several reports on water-splitting photocatalytic activity using composites including metal NCs, such as graphitic carbon nitride nanosheets carrying mercaptosuccinic acid-protected Ag₉ NC, TiO₂ carrying SG-protected Au NC, etc.  

2.4. Photosensitization for solar cell applications

Solar power generation systems, which directly convert light energy into electricity, continue to be important renewable energy sources and are the key components of the world’s technological advancement. A photoelectrode cell, commonly known as the solar cell, comprises a light absorption layer, a photoresponse was observed (Fig. 12A and B) and its photocurrent behavior was consistent with photocurrent action spectrum and absorption spectrum (Fig. 12C and D). These results indicate that an electron is excited and promoted from the HOMO to the LUMO by photoirradiation in Au NC and that the photoexcited electron of LUMO is transferred to the CB of TiO₂. In this way, the Au NC functions like a dye in dye-sensitized solar cells (DSSCs). The same research group observed the generation of photovoltaic power even when the other element NCs (Ag, Pt and Pd NCs) were employed. In addition, various other metal and alloy cluster sensitized solar cells have been reported by a number of research groups.

Regarding the solar cells, Kamat et al. achieved a high external quantum efficiency (EQE) of 70% at 400–425 nm by
using a Co(bpy) redox pair (Co(bpy)3(PF6)2/Co(bpy)3(PF6)3) in SG-protected Au NC/TiO2 system (Fig. 13). This value compares favorably even with the CdS-based quantum dot solar cells. The power conversion efficiency (PCE) was 2.36% at maximum, indicating that metal NCs can act as a high-performance sensitizer in sensitized solar cells. Bang, Kang, and Lee et al. achieved a PCE value as high as 3.8% when investigating SG-protected Au18 NC/TiO2 solar cells using the I2/I3 redox pair (Fig. 14).76 They reported that Au18 NC barely underwent exciton recombination and absorbed light in a wide wavelength range, resulting in high solar cell characteristics (Fig. 14A–C).

However, to improve the stability of the system, other ligand-protected metal NCs should be used. Pradeep et al. compared the photovoltaic performance of solar cells using various ligand-protected metal NCs, such as bovine serum albumin, TBBT, and 4-mercaptobenzoic acid.77 They reported that the Au30 NC protected with bovine serum albumin has highest PCE (0.35%).

In the described systems, there is a correlation between the expansion of the light absorption wavelength range of the metal NCs and the decrease in opening photovoltage accompanying the bandgap decrease. To further improve the PCE, combination with other light-absorbing materials is required. DSSC using a squalene dye as the co-sensitizer was reported to provide a PCE of 4%,77 and a maximum PCE of 9.15% (ref. 78) by incorporating Au38 clusters in organic thin-film solar cells.

3. Photosensitization of metal NCs for therapeutic applications

3.1. Photo-based therapeutic applications of water-soluble metal NCs

Water-soluble noble metal (such as Au and Ag) NCs are composed of a metal core with several to a few hundred atoms, capped by water-soluble ligands such as amino acids, peptides, proteins, deoxyribonucleic acid (DNA), and hydrophilic thiolate ligands with different functional groups (e.g., –COOH, –OH, and –NH2). These water-soluble metal NCs exhibit unique physico-chemical properties including high photostability, low toxicity, and luminescence. In addition, the good penetration of such ultra-small metal NCs into the cells, the ability to target tumors through:

![Image](image_url)
proper surface modification, and their superior renal clearance make the water-soluble metal NCs promising materials for utilization in the field of biomedicine, e.g., bioimaging, sensing, drug delivery, and diagnostic and therapeutic applications.

Cancer is a class of common life-threatening diseases, understanding of which is incomplete, despite significant efforts and extensive research. Developed therapies against cancer include chemotherapy (chemo-T), radiotherapy (RT), surgery, immunotherapy, NPs-based therapy, photothermal therapy (PTT), and PDT.77 Among them, PDT is considered clinically reliable and non-invasive. In this method reactive oxygen species (ROS) generated by a photosensitized tumor kill the tumor cells.

Traditional PDT utilizes organic photosensitizers with organic dye molecules such as porphyrin and its derivatives, chlorin e6, methylene blue, rose bengal, eosin Y, and indocyanine green. However, organic photosensitizers suffer from common drawbacks including low water-solubility, poor selectivity, toxicity, and photo-instability. Meanwhile, known inorganic photosensitizers include quantum dots, silicon nanocrystals, fullerene (C60), and metal NPs.80–83 More recently, Auₙ(SR)ₙ NCs have been considered as promising photosensitizers for PDT. Their electronic structures can be optimized for efficient singlet oxygen (¹O₂) production using atomically precise size control. Several fundamental properties of the Auₙ(SR)ₙ NCs are also desirable for PDT, such as good biocompatibility in dark conditions, photosensitization under near-infrared light irradiation, good resistance to photo-bleaching, and target specificity via surface modification. The following section focuses on the photosensitizing ability of Auₙ(SR)ₙ NCs toward PDT applications. A number of recent reviews on other biomedical applications of metal NCs have also been published.15–17

3.2. Basic principle of photosensitization for PDT

Upon absorbing the appropriate light, the photosensitizer transitions from the ground singlet state (S₀) to the excited singlet state (S₁). Through non-radiative transition, it subsequently changes the multiplicity from S₁ to a triplet state (T₁) via intersystem crossing (ISC). The photosensitizer in the T₁ state can then decay via two distinctive processes: Type I and Type II (Fig. 15). In Type I, the excited photosensitizer undergoes single-electron transfer with the substrate to produce a radical or a radical ion, such as hydroxyl radical (·OH) and superoxide (O₂⁻). These highly reactive radical species can further react with biological substrates to modify their structure and/or function. In the Type II process, however, ¹O₂ produced via the energy transfer from the photosensitizer to oxygen, readily reacts with biological molecules (e.g., lipids, proteins, and DNA), which are the main components of cells and nuclear membranes. The majority of the effective photosensitizers are characterized by high quantum yields of their T₁ state, since a relatively longer living T₁ state allows more chance for energy and/or electron transfer. Thus, ROS such as O₂⁻, ·OH, and ¹O₂ are key species in the PDT process.84,85

The lifetime of ¹O₂ in most biological environments is in the range of a few microseconds. Thus, ¹O₂ produced from Type II photosensitization can affect biological substrates within a moderate distance from the photosensitizer itself (0.02–0.15 μm). In contrast, ·OH produced in Type I photosensitization is highly reactive and interacts with biological molecules within a range of less than 5 nm, restricting its effects to the location where it is produced.84,85 Thus, ¹O₂ formed from the Type II reaction is thought to be primarily responsible for the biological effect in PDT.

The direct confirmation of ¹O₂ generation in photosensitization reactions comes from detecting phosphorescence at around 1270 nm resulting from the spontaneous decay of ¹O₂ to its ground state. Other methods of ¹O₂ detection are based on analyzing the spectral change of a probe molecule upon its interaction with ¹O₂, using electron spin resonance (ESR), UV-vis absorption, or fluorescence. The various ¹O₂ detection techniques and their probes are summarized in Table 2.

![Fig. 15](Image)

**Fig. 15** Schematic Jablonski’s diagram of Type I and Type II reactions in PDT. PS: photosensitizer.
\(^1\text{O}_2\) scavengers can also be used to confirm the \(^1\text{O}_2\) generation. Azide ion and histidine are often utilized as quenchers for \(^1\text{O}_2\). They rapidly and preferentially interact with \(^1\text{O}_2\) and convert it to the ground state \(\text{O}_2\) before reacting with any other molecules in the system. Further confirmation of \(^1\text{O}_2\) can be obtained by replacing water with deuterated water, which extends the lifetime of \(^1\text{O}_2\) by as much as 15-fold.

### 3.3. \textit{Au} NC-based photosensitizer for PDT

In previous studies, protein-stabilized \(\text{Au}\) NCs and \(\text{Au}\) NCs embedded in polymer matrix were reported to produce \(^1\text{O}_2\) upon photoexcitation at 330 and 532 nm (UV and visible light, respectively).\(^{86,87}\) Following these reports, Kawasaki and Jin et al. described the formation of \(^1\text{O}_2\) through direct sensitization of \(\text{Au25(SR)}_{18}\) (\(\text{H-SR} = \text{phenylethanethiol or captopril}\)) under visible/NIR light (532, 650, and 808 nm) irradiation.\(^{88}\) The generation of \(^1\text{O}_2\) by photoexcited \(\text{Au25(SR)}_{18}\) was confirmed by observation of the \(^1\text{O}_2\) emission at approximately 1270 nm, \(^1\text{O}_2\)-selective probes, and the use of a \(^1\text{O}_2\) quencher.\(^{89}\) The larger HOMO–LUMO gap of \(\text{Au25(SR)}_{18}\) NCs (1.3 eV) than the energy of \(^1\text{O}_2\) (0.97 eV), the long lifetime of the electronic excitations, and the well-defined \(\text{O}_2\) adsorption sites are suggested to be the key factors promoting the energy transfer from the \(\text{Au25(SR)}_{18}\) NCs to molecular oxygen resulting in the formation of \(^1\text{O}_2\). Photodynamic activity of water-soluble \(\text{Au25(Capt)}_{18}\) NCs toward cancer cells under NIR light (808 nm) was also demonstrated (Fig. 16A). Moreover, Miyata and Miyaji et al. developed \(\text{Au25(Capt)}_{18}\) NCs exhibiting photodynamic activity toward oral bacteria (Fig. 16B).\(^{89}\)

The following section includes discussion of several strategies to improve the \(^1\text{O}_2\) generation efficiency and PDT activity of \(\text{Au}\) NCs by using: (i) atomically precise size control, (ii) NIR activation for deep-tissue treatments, (iii) aggregation-induced emission (AIE), (iv) resonance energy transfer (RET), and (v) forming nanocomposites with other nanomaterials for multi-modal synergistic therapy (Fig. 17).

#### 3.3.1. Atomically precise size control of \textit{Au} NC (or \textit{Ag} NC)-based photosensitizers

\(\text{Au}\) NCs with different sizes and ligands have been used to improve the \(^1\text{O}_2\) generation efficiency, depending on the size of NCs at the atomic level. For example, \(\text{Au}_{144}/\text{C}_{24}\) NCs, \(\text{Au}_{25}/\text{C}_{24}\) NCs, and \(\text{Au}_{10}/\text{C}_{24}\) NCs in toluene. Ho-Wu et al. investigated the size effect of \(\text{Au}\) NCs on the \(^1\text{O}_2\)-generation efficiency from \(\text{Au}_{25}(\text{SG})_{18}\), \(\text{Au}_{144}(\text{C}_{6})_{60}\), and plasmonic \(\text{Au}\) NPs (~40 nm). The \(\text{Au}_{144}\) NCs had a much higher \(^1\text{O}_2\) generation rate (\(^1\text{O}_2/\text{NC}/\text{min} = \sim 3.2\)) than \(\text{Au}_{25}\) NCs (~0.077). The following order for the \(^1\text{O}_2\) generation rate was reported: \(\text{Au}_{144} > \text{Au}_{25} \gg \text{Au}\) NPs (Fig. 18A).

### Table 2 Singlet oxygen (\(^1\text{O}_2\)) detection methods

| Method                  | Probe                                      | Detection                                      |
|-------------------------|--------------------------------------------|------------------------------------------------|
| Phosphorescence         | \(^1\text{O}_2\)                           | Phosphorescence of \(^1\text{O}_2\) at 1270 nm  |
| UV-vis spectroscopy     | 9,10-Diphenyl-anthracene (DPA)             | Decrease peak at 355 nm                         |
| UV-vis spectroscopy     | 9,10-Anthracenediybis(methylene) dimalonic acid (ABDA) | Decrease peak at 382 nm                         |
| UV-vis spectroscopy     | 9,10-Anthracenediisopropionic acid (ADPA)  | Decrease peak at 400 nm                         |
| UV-vis spectroscopy     | Anthracene-9,9-bisethanesulfonic acid (AES) | Decrease peak at 360, 378 and 400 nm            |
| UV-vis spectroscopy     | 1,3-Diphenyl-isobenzofuran (DPBF)          | Decrease peak at 410 nm                         |
| UV-vis spectroscopy     | \(p\)-Nitrosodimethylaniline imidazole (RNO method) | Decrease peak at 440 nm                         |
| Fluorescence            | Singlet oxygen sensor Green (SOSG)         | Increased fluorescence at 540 nm                |
| Fluorescence            | Methotrexate (MTX)                         | Increased fluorescence at 450 nm                |
| ESR                     | 2,2,6,6-Tetramethyl-piperidine (TEMP)      | Change in enhanced permeability and ESR spectrum |
The superior $^{1}\text{O}_2$ generation with Au$_{144}$ was attributed to the combination of a high absorption cross section relative to the volume and a high triplet excited state population via core-localized plasmon resonance.

Compared to the Au NC-based photosensitizers, reports on Ag NC-based photosensitizers are limited due to their low photostability. Yu et al. examined bovine serum albumin (BSA)-protected Ag$_{13}$ NC as a photosensitizer. Due to a large population in the triplet state, the BSA-Ag$_{13}$ NCs showed high $^{1}\text{O}_2$ generation quantum efficiency (~1.26 using rose bengal as the standard). Owing to the good cellular uptake and high $^{1}\text{O}_2$ generation efficiency, the BSA-Ag$_{13}$ can effectively kill the MCF-7 breast cancer cells following uptake and white light treatment (Fig. 19B). Tominaga and Kawasaki et al. demonstrated that Ag$_{16}$(MBISA)$_6$ (MBISA = 2-mercapto-5-benzimidazolesulfonic acid sodium salt) NCs also generate $^{1}\text{O}_2$ with high efficiency under white light irradiation. The following order was suggested for the $^{1}\text{O}_2$ generation efficiency on different Ag NCs: Ag$_{16}$(MBISA)$_6 >$ BSA-Ag$_{13}$ $>$ Ag$_{75}$(SG)$_{40} >$ Ag$_{35}$(SG)$_{18} >$ BSA-Ag$_8$ (not detected).

3.3.2. NIR activation of Au NC photosensitizers for deep-tissue treatments. NIR light (700–950 nm, also named the NIR-I window) has much deeper tissue penetration compared to visible light for cancer PDT. Ho-Wu et al. utilized two-photon excited Au$_{135}$(SR)$_{14}$ from a pulsed 800 nm laser to generate $^{1}\text{O}_2$ and trigger PDT. The two-photon NIR-triggered PDT was more effective in live cells compared to the one-photon excitation. More recently, the “NIR-II” window (1000–1700 nm) has also been attracting interest because of the decreased light scattering by tissues, lower background autofluorescence, and deeper tissue penetration. Vankayala et al. reported a mercaptoundecanoic acid (MUA)-protected Au NCs conjugated transactivator of transcription (TAT) peptide (peptide sequence: N-GRKKRRQRRR-C). The TAT peptide–Au NCs not only produced $^{1}\text{O}_2$ under NIR-II light (980 nm), but also acted as DNA nano-cargo to achieve high gene transfection efficiencies.
(≈ 81%) in HeLa cells (Fig. 18C). Furthermore, Chen et al. developed NIR-II light-activated PDT using MUA-protected Au NCs.\textsuperscript{24} The Au NCs were modified with human serum albumin and catalase (AuNC@HSA/CAT). The nanocomposite produced $^{1}$O$_2$ upon NIR-II light excitation (1064 nm), which effectively inhibited tumor growth by deeper tissue penetration of the NIR-II light (Fig. 18D).

Recently, X-ray was also combined with Au NCs as “radiosensitizer” for cancer radiotherapy. The use of X-ray as the light source is most suitable for activating the Au NCs for deep-tissue cancer treatment and biomedical imaging applications, due to its nearly unlimited penetration depth in living tissues and organisms. An interesting review,\textsuperscript{29,106} as well as various other recent publications\textsuperscript{101–103} covering the applications of Au NCs as radiosensitizers are available.

### 3.3.3. AIE-active Au NC-based photosensitizer

A number of strategies to improve the $^{1}$O$_2$-generation efficiency have been proposed for organic photosensitizers. The incorporation of heavy atoms into the molecular structures is the most widely utilized approach. In particular, photosensitizers with the AIE photosensitizers property have recently attracted significant attention.\textsuperscript{104} NPs with a dense core of AIE fluoropen show strong emission in the aggregate state due to the restriction of intramolecular motions. They could also be designed to possess efficient photosensitizing abilities in the aggregate state, by reducing the single-triplet gap of AIE photosensitizers for efficient ISC. Hikosou and Kawasaki et al. applied the AIE-active strategy for NCS of AuAg alloy to enhance the $^{1}$O$_2$ generation.\textsuperscript{105} The AuAg alloy NCS were encapsulated by chitosan self-assembly, resulting in inhibited energy dissipation through non-radiative pathways and enhanced the $^{1}$O$_2$ generation. Xia et al. also reported SG-protected Au NCs embedded in a hyaluronic acid/protein protamine self-assembly (AuNC–HA–PROT). The AuNC–HA–PROT nanocomposite showed enhancement in both light emission and $^{1}$O$_2$ generation by inhibiting energy dissipation through non-radiative pathways (Fig. 19A).\textsuperscript{106} Results of in vitro experiments revealed that the AuNC–HA–PROT nanocomposite showed effective endocytosis of target MDA-MB-231 cancer cells, high PDT activity, as well as fluorescence imaging.

### 3.3.4. FRET-mediated Au NC photosensitizer

Forster RET (FRET) involves energy transfer from an excited molecular chromophore (the donor) to another chromophore (the acceptor).\textsuperscript{107,108} The following factors are primarily required to cause FRET: (i) a spectral overlap between the fluorescence of the donor chromophore and the absorption of the acceptor chromophore, (ii) small distance between the donor and the acceptor (typically, 10–100 Å), and (iii) parallel orientations of the donor and the acceptor transition dipoles. Yamamoto and Kawasaki et al. applied FRET for a nanocomposite of BSA–Au NC and methylene blue (MB) (BSA-Au NC-MB) to enhance the $^{1}$O$_2$ generation.\textsuperscript{109} The BSA-Au NC–MB nanocomposite exhibited good overlap between the absorption spectrum of MB and the emission spectrum of BSA-AuNCs. This resulted in enhanced FRET-mediated $^{1}$O$_2$ production by energy transfer from the Au NC (the donor) to the MB (the acceptor) in the nanocomposite. In the conjugate of Ag$_2$-MBISA$_6$ and quinacrine (QC), Tominaga and Kawasaki et al. reported that the QC acts as a donor chromophore, while the Ag NC plays the role of the acceptor chromophore in the FRET process.\textsuperscript{24} The FRET-mediated conjugate of Ag$_2$-MBISA$_6$ and QC caused a 2.3-fold increase in the $^{1}$O$_2$ generation compared to that obtained with Ag$_2$-MBISA$_6$ NC alone.

The use of chromophore ligands can control photo-functions of metal nanoparticles and metal NCs.\textsuperscript{110–113} Two-photon absorption of ligand-protected metal NCs shows a nonlinear optical property that is attractive for applications such as biological imaging and PDT.\textsuperscript{114} Vangara et al. demonstrated two-photon PDT under 860 nm NIR excitation for multiple drug resistance bacteria (MDRB) using a nanocomposite of z-lipoic acid stabilized Au NCs and graphene quantum dots (GQDs) (Au NCs–GQDs nanocomposite),\textsuperscript{115} where the GQDs with high NIR absorption act as two-photon donor-chromophores, while the Au NCs act as acceptors. Due to the FRET process between the Au NCs and the GQDs, the $^{1}$O$_2$ generation capability of Au NCs–GQD nanocomposite enhanced tremendously, which was higher than that of rose bengal, which is an efficient organic photosensitizer ($^{1}$O$_2$ quantum yield of rose bengal, $\Phi_{\text{SB}} = 0.75$) (Fig. 19B). The Au NCs–GQD nanocomposite allowed bright two-photon bioimaging and two-photon PDT against MDRB and carbapenem-resistant Escherichia coli.

The singlet fission (SF) is a photophysical process in which a single exciton is converted to two singlet-excited states $S_1$ by different intersystem crossing (ISC). Saegusa and Hasobe et al. newly synthesized a series of mixed tetracene (TC)-protected Au NCs prepared from a TC-modified heterosulfide with two different chain lengths, which achieved a high-yield SF ($\Phi_{\text{SF}} = 90\%$) and individual triplet excited states ($\Phi_T = 160\%$). High-yield and long-lived triplet excited states through SF-based metal NCs may be used for PDT application.

Feng et al. fabricated a dual-photosensitizer nanocomposite by coating a mesoporous layer of graphene-phosphate carbon nitride (g-C$_3$N$_4$) on Tm$^{3+}$-activated up-conversion NPs (UCNPs), followed by attachment of Au$_{125}$[MHA]$_{18}$ (MHA = 6-mercaptohexanionic acid) and polyethylene glycol molecules (UCNPs@g-C$_3$N$_4$–Au$_{125}$–PEG) for PDT and bioimaging under NIR light.\textsuperscript{115} The higher PDT efficiency of this nanostructure in comparison with any single modality was demonstrated by the increased ROS production via the energy transfer in the UCNPs@g-C$_3$N$_4$–Au$_{125}$–PEG system when excited by NIR light (980 nm). In addition, the effective separation of photogenerated electron–hole pairs in the nanocomposite could also promote the production of $^{1}$OH (Fig. 19C) and, consequently, cancer cell death. The therapeutic efficacy of the nanocomposite in animal experiments and tissue section analysis demonstrated the ability to inhibit tumor growth without damaging the major organs.

### 3.3.5. Au NC-based photosensizers for hypoxic environment

Photosensitizers with Type II mechanism (i.e., $^{1}$O$_2$ generation) are the majority for PDT applications; however, their therapeutic efficacy is dependent on the oxygen level in the targeted microenvironment. Meanwhile, the native microenvironment of many tumors is low in oxygen (i.e., hypoxic), since the rapid tumor growth outpaces the oxygen supply. As a result,
the PDT efficiency is reduced in such hypoxic environments.\textsuperscript{119} Several approaches for solving this challenge have been proposed:\textsuperscript{120} (1) \textit{in situ} generation of O\textsubscript{2}, (2) O\textsubscript{2} independent PDT (Type I PDT), and (3) multimodal synergistic therapy. In the first approach (\textit{in situ} O\textsubscript{2} generation), H\textsubscript{2}O\textsubscript{2} is catalytically decomposed to form O\textsubscript{2} and water. In cancer cells, the levels of H\textsubscript{2}O\textsubscript{2} are usually larger than in healthy cells.\textsuperscript{121} With this in mind, Chen \textit{et al.} constructed a self-supply O\textsubscript{2} system for PDT against hypoxic tumors using the nanocomposite of AuNC@HSA/CAT.\textsuperscript{8} The AuNC@HSA/CAT could self-supply O\textsubscript{2} for PDT as a consequence of its intrinsic catalase-like activity to decompose H\textsubscript{2}O\textsubscript{2} and form O\textsubscript{2} (Fig. 20A). This resulted in greatly improved O\textsubscript{2} generation and increased PDT efficacy for hypoxic cancer cells (Fig. 20B and C). Liu \textit{et al.} also described self-supplying O\textsubscript{2} through catalase-like activity of PAMAM dendrimer-encapsulated Au NCs (AuNCs–NH\textsubscript{2}) for hypoxic tumor PDT.\textsuperscript{122} The AuNCs–NH\textsubscript{2} exhibited catalase-like activity in the physiological pH range (i.e., 4.8–7.4), hence decomposed H\textsubscript{2}O\textsubscript{2} to self-supply O\textsubscript{2}. The proposed mechanism was that in acidic solutions the protonated tertiary amine groups of dendrimers facilitate the pre-adsorption of OH on the metal surface, triggering the catalase-like reaction.

To overcome the hypoxia limitation in Type II PDT, an O\textsubscript{2} independent Type I PDT has recently been developed, as these photosensitizers produce HO\textsuperscript{•}.\textsuperscript{119,128} HO\textsuperscript{•} is a stronger oxidant than O\textsubscript{2}, and could react with virtually any biological molecule, including DNA, proteins, lipids, and carbohydrates (Fig. 21).\textsuperscript{123} Yang \textit{et al.} fabricated Au\textsubscript{25} NCs anchored on black anatase TiO\textsubscript{2}–x nanotubes (Au\textsubscript{25}/B-TiO\textsubscript{2}–x NTs) for Type I PDT.\textsuperscript{124} Under NIR light, the Au\textsubscript{25}/B-TiO\textsubscript{2}–x NTs could achieve separation of the e\textsuperscript{−}–h\textsuperscript{+} pair, leading to the production of HO\textsuperscript{•} and O\textsubscript{2}– radicals. \textit{In vivo} and \textit{in vitro} experiments demonstrated an obviously enhanced PDT effect of Au\textsubscript{25}/B-TiO\textsubscript{2}–x NTs. Cheng \textit{et al.} also fabricated titanium dioxide NP-Au NCs–graphene heterogeneous nanocomposites to induce a large production of HO\textsuperscript{•} and O\textsubscript{2}– radicals, which could serve as Type I PDT for B16F1 melanoma cells.\textsuperscript{125}

3.3.6. Multimodal synergistic \textit{in vivo} therapy using Au NC-based photosensitizer. The efficacy of PDT using Au NC-based photosensitizers can be enhanced by combination with other therapeutic modalities, such as conjugates with organic photosensitizers, chemo-T, RT, PTT, and targeted imaging. In this context, we focused on Au NC-based multimodal synergistic therapies, particularly PTT.\textsuperscript{119,126–129} RT, PTT, and conjugates with organic photosensitizers.

He \textit{et al.} assembled Au\textsubscript{25}(Capt)\textsubscript{18} onto mesoporous silica-coated Nd\textsuperscript{3+}-sensitized up-conversion NPs (UCNPs@MS-Au\textsubscript{25}) to form a multifunctional platform for photoacoustic (PA) imaging and dual phototherapy (PTT/PDT).\textsuperscript{126} The UCNPs@MS-Au\textsubscript{25} exhibited considerable PTT effect, by combining its intrinsic PTT effect to further enhance \textit{in vivo} tumor inhibition under 808 nm laser.

Yang \textit{et al.} fabricated metal–organic frameworks (MOFs) of Fe\textsubscript{3}O\textsubscript{4}/ZIF-8-Au\textsubscript{125} (IZA) nanospheres.\textsuperscript{127} The IZA nanospheres not only exhibited PTT effects upon NIR light irradiation to effectively kill tumor cells, but also proved useful in targeting and magnetic resonance imaging (MRI). The Au\textsubscript{25}(Capt)\textsubscript{18} in IZA nanospheres produced highly reactive \textsuperscript{3}O\textsubscript{2} to cause PDT as well as PTT effects under NIR light irradiation. As a result, the IZA nanospheres exhibited synergistic therapeutic effect superior to any single therapy both \textit{in vitro} and \textit{in vivo} (Fig. 22A). Tumor-bearing mice treated only with PDT (Au\textsubscript{25}(Capt)\textsubscript{18} NCs under NIR) or PTT (IZ under NIR) displayed much less inhibition in tumor growth than those treated by the multimodal synergistic therapy with combined PDT, PTT, and MRI approaches (Fig. 22A).

Han \textit{et al.} described a BSA-stabilized multifunctional theragnostic nanoplatform, gadolinium oxide–Au NCs–indocyanine green (ICG) hybrid (Gd\textsubscript{2}O\textsubscript{3}–AuNCs–ICG). The Gd\textsubscript{2}O\textsubscript{3}–AuNCs–ICG nanocomposites demonstrated excellent \textit{in vivo} triple imaging capability for NIR fluorescence (NIRF), magnetic
resonance, and computed topography, as well as efficacy in combined PDT and PTT (Fig. 22B). Furthermore, Cui et al. constructed a nanocomposite of BSA-Au NCs–ICG to allow multimodal synergistic therapy, namely dual-modal NIRF/PA imaging, cancer treatment by synergistic action of PDT/PTT, and real-time therapeutic monitoring based on FRET. Multi-modal synergistic therapy using this nanocomposite resulted in 95% cancer cell death and complete tumor disappearance. Lv et al. produced a core/shell structured nanocomposite by conjugating Au25(SR)18 NC (a PDT/PTT agent), the pH/temperature-responsive polymer P(NIPAm-MAA), and the anticancer drug doxorubicin (DOX) onto the surface of mesoporous silica-coated core–shell up-conversion NPs (UCNPs) (Fig. 22C). The controlled DOX release in the cancer cells was triggered by a high temperature from the PTT under NIR irradiation and low pH. The combined PDT, PTT, and pH/temperature-responsive chemo-T could significantly improve the therapeutic efficacy, as confirmed by both in vitro and in vivo assays. Moreover, the nanocomposite showed dual-modal imaging properties (computer tomography and up-conversion luminescence) when irradiated with 980 nm NIR light, demonstrating the potential for imaging-guided therapy.

In addition to their highly efficient 1O2 generation, the physiological properties of Au NCs in biological environments must be further evaluated in terms of the toxicity, renal clearance, and stability for in vivo PDT applications. As for the renal clearance, NPs larger than 6 nm are eliminated from the blood stream by the reticuloendothelial system (RES; liver, spleen, etc.), while those smaller than 6 nm can be eliminated via the kidneys by passing through the glomerular capillary wall (GCW; i.e., the kidney filtration) (Fig. 23A). The longer circulation time of Au10,11 NCs in the blood compared to Au25 NCs allowed their accumulation in cancerous tissues through EPR (Fig. 23B). The unique renal clearance behavior of the sub-nm Au NCs was explained by the filtration mechanism of GCW like-size separation utilizing size exclusive chromatography. Compared to the neutral NCs, it is more difficult for the negatively charged NCs to cross the GCW, since the GCW is negatively charged. Zwitterionic or non-ionic surface ligands (e.g., SG or PEG) are desirable for the efficient urinary elimination of small NCs from the body.

4. Conclusions and perspectives

In summary, we have reviewed the recent advances in the fields of photo/electrocatalysis and photosensitization using metal NCs, and their related green energy and medical applications. Owing to the unique properties of metal NCs, including their attractive photo-/electro-functional properties, as well as recent developments in nanotechnology, metal NCs are promising candidates for future applications in the fields of environmental remediation and medical diagnostics.
developments in their atomically precise synthesis, these functionalized moieties show excellent potential for the abovementioned applications.

Considering the use of metal NCs in photo/electrocatalysis and photosensitization in green chemistry, we summarized several strategies to improve conversion efficiency and selectivity of the following materials: (i) electrocatalysts for water splitting and fuel cells, (ii) photocatalysts for water splitting, and (iii) solar cells. As described in this review, atomically precise control can contribute to the improvement of these materials. However, considering the practical applications, further developments are expected for simple and precise synthesis and isolation of metal NCs, as well as their loading. In addition, the following studies are envisaged for the improvement of these materials.

(1) Deeper understanding of the electronic structures of the loaded mono-metal and alloy NCs is essential for all of the applications. The electronic structures of the small NCs strongly depend on the number of the constituent atoms and the types of heteroatoms. Recent studies revealed the relationship between the electronic structures and these factors for the isolated NCs. However, the NCs loaded on the substrate seem to show different electronic structures as a result of the interaction between the NCs and the substrate, especially when the ligands are removed from the NC surface. It is expected that future studies would reveal the electronic structures of the loaded NCs for their application as active site on the substrate. In addition, the method for controlling the heteroatom position in the loaded alloy NCs is also expected to be developed in the future studies.

(2) For the improvement of photocatalysts, an effective method for separating e−h+ pairs should be established. The Fermi energy of the cocatalysts strongly affects the charge transfer of the excited electron. Therefore, the electronic structure of cocatalysts, which effectively facilitates the charge transfer from photocatalysts to cocatalysts must be designed. In addition, although most studies concentrate on the loading of cocatalysts only for the reduction reaction, the future studies should conduct the co-loading of the cocatalysts for both reduction and oxidation reactions. It is also important to deepen the understanding on the reaction intermediates, the mechanism, and the methods for suppression of the reverse reactions.

(3) Regarding the photosensitization application for solar cells, NCs, which are able to absorb the visible and infrared light to effectively use the sunlight, should be fabricated and utilized. The stability of NCs should also be improved for this application. In addition, improvements in the energy-conversion efficiency must be made by combining several systems.

Considering photosensitization of metal NCs for therapeutic applications, we summarized several strategies to improve the 1O2 generation efficiency and PDT activity of metal NCs: (i) atomically precise size control, (ii) NIR activation for deep-tissue treatments, (iii) AIE, (iv) RET, and (v) forming nanocomposites with other nanomaterials for multimodal synergistic therapy. Despite these efforts, further research into the following aspects is necessary:

(4) By adjusting n and m, the discrete electronic/geometrical structures of metals, and thereby their photosensitizing capability, can be controlled. Extensive studies on the syntheses of organo-soluble metal NCs with atomic precision have been described, while the synthesis of water-soluble metal NCs remains undeveloped. Therefore, further research into the synthesis of water-soluble metal NCs is required for therapeutic applications. Ligand exchange method using organo-soluble metal NCs may be useful for the synthesis of water-soluble metal NCs and alloy metal NCs would be valuable for the exploration of their photosensitizing capability.

(5) A photosensitizer is primarily required to possess the following properties: (1) constant composition, (2) simplicity of synthesis, (3) lack of toxicity in the dark, (4) target specificity, (5) having a triplet state energy higher than 0.97 eV (the energy of single state oxygen, 1O2), (6) photostability, (7) high triplet state quantum yield, (8) fast clearance from the body, and (9) minimal self-aggregation. Metal NCs satisfy the abovementioned requirements; however, their 1O2 generation efficiencies are lower than those of organic photosensitizers. The high triplet state quantum yield and inhibition of energy dissipation through non-radiative pathways would be the key factors to improve the 1O2 generation efficiency of the metal NCs. Since water-soluble thiolated metal NCs have multifunctionality such as imaging, drug delivery, and multiple sensing capability (photo-sensitizer, radiosensitizer, and sonosensitizer), it would be useful as a multipurpose ROS mediated nanomedicine.

(6) Regarding the in vivo PDT applications, the use of specific ligands for metal NCs increases the selectivity toward the target (e.g., cancerous tumors), an approach called “active targeting”. Targeting ligands on metal NCs are responsible for the selective interaction between the metal NCs and specific receptors on the surface of tumor cells, but not healthy cells, thus increasing the internalization of the NCs. Various types of surface modification of metal NCs, such as aptamer, specific peptides, glucose, DNA, and folic acid have been developed for efficient delivery of the metal NCs to the target (e.g., cancerous tumors) for in vivo applications. Further studies involving active targeting of metal NCs would be important for in vivo PDT applications.

Conflicts of interest

There are no conflicts to declare.

Authorship contributions

Photo/electrocatalysis of metal nanoclusters in green energy applications: Tokuhisa Kawakaki and Yuichi Negishi. Photosensitization of metal nanoclusters for therapeutic applications: Hideya Kawakaki. Introduction and conclusion: equal contribution by all authors.

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