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Review Article

Gold Nanoparticles: Innovative Supramolecular Platforms for Targeted Drug Delivery and Bioorthogonal Catalysis

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ABSTRACT

Gold Nanoparticles (AuNPs) have gained significant attention across multiple fields, including drug delivery, therapy, sensing, material science and catalysis, due to their tunable properties. These nanoparticles exhibit high stability, water solubility, biocompatibility and chemical versatility, primarily attributed to the Self-Assembled Monolayers (SAMs) of organic ligands on their metal cores. Key features such as size, shape and surface functionality play a critical role in determining their interactions with biological systems, influencing uptake, distribution, cytotoxicity and biomolecular interactions. The aim of this review is to provide an in-depth analysis of the application of AuNPs in drug delivery and therapy, highlighting their role in drug conjugation, controlled release and targeted therapeutic interventions. Additionally, the review aims to explore the expanding domain of bioorthogonal catalysis and its relevance to drug delivery systems. This study focuses on reviewing various research articles and case studies that discuss the principles of supramolecular chemistry related to AuNPs. Specifically, it examines methods of drug conjugation, the process of self-assembly in supramolecular drug delivery systems and the application of transition metal catalysts in bioorthogonal catalysis. Key breakthroughs in the field, including advancements made by researchers like Meggers and Bradley, are analyzed to illustrate the cutting-edge developments in the use of AuNPs. The analysis reveals that AuNPs can significantly enhance drug delivery by enabling precise targeting and controlled release. Their interaction with complementary molecules allows for tailored therapeutic interventions. In bioorthogonal catalysis, AuNPs demonstrate the ability to perform targeted conversions and synthetic reactions, with key achievements in intracellular catalytic processes. The versatile properties of AuNPs, particularly their ability to participate in supramolecular self-assembly and bioorthogonal catalysis, position them as promising tools for advancing drug delivery and therapeutic applications. Their unique characteristics hold great potential to revolutionize targeted drug administration and bioorthogonal catalytic techniques in modern medicine.

Keywords: Bioorthogonal Catalysis, Drug Delivery, Gold Nanoparticles, Supramolecular Chemistry.

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INTRODUCTION

Nanoparticles have enormous promise in the fields of delivery systems, medicines, sensing technology, materials science and catalysis because of their adjustable characteristics. Because of their highly modifiable core and surface properties, monolayer-protected inorganic nanoparticles find extensive application in the fields of biotechnology and nanotechnology. The organic ligands in these nanoparticles form Self-Assembled Monolayers (SAMs) around a metal core. Stability, water solubility, biocompatibility and chemical flexibility are provided by the SAMs, which are chemisorbed onto the surface of the core. The advantages of both the strong core material and the flexible monolayer ligands are brought together in this hybrid structure.[1]

The characteristics of nanoparticles are different from those of bulk materials. It is possible to tailor their physical and chemical properties to meet certain needs. Size, form and surface functioning are important characteristics that affect how they behave and interact in biological systems.[2] Nanoparticles with

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tailored optical, electrical, catalytic, or magnetic characteristics can be synthesised by modifying these traits. Their cytotoxicity, absorption, distribution and interactions with biomolecules are all affected by these qualities. They are good platforms for drug delivery because they can be surface-functionalized with different ligands to create well-defined structures. Their high surface-to-volume ratio also allows for multivalency, which improves their interactions with the environment. Because of these properties, nanoparticles have many potential uses, such as research into the interactions between nanoparticles and biomolecules, as well as in transport and medicine.[3,4]

With their simple synthesis and functionalization, inert core, biocompatibility and flexible functionality, Gold Nanoparticles (AuNPs) have garnered a lot of attention among inorganic nanoparticles. The most researched monolayer-protected nanoparticles since the seminal study by Brust *et al.*, are thiol-protected AuNPs. The potential uses of AuNPs in medicines, sensing, delivery and catalysis are being investigated.[5]

Functionalizing Gold Nanoparticles (AuNPs) usually entails reducing them using Brust-Schiffrin and then using Murray place-exchange reactions with application-specific ligands.[6] Washing, centrifugation and dialysis are some of the post-synthesis purification procedures that result in nanoparticles that are about the same size as DNA, proteins and cell membranes, among other biological things. Several bio-nano interface applications are made possible by this biomimetic scale, including gene transfection, regulation of DNA transcription and protein-protein interactions.[7,8]

This review article will focus on the use of supramolecular chemistry to analyse AuNPs as scaffolds for medicinal, delivery and catalytic applications. In the parts that follow, we will talk about the uses of AuNPs in transport and therapies, how tiny molecules interact with AuNP monolayers supramolecular, bioorthogonal catalysis and other similar uses.

APPLICATION OF GOLD NANOPARTICLES IN DRUG DELIVERY AND THERAPEUTICS

Gold Nanoparticles (AuNPs) are synthesized and functionalized through various techniques that allow for the precise control of their properties. The method developed by Mirkin *et al.*, which uses DNA linkers to covalently attach paclitaxel, is one such example of how these nanoparticles can be tailored for specific therapeutic applications. This process enhances the solubility and overall effectiveness of the drug, making it a powerful tool in targeted drug delivery.[9]

Covalent Association

The method by Mirkin *et al.* stands out because it uses DNA linkers to covalently attach paclitaxel, a chemotherapeutic medication, to AuNPs.[10] The solubility and overall effectiveness of paclitaxel are greatly improved by this technique. In addition, Zubarev *et al.*, have devised a method that allows paclitaxel to be conjugated to phenol-terminated AuNPs by attaching a flexible hexamethylene glycol linker to its C-7 position. One single AuNP can be controlled-loaded with up to 70 paclitaxel molecules using this method.[11]

This method has been further developed by Mirkin, Lippard and colleagues who have created a drug delivery agent that combines the characteristics of DNA, AuNPs and Pt (IV) prodrugs. They used HeLa cells to incubate these particles in their tests. The nanoparticles went into vesicles after 6 hr and were released into the cytosol after 12 hr. Washington State the colocalization of these nanoparticles with the microtubules in HeLa cells was identified using green 488 taxol bisacetate, a stain for microtubules. They showed that Pt (IV) can be reduced to cytotoxic Pt (II) species in the acidic environment of cancer cells, which improves the therapeutic efficacy.[12]

Non-Covalent Association

The hydrophobic interior of AuNP monolayers has been utilised by Rotello *et al.*, to encapsulate and transport hydrophobic medicinal molecules in a non-covalent manner. Substances with different hydrophobicities, pH levels, temperatures, magnetic fields, enzymes, Ultraviolet (UV) light and Near-Infrared (NIR) photoluminescence can all cause the medicine to be released from its carrier. One example is the work of Burda *et al.*, who showed that PEGylated AuNPs could be successfully adsorbed onto the Photodynamic Treatment (PDT) medication silicon phthalocyanine, making them a powerful drug delivery vector for PDT in both laboratory and animal studies.[13]

It is also possible to create inorganic nanoparticles, such as AuNPs, to improve targeted distribution and hence increase the efficacy of drugs. To demonstrate the promise of AuNPs for targeted cancer treatment, El-Sayed *et al.*, measured the amount of tumour cell absorption of Au nanorods coupled to tumour-targeting peptides.

Advanced treatments with improved efficacy and lower adverse effects are possible thanks to AuNPs, which offer robust platforms for targeted drug delivery and therapy by utilising both covalent and non-covalent techniques.[14]

Gold Nanoparticles (AuNPs) offer versatile platforms for drug delivery through both covalent and non-covalent conjugation techniques. Covalent associations involve creating stable, often irreversible bonds between the drug and the nanoparticle, as demonstrated by Mirkin *et al.*, where DNA linkers are used to covalently attach paclitaxel, enhancing its solubility and effectiveness. Conversely, non-covalent associations rely on weaker, reversible interactions, such as hydrophobic forces, making them suitable for drugs like silicon phthalocyanine, which can be encapsulated within the nanoparticle monolayer. The following Table 1 summarizes the key techniques used

for drug conjugation with AuNPs, along with their respective advantages and disadvantages.

SUPRAMOLECULAR CHEMISTRY

The field of study known as supramolecular chemistry is concerned with complexes consisting of more than two molecules and their non-covalent interactions. The goal of this area of study is to create synthetic structures with structures and properties similar to those of naturally occurring molecules, primarily proteins, oligonucleotides and lipids. Recognition, assembly and function of molecules are the fundamental concepts. Hydrogen bonding, electrostatic interactions, metal coordination, host-guest recognition and other non-covalent interactions allow the construction of nanoscale systems from self-assembling molecules in supramolecular chemistry. Innovative solutions to complicated molecular problems are offered by these systems, which find substantial use in materials and biological research.[20]

Supramolecular Drug Delivery Chemistry

Non-covalent interactions are employed in supramolecular drug delivery chemistry to create customised building blocks. Easy preparation and functionalization, controllable morphologies and structures, dynamic self-assembly and customisable performance are all facilitated by the reversibility of these interactions. Bioimaging, gene transfection, protein delivery, regenerative medicine, tissue engineering, sensing and drug delivery are among the applications of these self-assembled supramolecular structures.[21]

Drug delivery systems are particularly promising due to their biocompatibility, biodegradability, responsiveness and incorporation of multiple functional units in supramolecular platforms.[22] These characteristics are essential for the development and manufacture of effective drug carriers. The assembly and disassembly processes of supramolecular structures are more manageable than covalent assemblies due to the reversible character of non-covalent interactions.[23]

For example, Scherman *et al.* created a supramolecular double hydrophilic block copolymer micelle system that is responsive to triple stimuli. Micelles containing the chemotherapeutic drug Doxorubicin (Dox) were generated by combining thermo-responsive poly (PNIPAM) and pH-responsive poly (PDMAEMA) with a host molecule, Cucurbituril[8] (CB[8]). The drug was released as a result of the carrier disassembling in response to fluctuations in temperature, pH, or the presence of competing visitors. In contrast to covalently linked micelles, these supramolecular micelles exhibited more flexible and rapid drug release profiles, which were influenced by the three stimuli.[24,25]

Gold Nanoparticle Supramolecular Platforms

Gold Nanoparticles (AuNPs) with various surface ligands are promising self-assembly scaffolds. Designing interactions between AuNPs and complementary components including proteins, polymers and small molecules can create unique materials with controllable properties and desirable uses. Nanoparticle self-assembly is regulated by supramolecular interactions such as hydrogen bonding, electrostatic attraction, π-π stacking and van der Waals interactions between complementary units.[26]

Rotello *et al.*, developed the "chemical nose" sensing device using supramolecular interactions between functionalized AuNPs, fluorescent proteins and analytes. AuNPs were non-covalently coupled to fluorescent proteins (EBFP2, EGFP and tdTomato) to create this sensor. The fluorescent proteins' supramolecular affinity for particles helps transmit binding events. The particle core of these supramolecular complexes quenches protein fluorescence by binding cationic AuNP to anionic fluorescent proteins.[27] Competitive binding to analytes alters the binding equilibria between AuNP and Fluorescent proteins (FBs), causing fast protein displacement from the particle surface and fluorescence restoration. The emission channel fluorescence 'turn-on' depends on analyte surface fingerprints. This method uses signal patterns to identify proteins, cell surface glycomic fingerprints, microbes and cancer medication processes.[28] The array-based cancer diagnostic sensor's information content doubles with host-guest chemistry. This modification non-covalently alters nanoparticle surfaces with complementary Cucurbit[7] uril (CB[7]) moieties to alter particle interaction with fluorescent protein transduction elements and cell lysate analytes. This competitive binding adjustment quadrupled the output channels from three to six, maintaining the one-well format with 100% accuracy and a 200 ng, 1000 cell sample size.[29]

Rotello and colleagues used supramolecular chemistry to modulate AuNPs' therapeutic potency. AuNPs with complementary head group functionality and synthetic host molecule Cucurbit[7] uril (CB[7]) formed this system. AuNPs complexed with CB formed a cell-friendly, non-toxic assembly[7]. 1-Adamantylamine (ADA), an orthogonal competitive molecule with a considerable affinity for CB, can dismantle this host-guest combination intracellularly[7]. Intracellular CB[7] removal from nanoparticle surfaces releases poisonous AuNPs that escape endosomes and kill cells. This shows supramolecular host-guest interactions' therapeutic and drug transport potential.[30]

Characterization and Monitoring of Solution and Living Cell Host-Guest Interactions

The characterization of host-guest interactions is crucial for understanding the mechanisms behind drug delivery and bioorthogonal catalysis involving AuNPs. Various techniques, such as Isothermal Titration Calorimetry (ITC) and Mass Spectrometry (MS), provide detailed insights into these interactions. ITC, for example, measures the heat changes during molecular binding, offering a comprehensive thermodynamic profile, while MS identifies the molecular composition of

supramolecular assemblies. Advanced techniques like Laser Desorption/Ionization Mass Spectrometry (LDI-MS) allow for the selective detection of nanoparticle surface ligands in complex biological samples, enabling precise monitoring of nanoparticle interactions in living cells. Each technique offers distinct advantages and comes with specific limitations, as summarized in the following Table 2.[26,31]

Isothermal Titration Calorimetry (ITC)

ITC is renowned for its rapid calorimetric response, efficient thermal equilibration and straightforward sample preparation. It enables the acquisition of a comprehensive thermodynamic profile (ΔH, ΔS, ΔG, KB and stoichiometry n) from a single experiment. During an ITC experiment, one interacting molecule (ligand or host) is incrementally injected into a cell containing the second molecule at a constant temperature. The heat exchange observed during the titration quantifies the molecular interaction, revealing binding stoichiometry, thermodynamic parameters of host-guest complexation, association and dissociation constants, enthalpy, entropy and free energy. ITC has proven instrumental in illustrating supramolecular interactions across various systems, including protein-protein, small molecule/drug-protein, protein-polymer, biomolecule-nanoparticle and enzyme kinetic dynamics.[37,38]

Mass Spectrometry (MS)

Mass Spectrometry (MS) offers distinct advantages over ITC for analyzing host-guest interactions in complex biological systems. Techniques such as Electrospray Ionization (ESI) MS and Matrix-Assisted Laser Desorption/Ionization (MALDI) MS are employed to identify host-guest complexes. For instance, Nau and colleagues utilized MS to investigate inclusion complexes between cucurbit[n]urils (CBn, *n*=6-8) and bicyclic azoalkanes, revealing the selective retro-Diels-Alder processes in the gas phase. MS provides a detailed analysis of the molecular composition and structure of supramolecular assemblies, crucial for understanding their role in drug delivery and bioorthogonal catalysis.[39,40]

Laser Desorption/Ionization Mass Spectrometry (LDI-MS)

Laser Desorption/Ionization Mass Spectrometry (LDI-MS) is a technique that selectively identifies ligands on intact Nanoparticles (NPs) within complex biological samples. By inducing selective desorption/ionization of NP surface ligands, LDI-MS offers a sensitive and specific method for detecting NP monolayers in cell lysates. The supramolecular complexes formed by NP surface ligands and host molecules serve as "mass barcodes" to track the development of cell complexes. This technique allows for the monitoring of host-guest interactions without the need for labelling, providing a powerful tool for studying interactions in living cells.[41]

These advanced characterization technologies, particularly ITC and MS, enable the detailed examination and monitoring of host-guest interactions in both solution and living cells. Understanding these interactions in complex biological contexts is pivotal for the development and application of supramolecular systems in drug delivery and therapeutic interventions.[42,43]

BIOORTHOGONAL CATALYSIS

In bioorthogonal chemistry, artificial chemical reactions can occur in the same environment as biological processes without compromising them. Bertozzi pioneered bioorthogonal chemical techniques to study biomolecules in their natural habitats.[44,45]

Staudinger Ligation and Cu-Free Click Chemistry

Staudinger ligation and copper-free click chemistry are valuable techniques for visualizing biomolecules and cellular processes in real time. The azide-ester-derivatized phosphine Staudinger ligation forms a biocompatible amide bond, making it suitable for use in living organisms and animals. However, the high susceptibility of phosphine reagents to oxidation and their slow reaction rates limit their effectiveness in detecting low-abundance species or observing fast biological events.[46,47]

To better align this discussion with the main theme of Gold Nanoparticles (AuNPs) in drug delivery and bioorthogonal catalysis, it is crucial to explore how these bioorthogonal reactions can be integrated with AuNPs. AuNPs can be functionalized with azide or alkyne groups, allowing them to participate in click chemistry. This functionalization enhances targeted drug delivery by enabling precise bioorthogonal ligation processes on the nanoparticle surfaces.

The integration of bioorthogonal chemistry techniques with AuNPs significantly advances the field of supramolecular platforms. It offers innovative approaches for the development of targeted drug delivery systems and catalytic applications, thus ensuring the discussion remains relevant to the primary focus of this review. Highlighting these intersections not only underscores the versatility of AuNPs but also their potential to revolutionize therapeutic and diagnostic methodologies through precise and efficient bioorthogonal reactions.

Azide-Alkyne Cycloaddition Reaction

The azide-alkyne cycloaddition reaction is highly reactive and sensitive to bioorthogonal functionalization in click chemistry. Copper-catalyzed click chemistry, which was initially discovered by Sharpless, Meldal and colleagues, has been extensively employed to detect enzymes in cell lysates and biomolecules in immobilised cells. Nevertheless, the copper catalyst's cytotoxicity renders this procedure unsuitable for dynamic reactions in living biological systems.[48,49]

Click Chemistry Without Copper

A copper-free bioorthogonal reaction for dynamic cellular imaging was devised by Bertozzi *et al.*, to circumvent these constraints. They eliminated the necessity for a copper catalyst by employing the strain-promoted [3+2] cycloaddition of azides with cyclooctynes. The ring strain in cyclooctynes facilitated bioorthogonal azide labelling, which improved azide detection when a Difluoromethylene (DIFO) moiety was incorporated into the cyclooctynes. The reaction kinetics and sensitivity were enhanced by this modification.[48,49]

Applications of Bioorthogonal Chemistry

Bioorthogonal chemistry is frequently employed to produce intracellular and extracellular molecules for medicinal, imaging and sensing applications. Researchers can selectively activate compounds in complex environments through bioorthogonal catalysis. These systems must be capable of operating promptly under physiological conditions and remaining inert to a variety of *in vitro* and *in vivo* functions to be effective.

Transition Metal Bioorthogonal Catalysis

The rapid and efficient catalysis of a diverse array of reactions, which are frequently beyond the capacity of enzymes, renders Transition Metal Catalysts (TMCs) an ideal choice for bioorthogonal chemistry.[50] By incorporating a transition metal into artificial metalloenzymes, TMCs are employed to produce highly selective hybrid catalysts for a variety of asymmetric catalytic processes. TMCs have been investigated in recent research for bioorthogonal selective transformations or synthetic systems.[51]

Ruthenium (II) Complexes in Bioorthogonal Catalysis

Meggers and colleagues introduced bioorthogonal catalysis by cleaving cell protection groups with organometallic nanocatalysts.[51] They found that the ruthenium (II) half-sandwich complex [Cp*Ru (COD)Cl] (Ru1) may free allylcarbamates under bio-relevant circumstances. The non-fluorescent profluorophore N, N-bis-allyloxycarbonyl protected rhodamine 110 was used to assess catalytic efficiency in living mammalian cells. The Ru-catalyst and thiophenol quickly boosted fluorescence by cleaving both allylcarbamate-protecting groups after 30 min of substrate application to HeLa cells and PBS rinse.[50]

Nanoparticle-Based Bioorthogonal Catalysis

Biocompatibility, water solubility/stability and fast efflux from living cells make TMC-mediated processes difficult to apply directly to biological systems. Bradley *et al.* developed nanoparticle-based bioorthogonal catalysis to address these restrictions. They used 500 nm polystyrene microspheres with 3 nm palladium nanoparticles for bioorthogonal chemical processes. After one day, 75% of HeLa cells internalised the microspheres and 91% survived 48 hr. These microparticles catalysed cell Susuki-Miyaura cross-coupling, forming C-C bonds and cleaving allylcarbamate.[52] Bradley *et al.* extended this method by using a 150 µm polystyrene composite with palladium catalyst to activate prodrugs like 5-Flurouracil (5-FU) extracellularly. This approach could also convert Gemcitabine and Floxuridine into Pd-activated prodrugs.[53,54]

Table 1: Summary of Drug Conjugation Techniques with Gold Nanoparticles (AuNPs).

Conjugation Technique	Example Drug	Key References	Advantages	Disadvantages	References
Covalent Association.	Paclitaxel (via DNA linkers).	Mirkin *et al.*	Enhanced solubility and efficacy.	Complex synthesis, potential cytotoxicity.	15
Covalent Association.	Paclitaxel (via Phenol-Terminated AuNPs).	Zubarev *et al.*	High drug loading capacity.	Requires precise control of synthesis conditions.	16
Non-Covalent Association.	Silicon Phthalocyanine.	Burda *et al.*	Simplicity of preparation, versatility in drug release stimuli.	Potential for premature drug release.	17
Non-Covalent Association.	PEGylated AuNPs.	Rotello *et al.*	Targeted drug delivery, improved efficacy.	Stability concerns in complex biological environments.	18
Non-Covalent Association.	Doxorubicin (DOX).	Scherman *et al.*	Responsive to multiple stimuli, flexible drug release profiles.	Complex synthesis, potential drug leakage.	19

Table 2: Techniques for Characterizing Host-Guest Interactions in Gold Nanoparticles.

Technique	Description	Example Application	Advantages	Limitations	References
Isothermal Titration Calorimetry (ITC).	Measures heat changes during binding interaction.	Studying host-guest complexation thermodynamics.	Provides comprehensive thermodynamic profiles.	Requires large sample sizes and lengthy measurements.	32
Mass Spectrometry (MS).	Identifies molecular composition and structure of complexes.	Analysis of supramolecular assemblies.	High sensitivity and specificity.	Complex sample preparation, potential ionization bias.	33
Laser Desorption/ Ionization Mass Spectrometry (LDI-MS).	Selective detection of NP surface ligands in biological samples.	Monitoring of NP interactions in cells.	No need for labeling, applicable in living cells.	Limited to detecting specific ligand types.	34
Fluorescence Spectroscopy.	Measures light emission from excited molecules.	Real-time monitoring of drug release.	High sensitivity, applicable in real-time.	Potential interference from background fluorescence.	35
Nuclear Magnetic Resonance (NMR) Spectroscopy.	Analyzes magnetic properties of atomic nuclei to determine molecular structure.	Structural analysis of supramolecular complexes.	Detailed structural information, non-destructive.	Requires expensive equipment and expertise.	36

Non-Covalent Hydrophobic Transition Metal Catalysts in AuNP Monolayers

Nanoparticle encapsulation or stabilisation pockets help deliver non-covalent drugs. These compartments' exterior hydrophobicity controls hydrophobic cargo release. Drugs permeate into cell membranes when nanoparticle carriers enter hydrophobic environments. AuNPs' hydrophobic monolayer compartments can encapsulate transition metal catalysts, cancer medicines, colourants and antibiotics. Hydrophobic ligands functionalized with AuNPs generate pockets, forming a radial monolayer structure with decreasing ligand density away from small AuNP cores (<6 nm).[55,56]

Thus, AuNP monolayers provide "hydrophobic pockets" for hydrophobic molecules. Pasquato *et al*., used EPR spectroscopy to monitor the partitioning of a lipophilic probe between an AuNP monolayer and ambient water. They found that smaller particles with stronger radial monolayers enclose guest molecules better.[57]

Rotello and colleagues used AuNP monolayers to encapsulate hydrophobic dyes and medicines. They found that non-interacting monolayers (zwitterionic layers) on tiny AuNPs (less than 10 nm hydrodynamic diameter) could trap hydrophobic dyes and medicines. Bodipy, a fluorescent probe, was used with hydrophobic medicines Tamoxifen (TAF) and Lapachone (LAP) as guest molecules. Solvent displacement produced AuNP-Zwit-Bodipy, TAF and LAP nanoparticle-payload conjugates. These conjugates deliver payloads to cells without carrier nanoparticle absorption via membrane-mediated diffusion. Due to their biocompatible surfaces and tiny size, these nanocarriers can circulate for long durations and concentrate in cancer tissues due to the increased Permeability and Retention (EPR) effect.[57]

Burda *et al*., used PEG-functionalized AuNPs to deliver hydrophobic photodynamic treatment medication Pc 4 to tumours, increasing drug accumulation. After dosing and PEG layer removal, the medication fluoresced, suggesting successful distribution. When covalently linked to Au, Pc 4 released little drug.[58,59]

RECENT PATENTS ON GOLD NANOPARTICLES IN DRUG DELIVERY AND BIOORTHOGONAL CATALYSIS

The innovative applications of Gold Nanoparticles (AuNPs) in drug delivery and bioorthogonal catalysis have attracted considerable attention in recent years, leading to the publication of numerous patents. These patents represent significant advancements in the field, highlighting novel methods, compositions and systems that leverage the unique properties of AuNPs for therapeutic and diagnostic purposes. Both the United States and India have seen a surge in patent activity related to these technologies, reflecting the global interest in harnessing AuNPs for medical and scientific breakthroughs. The following Table 3 summarizes key patents published in the USA and India, showcasing the diversity of approaches and the breadth of innovation in this domain.

FUTURE DIRECTIONS AND LIMITATIONS

Gold Nanoparticles (AuNPs) are at the forefront of innovation in bioorthogonal catalysis and targeted drug delivery because of their versatility and distinctive properties. The following sections emphasise the substantial impact, limitations and prospective directions of this research.

Controlled Drug Release

The development of precise mechanisms for the controlled release of therapeutic agents from AuNP carriers is essential. Targeting and side effect reduction could be substantially enhanced through techniques that are responsive to specific physiological stimuli, such as pH changes, temperature fluctuations, or enzymatic activity. It will be a primary area of focus to research sophisticated delivery systems that release medications at the desired site of action.

Scalability and Reproducibility

The synthesis and functionalization of AuNPs must be both reproducible and scalable to be suitable for clinical and industrial applications. To convert laboratory discoveries into practical treatments, it is imperative to standardise production methods to guarantee the consistent quality and performance of AuNPs. The development of manufacturing processes that are both cost-effective and efficient will be of paramount importance.

Long-Term Effects

An understanding of the long-term effects of AuNPs and transition metal catalysts *in vivo* is crucial for their safe application. Insights into the safety profiles of these nanoparticles will be gained through comprehensive investigations of their biodistribution, metabolism and excretion. To assess potential hazards, chronic exposure assessments and long-term toxicity studies are required.

Multi-Functional Platforms

There is significant potential for personalised medicine in the development of multifunctional nanoparticle platforms that combine drug delivery, imaging and therapeutic properties. Effective diagnosis and treatment can be improved by integrating multiple functions into a single nanoparticle system. Research into hybrid systems that provide synergistic effects will be crucial.

Regulatory Challenges

Extensive preclinical and clinical data is necessary to navigate the regulatory landscape for nanoparticle-based therapies. To address safety concerns and expedite the approval process, it is essential to establish effective collaboration among regulatory agencies, industry stakeholders and researchers. The establishment of standardised protocols for safety and efficacy testing will simplify regulatory conformance.

Enhanced Bioorthogonal Catalysis with Gold Nanoparticles

Future research should prioritise the development of more efficient and selective catalysts that function effectively under physiological conditions to enhance bioorthogonal catalysis using Gold Nanoparticles (AuNPs). It is imperative to achieve high catalytic efficiency and specificity in these applications, as it reduces off-target effects and maximises reaction rates. This can be achieved by designing AuNPs with customised surface chemistries that optimise their interaction with target substrates and safeguard catalytic sites from deactivation. In addition, the therapeutic and diagnostic applications of AuNPs will be expanded by the inclusion of a broader range of catalytic reactions, including Strain-Promoted Azide-Alkyne Cycloaddition (SPAAC) and Inverse Electron-Demand Diels-Alder (IEDDA) reactions. This bioorthogonal reaction is particularly advantageous because of its rapid kinetics and biocompatibility, which enable precise, site-specific drug activation and minimal systemic toxicity. The integration of these reactions into AuNP platforms can enable

Table 3: Summary of Recent Patents on Gold Nanoparticles in Drug Delivery and Bioorthogonal Catalysis.

Patent Number	Title of the Patent	Country	Focus Area	Publication Date	References
US9234078B2	Conjugated Gold Nanoparticles.	USA	Functionalized AuNPs for targeted delivery.	January 12, 2016	60
US11547720B2	Ayurvedic Encapsulated Gold Nanoparticles, Fabrication Methods and Cancer Therapeutic Methods.	USA	AuNPs in cancer therapy.	January 10, 2023	61
US8241393B2	Methods and Articles for Gold Nanoparticle Production.	USA	Production methods for AuNPs.	August 14, 2012	62
US9587071B2	Conjugated Gold Nanoparticles.	USA	Functionalized AuNPs for therapeutic use.	March 7, 2017	63
US10016495B2	Gold Nanoparticle Conjugates and Methods of Making and Using the Same.	USA	AuNP conjugates for medical applications.	July 3, 2018	64

the real-time monitoring of biological processes and targeted therapy. AuNPs can function as catalytic platforms for signal amplification in diagnostics, thereby enhancing the specificity and sensitivity of biomolecular detection. This development is particularly advantageous for the early diagnosis of diseases, as the identification of low-abundance biomarkers is essential. Ultimately, the field of nanomedicine can be advanced and patient outcomes can be improved by researchers who can develop innovative therapeutic and diagnostic strategies by enhancing bioorthogonal catalysis with AuNPs.

CONCLUSION

In conclusion, Gold Nanoparticles (AuNPs) have shown great promise as adaptable platforms for precise drug delivery and bioorthogonal catalysis. Due to their distinctive physical and chemical characteristics, as well as their capacity to modify their surfaces with different ligands, they are highly suitable for a variety of biomedical uses. Supramolecular chemistry allows for the precise manipulation of these nanoparticles, making it possible to create advanced drug delivery systems and novel catalytic processes. By incorporating transition metal catalysts into monolayers of AuNPs, their range of uses is expanded, providing new opportunities for treatments and dynamic cellular imaging.

Although there have been notable progressions, there still exist various obstacles and constraints. It is essential to comprehensively assess the biocompatibility and stability of AuNPs in physiological conditions to guarantee their safety and effectiveness. Furthermore, it is necessary to conduct additional research to determine the possible toxicity of transition metal catalysts and their long-term impact on living systems. It is crucial to optimise treatment outcomes by ensuring the regulated release of medications from nanoparticle carriers and minimising off-target effects.

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ABBREVIATIONS

AuNPs: Gold Nanoparticles; **SAMs:** Self-Assembled Monolayers; **DNA:** Deoxyribonucleic Acid; **Pt (IV):** Platinum (IV); **Pt (II):** Platinum (II); **PDT:** Photodynamic Therapy; **PEG:** Polyethylene Titration Calorimetry; **MS:** Mass Spectrometry; **LDI-MS:** Laser Desorption/Ionization Mass Spectrometry; **NMR:** Nuclear Magnetic Resonance; **EPR:** Electron Paramagnetic Resonance; **DIFO:** Difluoromethylene; **SPAAC:** Strain-Promoted Azide-Alkyne Cycloaddition; **IEDDA:** Inverse Electron-Demand Diels-Alder; **5-FU:** 5-Fluorouracil; **TAF:** Tamoxifen; **LAP:** LapachoneGlycol; **PNIPAM:** Poly(N-isopropylacrylamide); **PDMAEMA:** Poly(2-(dimethylamino)ethyl methacrylate); **CB[8]:** Cucurbit[8]uril; **DOX:** Doxorubicin; **ITC:** Isothermal.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CREDIT STATEMENT

Anil Pawar: Conceptualization, Methodology, Writing – Original Draft Preparation, Supervision, Writing – Review and Editing. **Alka Zade:** Data Curation, Investigation, Validation, Writing – Review and Editing, Resources, Formal Analysis, Visualization. **Aarti Shastri:** Investigation, Data Curation, Validation, Writing – Review and Editing. **Ramesh Ingole:** Methodology Support, Formal Analysis, Resources, Writing – Review and Editing. **Jeevan Rajguru:** Supervision, Conceptual Guidance, Review and Editing, Project Administration.

SUMMARY

Gold Nanoparticles (AuNPs) have emerged as versatile tools in drug delivery and bioorthogonal catalysis, owing to their tunable properties such as high stability, biocompatibility and chemical versatility. These nanoparticles are primarily characterized by Self-Assembled Monolayers (SAMs) of organic ligands on their metal cores, which significantly influence their size, shape and surface functionality. These features are essential for determining how AuNPs interact with biological systems, including their uptake, distribution and cytotoxicity. In drug delivery, AuNPs enable precise drug conjugation, controlled release and targeted therapeutic interventions, ensuring more effective treatment outcomes. Additionally, AuNPs play a crucial role in bioorthogonal catalysis, where they facilitate targeted intracellular catalytic reactions, thus enhancing the efficiency of synthetic processes. The integration of supramolecular chemistry with bioorthogonal catalysis offers novel possibilities in drug delivery and therapeutic applications, positioning AuNPs as transformative agents in modern medicine.

REFERENCES

1. Beydoun D, Amal R, Low G, McEvoy S. Role of nanoparticles in photocatalysis. Journal of Nanoparticle Research. 1999;1(4):439-58.
2. Beydoun D, Amal R, Low G, Research SMJ of N, 1999 undefined. Role of nanoparticles in photocatalysis. Springer [Internet]. [cited 2024 Jun 2] 1999;1:439-58. Available from: https://link.springer.com/article/10.1023/A:1010044830871
3. pharmaceutics JKI journal of, 2007 undefined. Nanoparticles-a historical perspective. Elsevier [Internet]. [cited 2024 Jun 2]; Available from: https://www.sciencedirect.com/science/article/pii/S0378517306008878?casa_token=QpFUGy5exxAAAAAA:O3__aH2tLtElya16Icy7KscJ_-ij6IFypXMIoKcLCrR03uWqD9v2bn_B-R74AtRiupYBtHjqtnNhSg
4. Schmid G, WILEY-VCH Verlag GmbH W vch, KGaA C, Schmid C, Parak W, Manna L, *et al.* Nanoparticles-a review. ajol.info [Internet]. [cited 2024 Jun 2]; Available from: https://www.ajol.info/index.php/tjpr/article/view/14634

5. Brust M, Walker M, Bethell D, Schiffrin DJ, Whyman R. Synthesis of thiol-derivatised gold nanoparticles in a two-phase Liquid-Liquid system. J Chem Soc Chem Commun [Internet]. [cited 2024 Jun 2] 1994;0(7):801-2. Available from: https://pubs.rsc.org/en/content/articlelanding/1994/c3/c39940000801
6. reviews RMC, 2008 undefined. Nanoelectrochemistry: metal nanoparticles, nanoelectrodes and nanopores. ACS Publications [Internet]. [cited 2024 Jun 2] 2008;108(7):2688-720. Available from: https://pubs.acs.org/doi/full/10.1021/cr068077e
7. Zhao X, Cai Y, Wang T, Shi Y, Jiang G. Preparation of alkanethiolate-functionalized core/shell Fe 3O4@Au nanoparticles and its interaction with several typical target molecules. Anal Chem. 2008;80(23):9091-6.
8. Sardar R, Funston A, Mulvaney P, Langmuir RM, 2009 undefined. Gold nanoparticles: past, present and future. ACS Publications [Internet]. [cited 2024 Jun 2] 2009;25(24):13840-51. Available from: https://pubs.acs.org/doi/abs/10.1021/la9019475
9. Daraee H, Eatemadi A, Abbasi E, Aval SF, Kouhi M, Akbarzadeh A. Application of gold nanoparticles in biomedical and drug delivery. Artif Cells Nanomed Biotechnol. 2016;44(1):410-22.
10. Mirkin C, Letsinger R, … RMSN, 2020 undefined. A DNA-based method for rationally assembling nanoparticles into macroscopic materials. api.taylorfrancis.comCA Mirkin, RL Letsinger, RC Mucic, JJ StorhoffSpherical Nucleic Acids, 2020•api.taylorfrancis.com [Internet]. [cited 2024 Jun 2]; Available from: https://api.taylorfrancis.com/content/chapters/edit/download?identifierName=doiandidentifierValue=10.1201/9780429200151-2andtype=chapterpdf
11. Zubarev E, Xu J, Society AS… C, 2006 undefined. Amphiphilic gold nanoparticles with V-shaped arms. ACS PublicationsER Zubarev, J Xu, A Sayyad, JD GibsonJournal of the American Chemical Society, 2006•ACS Publications [Internet]. [cited 2024 Jun 2] 2006;128(15):4958-9. Available from: https://pubs.acs.org/doi/abs/10.1021/ja060782h
12. Dhar S, Daniel WL, Giljohann DA, Mirkin CA, Lippard SJ. Polyvalent oligonucleotide gold nanoparticle conjugates as delivery vehicles for platinum (IV) warheads. J Am Chem Soc. 2009;131(41):14652-3.
13. Yang Y, Zhang YM, Chen Y, Zhao D, Chen JT, Liu Y. Construction of a graphene oxide based noncovalent multiple nanosupramolecular assembly as a scaffold for drug delivery. Chemistry-A European Journal. 2012;18(14):4208-15.
14. Caporale A, Adorinni S, Lamba D, Molecules MS, 2021 undefined. Peptide-Protein Interactions: From Drug Design to Supramolecular Biomaterials. mdpi.com [Internet]. [cited 2024 Jun 2]; Available from: https://www.mdpi.com/1420-3049/26/5/1219
15. Kaminskas LM, McLeod VM, Porter CJH, Boyd BJ. Association of chemotherapeutic drugs with dendrimer nanocarriers: An assessment of the merits of covalent conjugation compared to noncovalent encapsulation. Mol Pharm [Internet]. [cited 2025 Jan 16] 2012;9(3):355-73. Available from: https://pubs.acs.org/doi/abs/10.1021/mp2005966
16. Gibson JD, Khanal BP, Zubarev ER. Paclitaxel-functionalized gold nanoparticles. J Am Chem Soc [Internet]. [cited 2025 Jan 16] 2007;129(37):11653-61. Available from: https://pubs.acs.org/doi/abs/10.1021/ja075181k
17. Barata JFB, P.M.S. Neves MG, Lacerda PSS, Conceição P, Trindade T. Quantum dot phthalocyanine non-covalent assemblies - A review. Dyes and Pigments. 2022;198:109931.
18. Ho KW, Liu YL, Liao TY, Liu ES, Cheng TL. Strategies for Non-Covalent Attachment of Antibodies to PEGylated Nanoparticles for Targeted Drug Delivery. Int J Nanomedicine [Internet]. [cited 2025 Jan 16] 2024;19:10045-64. Available from: https://www.tandfonline.com/action/journalInformation?journalCode=dijn20
19. Bauer IA, Dmitrienko E V. Investigating Non-Covalent Interactions of Human Serum Albumin with Doxorubicin and Folic Acid. Biochemistry (Moscow), Supplement Series B: Biomedical Chemistry 2024 18:3 [Internet]. 2024;18(3):231-42. Availablefrom: https://link.springer.com/article/10.1134/S1990750823600413
20. Skopinska-Wisniewska J, … SD la FIJ of, 2021 undefined. From supramolecular hydrogels to multifunctional carriers for biologically active substances. mdpi.com [Internet]. [cited 2024 Jun 2]; Available from: https://www.mdpi.com/1422-0067/22/14/7402
21. Sinawang G, Osaki M, … YTC, 2020 undefined. Supramolecular self-healing materials from non-covalent cross-linking host-guest interactions. pubs.rsc.org [Internet]. [cited 2024 Jun 2]; Available from: https://pubs.rsc.org/en/content/articlehtml/2020/cc/d0cc00672f
22. Huang X, Zhou Y, Ding L, Yu G, Leng Y, Lai W, *et al.* Supramolecular Recognition-Mediated Layer-by-Layer Self-Assembled Gold Nanoparticles for Customized Sensitivity in Paper-Based Strip Nanobiosensors. Small. 2019;15(51).
23. Yang Y, Zhang Y, Chen Y, Journal DZ… -A E, 2012 undefined. Construction of a graphene oxide based noncovalent multiple nanosupramolecular assembly as a scaffold for drug delivery. Wiley Online Library [Internet]. [cited 2024 Jun 2]; Availablefrom: https://chemistry-europe.onlinelibrary.wiley.com/doi/abs/10.1002/chem.201103445
24. Salehi R, Rasouli S, of HHI journal, 2015 undefined. Smart thermo/pH responsive magnetic nanogels for the simultaneous delivery of doxorubicin and methotrexate. Elsevier [Internet]. [cited 2024 Jun 2]; Available from: https://www.sciencedirect.com/science/article/pii/S0378517315003592?casa_token=wU45VZ7e-NgAAAAA:zSf4obS-BfTYsnOXL2f6n2LsO3p50uinSMKYHf3b7xNbdWGezf_YMQMYv5whZmGUKluLOCHEyog
25. Lu B, Li L, Wu J, Wei L, Hou J, Liu Z, *et al.* Synthesis of a dual pH and temperature responsive star triblock copolymer based on β-cyclodextrins for controlled intracellular doxorubicin delivery release. pubs.rsc.org [Internet]. [cited 2024 Jun 2]; Available from: https://pubs.rsc.org/en/content/articlehtml/2016/nj/c6nj01360k
26. Ludden M, Reinhoudt D, Reviews JHCS, 2006 undefined. Molecular printboards: versatile platforms for the creation and positioning of supramolecular assemblies and materials. pubs.rsc.org [Internet]. 2006 [cited 2024 Jun 2]; Available from: https://pubs.rsc.org/en/content/articlehtml/2006/cs/b600093m
27. Xue Q, Liu Z, Guo Y, Bioelectronics SGB and, 2015 undefined. Cyclodextrin functionalized graphene-gold nanoparticle hybrids with strong supramolecular capability for electrochemical thrombin aptasensor. Elsevier [Internet]. [cited 2024 Jun 2]; Available from: https://www.sciencedirect.com/science/article/pii/S0956566315000263?casa_token=j0aYSLNaHk4AAAAA:jOAWe5zKkhJ0bXHaPNNF10CYk84URlfiRlCKbaJjYoxuNo ZPkjvcf1EQETvDtOc4aljLhqlJPgJY2g
28. Villalonga R, Díez P, Eguílaz M, Martínez P, Pingarrón JM. Supramolecular immobilization of xanthine oxidase on electropolymerized matrix of functionalized hybrid gold nanoparticles/single-walled carbon nanotubes for the preparation of electrochemical biosensors. ACS Appl Mater Interfaces. 2012;4(8):4312-9.
29. Daniel M, reviews DAC, 2004 undefined. Gold nanoparticles: assembly, supramolecular chemistry, quantum-size-related properties and applications toward biology, catalysis and nanotechnology. ACS Publications [Internet]. [cited 2024 Jun 2]; Available from: https://pubs.acs.org/doi/full/10.1021/cr030698+
30. Li H, Letters YYCC, 2013 undefined. Gold nanoparticles functionalized with supramolecular macrocycles. Elsevier [Internet]. [cited 2024 Jun 2]; Available from: https://www.sciencedirect.com/science/article/pii/S1001841713002088? casa_token= vc9xcs6IZy4AAAAA:4PbbRhXRpNfpr CStZgzhC3GQ2PXPRob1 HT63VxxuzZL6i3E7b8eP2wGP23oCfDpF04QFOtc6vSPZCg
31. Wu P, Wang J, He C, Zhang X, YWAF, 2012 undefined. Luminescent metal-organic frameworks for selectively sensing nitric oxide in an aqueous solution and in living cells. Wiley Online Library [Internet]. [cited 2024 Jun 2]; Available from: https://onlinelibrary. wiley.com/doi/abs/10.1002/adfm. 201102157
32. Velázquez-Campoy A, Ohtaka H, Nezami A, Muzammil S, Freire E. Isothermal Titration Calorimetry. Curr Protoc Cell Biol [Internet]. [cited 2025 Jan 16] 2004;23(1):17.8.1-17.8.24. Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/0471143030.cb1708s23
33. Urban PL. Quantitative mass spectrometry: an overview. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences [Internet]. [cited 2025 Jan 16] 2016;374(2079). Available from: https://royalsocietypublishing.org/doi/10.1098/rsta.2015.0382
34. Silina YE, Volmer DA. Nanostructured solid substrates for efficient laser desorption/ionization mass spectrometry (LDI-MS) of low molecular weight compounds. Analyst [Internet]. [cited 2025 Jan 16] 2013;138(23):7053-65. Available from: https://pubs.rsc.org/en/content/articlehtml/2013/an/c3an01120h
35. Royer CA. Fluorescence Spectroscopy. Methods Mol Biol [Internet]. 1995;40:65-89. Available from: https://link.springer.com/protocol/10.1385/0-89603-301-5:65
36. Hatzakis E. Nuclear Magnetic Resonance (NMR) Spectroscopy in Food Science: A Comprehensive Review. Compr Rev Food Sci Food Saf [Internet]. 2019;18(1):189-220. Available from: https://onlinelibrary.wiley.com/doi/full/10.1111/1541-4337.12408
37. Ghai R, Falconer RJ, Collins BM. Applications of isothermal titration calorimetry in pure and applied research-survey of the literature from 2010. Journal of Molecular Recognition. 2012;25(1):32-52.
38. Velázquez-Campoy A, Ohtaka H, Nezami A, Muzammil S, Freire E. Isothermal titration calorimetry. Current protocols in cell biology / editorial board, Juan S Bonifacino., *et al*. 2004; Chapter 17.
39. Yan B, Yesilbag Tonga G, Hou S, Fedick PW, Yeh YC, Alfonso FS, *et al.* Mass spectrometric detection of nanoparticle host-guest interactions in cells. Anal Chem. 2014;86(13):6710-4.
40. Lee HHL, Kim HI. Supramolecular Analysis of Monosaccharide Derivatives Using Cucurbit[7]uril and Electrospray Ionization Tandem Mass Spectrometry. Isr J Chem. 2018;58(3):472-8.
41. Chen W, Yu H, Hao Y, Liu W, Wang R, Huang Y, *et al.* Comprehensive Metabolic Fingerprints Characterize Neuromyelitis Optica Spectrum Disorder by Nanoparticle-Enhanced Laser Desorption/Ionization Mass Spectrometry. ACS Nano. 2023;17(20):19779-92.
42. Wang Y, Liu Y, Yang S, Yi J, Xu X, Zhang K, *et al.* Host-Guest Self-Assembled Interfacial Nanoarrays for Precise Metabolic Profiling. Small. 2023;19(51).
43. Yan B, Yesilbag Tonga G, Hou S, Fedick PW, Yeh YC, Alfonso FS, *et al.* Mass spectrometric detection of nanoparticle host-guest interactions in cells. Anal Chem. 2014;86(13):6710-4.
44. Liang T, Chen Z, Li H, Chemistry ZGT in, 2022 undefined. Bioorthogonal catalysis for biomedical applications. cell.com [Internet]. [cited 2024 Jun 2]; Available from: https://www.cell.com/trends/chemistry/fulltext/S2589-5974(21)00262-8
45. Völker T, Dempwolff F, Graumann PL, Meggers E. Progress towards bioorthogonal catalysis with organometallic compounds. Angew Chem Int Ed Engl. 2014;53(39):10536-40.
46. Baskin JM, Prescher JA, Laughlin ST, Agard NJ, Chang P V., Miller IA, *et al.* Copper-free click chemistry for dynamic *in vivo* imaging. Proc Natl Acad Sci U S A. 2007;104(43):16793-7.

47. Jewett JC, Bertozzi CR. Synthesis of a fluorogenic cyclooctyne activated by Cu-free click chemistry. Org Lett. 2011;13(22):5937-9.
48. Klein K, Loza K, Heggen M, Epple M. An Efficient Method for Covalent Surface Functionalization of Ultrasmall Metallic Nanoparticles by Surface Azidation Followed by Copper-Catalyzed Azide-Alkyne Cycloaddition (Click Chemistry). ChemNanoMat. 2021;7(12):1330-9.
49. Librando I, Mahmoud A, Catalysts SC, 2021 undefined. Heterogeneous gold nanoparticle-based catalysts for the synthesis of click-derived triazoles via the azide-alkyne cycloaddition reaction. mdpi.com [Internet]. [cited 2024 Jun 2]; Available from: https://www.mdpi.com/2073-4344/12/1/45
50. Liu Y, Bai Y. Design and Engineering of Metal Catalysts for Bio-orthogonal Catalysis in Living Systems. ACS Appl Bio Mater. 2020;3(8):4717-46.
51. Lewis JC. Beyond the Second Coordination Sphere: Engineering Dirhodium Artificial Metalloenzymes to Enable Protein Control of Transition Metal Catalysis. Acc Chem Res. 2019;52(3):576-84.
52. Tonga G, Jeong Y, Duncan B, Mizuhara T, … RMN, 2015 undefined. Supramolecular regulation of bioorthogonal catalysis in cells using nanoparticle-embedded transition metal catalysts. nature.com [Internet]. [cited 2024 Jun 2]; Available from: https://www.nature.com/articles/nchem.2284
53. Bao CJ, Duan JL, Xie Y, Feng XP, Cui W, Chen SY, *et al.* Bioorthogonal Engineered Virus-Like Nanoparticles for Efficient Gene Therapy. Nanomicro Lett. 2023;15(1).
54. Algar WR, Prasuhn DE, Stewart MH, Jennings TL, Blanco-Canosa JB, Dawson PE, *et al.* The controlled display of biomolecules on nanoparticles: A challenge suited to bioorthogonal chemistry. Bioconjug Chem. 2011;22(5):825-58.
55. Min Y, Axet M, Catalysis PSRA in N, 2020 undefined. Covalent Assemblies of Metal Nanoparticles-Strategies for Synthesis and Catalytic Applications. Springer [Internet]. [cited 2024 Jun 2]; Available from: https://link.springer.com/chapter/10.1007/978-3-030-45823-2_5
56. Carnerero J, Jimenez-Ruiz A, … PC, 2017 undefined. Covalent and Non-Covalent DNA-Gold-Nanoparticle Interactions: New Avenues of Research. Wiley Online Library [Internet]. [cited 2024 Jun 2]; Available from: https://chemistry-europe.onlinelibrary.wiley.com/doi/abs/10.1002/cphc.201601077
57. Ertem E, Diez-Castellnou M, Ong QK, Stellacci F. Novel Sensing Strategies Based on Monolayer Protected Gold Nanoparticles for the Detection of Metal Ions and Small Molecules. Chemical Record. 2018;18(7):819-28.
58. Min Y, Axet MR, Serp P. Covalent Assemblies of Metal Nanoparticles-Strategies for Synthesis and Catalytic Applications. 2020; 129-97.
59. Carnerero JM, Jimenez-Ruiz A, Castillo PM, Prado-Gotor R. Covalent and Non-Covalent DNA-Gold-Nanoparticle Interactions: New Avenues of Research. ChemPhysChem. 2017;18(1):17-33.
60. US9234078B2-Conjugated gold nanoparticles-Google Patents [Internet]. [cited 2025 Jan 16]. Available from: https://patents.google.com/patent/US9234078B2/en
61. Khoobchandani M. Ayurvedic encapsulated gold nanoparticles, fabrication methods and cancer therapeutic methods. 2018.
62. Raghuraman. Methods and articles for gold nanoparticle production. 2005;
63. US9587071B2-Conjugated gold nanoparticles-Google Patents [Internet]. [cited 2025 Jan 16]. Available from: https://patents.google.com/patent/US9587071B2/en?oq=US9587071B2
64. US10016495B2-Oil-in-water emulsion influenza vaccine-Google Patents [Internet]. [cited 2025 Jan 16]. Available from: https://patents.google.com/ patent/US10016495B2/en?oq=US10016495B2

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