Gold And Sliver Nanoparticles In Antimicrobial And Anti-Cancer Therapies

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Abstract: Gold and silver nanoparticles have emerged as powerful nanoparticles in modern medicine due to their unique physicochemical, optical, and properties. In antimicrobial therapy, they excited strong bactericidal and fungicidal activities by disrupting microbial membranes, generating reactive oxygen species, and interfering with essential cellular processes, therapy overcoming resistance mechanism of conventional antibiotics. In cancer therapeutics, both gold and silver nanoparticles demonstrate selective cytotoxicity against tumor cell, inducing apoptosis, inhibiting proliferation, and enhancing drug delivery through functionalization with targeting ligands. Moreover, green synthesis approaches enhance their stability, biocompatibility, and eco-friendly, making them highly suitable for biomedical applications.

Keywords: Gold Nanoparticles, Silver nanoparticles, Antimicrobial activity, Anti-cancer activities

1. Introduction

Nanotechnology refers to the engineering and modification of substances at a nanoscale range (1–100 nm), where materials exhibit exceptional biological and physicochemical behavior because of their increased surface area and quantum-related effects. Among various nanostructures, nanoparticles are the most widely studied due to their extensive applications in electronics, catalysis, and medicine. In biomedical research, metallic nanoparticles, especially gold (AuNPs) and silver nanoparticles (AgNPs), have gained significant attention due to their stability, ease of synthesis, and strong antimicrobial as well as anticancer potential. Gold nanoparticles are extremely small particles of gold that possess distinctive chemical and optical properties, making them beneficial in imaging, diagnostics, and therapeutic applications. Similarly, silver nanoparticles are nanosized particles composed of silver with exceptional antimicrobial action, enabling their use in medicine, textiles, coatings, and biosensing. Gold nanoparticles demonstrate remarkable physicochemical behaviour that enhances their suitability for medical applications. Their antimicrobial effect is attributed to the disruption of microbial cellular structures and metabolic functions, while anticancer activity results from induction of oxidative stress, apoptosis, and the capability for drug delivery. Various synthesis techniques are available to produce AuNPs with high yield under controlled physical and biological conditions. Although radiotherapy remains an established cancer treatment, its effectiveness is limited by tissue toxicity and damage to healthy cells. Plant-derived gold nanoparticles have shown promising anticancer potential, offering a safer and more efficient approach. This review highlights the synthesis methods, mechanisms of action, therapeutic benefits, and future opportunities of plant-mediated AuNPs in cancer management.

Silver nanoparticles (AgNPs) are widely recognized as one of the most extensively investigated nanomaterials due to their exceptional antimicrobial and anticancer capabilities, along with their distinct physicochemical characteristics and broad biomedical applications. Their nanoscale dimensions, high surface area-to-volume ratio, and strong interaction with biological systems contribute to their enhanced therapeutic performance. In antimicrobial applications, AgNPs demonstrate broad-spectrum efficacy against bacteria, fungi, and viruses through multiple mechanisms, including membrane disruption, production of reactive oxygen species (ROS), genetic damage, and inhibition of biofilm development. Notably, their activity against drug-resistant pathogens highlights their potential role as an alternative or supportive approach to conventional antibiotics. In cancer therapy, AgNPs promote cytotoxicity in cancer cells by inducing oxidative stress, apoptosis, mitochondrial dysfunction, and DNA fragmentation. Additionally, they serve as effective nanocarriers for controlled and targeted drug delivery, thereby improving the therapeutic index of chemotherapeutic drugs while reducing unwanted systemic toxicity. Their ability to be integrated into advanced therapeutic approaches such as photodynamic and photothermal therapy further strengthens their role in cancer management.

2. Characterization of AgNPs and AuNPs

Proper characterization of silver nanoparticles (AgNPs) and gold nanoparticles (AuNPs) is crucial to verify their physicochemical behaviour and relate these characteristics to their antimicrobial and anticancer performance. UV–Visible spectroscopy is one of the most commonly used analytical methods for monitoring nanoparticle synthesis, as it detects surface plasmon resonance (SPR) bands, which generally appear around ~400 nm for AgNPs and between 500–550 nm for AuNPs depending on morphology and particle size. Particle size distribution, colloidal behavior, and surface charge are analyzed using dynamic light scattering (DLS) and zeta potential measurements, where nanoparticles exhibiting an absolute zeta potential value greater than ±30 mV are considered highly stable with minimal aggregation risk.

Microscopic techniques such as transmission electron microscopy (TEM) and scanning electron microscopy (SEM) provide detailed insights into particle size, dispersion, and morphology. High-resolution TEM (HRTEM) combined with selected area electron diffraction (SAED) can further confirm crystalline patterns and lattice structures. X-ray diffraction (XRD) analysis is also widely employed to determine the crystalline nature and phase purity of synthesized nanoparticles. Functional group identification and surface chemistry evaluation—especially relevant in green synthesis—can be performed using Fourier transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS). Furthermore, elemental confirmation is achieved through energy dispersive X-ray spectroscopy (EDX), typically coupled with SEM or TEM. These integrated analytical approaches provide comprehensive characterization, enabling proper correlation between physicochemical features, biological interaction, and therapeutic efficacy of synthesized nanoparticles.

3. Synthesis of AgNPs and AuNPs nanoparticles

Silver nanoparticles (AgNPs) and gold nanoparticles (AuNPs) can be synthesized using multiple strategies including physical, chemical, and biological methods, with each technique selected depending on the required application and properties. Among these, chemical reduction is the most commonly applied method, where precursors such as silver nitrate ($AgNO_3$) or chloroauric acid ($HAuCl_4$) are reduced in the presence of reducing and stabilizing agents, such as sodium borohydride, trisodium citrate, or ascorbic acid, to regulate the particle dimension, uniformity, and shape. Physical approaches—such as laser ablation, evaporation–condensation, and microwave-assisted synthesis—produce high-purity nanoparticles; however, they often demand advanced instrumentation and higher operational energy. Recently, biological or green synthesis has become a preferred approach due to its environmentally friendly, safe, and economical nature. In this method, plant extracts, microorganisms, biopolymers, and natural biomolecules function simultaneously as reducing and capping agents, eliminating the need for hazardous chemicals. Plant-based synthesis is especially beneficial since phytoconstituents like flavonoids, phenolic compounds, tannins, terpenoids, and alkaloids contribute to the reduction and stabilization of both AuNPs and AgNPs, while improving their biological potential. Several experimental parameters—including temperature, pH level, precursor concentration, and reaction duration significantly influence nanoparticle yield, stability, and morphology.

4. Antimicrobial Application

I. Drug Delivery: Gold and silver nanoparticles can act as nanocarriers for antibiotics and other antimicrobial agents. Their large surface area and tunable surface chemistry allow drugs to be conjugated, adsorbed, or encapsulated. This enhances targeted delivery, ensuring that the antimicrobial drug reaches the infection site with higher efficiency and reduced systemic toxicity. In addition, nanoparticles help overcome drug resistance by facilitating the penetration of antibiotics into bacterial biofilms and resistant strains. For example, AgNP–antibiotic conjugates have shown synergistic effects against E. coli and Staphylococcus aureus, where the nanoparticles disrupt the bacterial membrane while the antibiotic inhibits intracellular processes, leading to improved therapeutic outcomes.

II. Theranostics (Combined Therapy and Diagnostics): Gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs) are gaining prominence in theranostic systems, where diagnostic and therapeutic functions are integrated into a single platform. Owing to their strong surface plasmon resonance characteristics, AuNPs are widely applied in biosensing and medical imaging to detect microbial components such as DNA, proteins, and metabolic biomarkers. When these nanoparticles are conjugated with antimicrobial molecules, they enable both rapid detection and targeted treatment at the same time. This dual capability is especially valuable for managing infections caused by multidrug-resistant pathogens, allowing early diagnosis and immediate therapeutic intervention. For example, colorimetric biosensors utilizing AuNPs can identify pathogens within a short time, while the same nanoparticles—when functionalized with antibiotics or bioactive peptides—deliver targeted antimicrobial effects against the identified organism.

III. Photocatalysis:Gold (AuNPs) and silver nanoparticles (AgNPs) also function as effective photocatalysts, producing reactive oxygen species (ROS) upon exposure to ultraviolet or visible light. These ROS—including hydroxyl radicals and superoxide ions—cause severe molecular and structural damage to microbial proteins, DNA, and cell membranes, resulting in quick microbial destruction. AgNPs demonstrate strong photocatalytic antimicrobial efficiency, making them suitable for applications such as water treatment, antimicrobial coatings, and sterilization systems in healthcare environments. Likewise, when AuNPs are incorporated with semiconductor materials such as TiO_2, their photocatalytic performance improves significantly under visible light, providing a greener and energy-efficient method for microbial removal. This light-responsive antimicrobial feature makes both types of nanoparticles valuable in environmental sanitation as well as clinical settings where controlled light activation is advantageous.

5. Anticancer application

i. Targeted Drug Delivery: Gold and silver nanoparticles can be modified with targeting molecules such as ligands, peptides, and antibiotics to specifically recognize and bind to cancer cells. These functionalized nanoparticles enhance drug solubility, stability, and controlled release, which helps minimize toxicity to healthy tissues. For example, gold nanoparticles conjugated with chemotherapeutic drugs such as doxorubicin or paclitaxel demonstrate improved accumulation at tumor sites through the enhanced permeability and retention (EPR) effect.

ii. Photothermal Therapy:Gold nanoparticles particularly nanostructures such as nanorods, nanoshells, and nanocageshave the ability to absorb near-infrared (NIR) light and convert it into heat, selectively inducing thermal damage to cancer cells while minimizing harm to surrounding healthy tissues. Although silver nanoparticles are also capable of photothermal activity, their application in this field is comparatively less explored than AuNPs.

iii. Photodynamic Therapy (PDT): Both AuNPs and AgNPs can be used as carriers for photosensitizing agents. Upon light exposure, these systems generate reactive oxygen species (ROS), which trigger apoptosis and cellular destruction in cancer cells, offering a minimally invasive therapeutic strategy.

iv. Radiosensitization: Gold nanoparticles possess a high atomic number ($Z = 79$), enabling them to enhance the local radiation dose during radiotherapy. When combined with gamma rays or X-ray exposure, AuNPs significantly increase DNA damage within tumor cells, improving radiotherapeutic outcomes.

v. Anti-Angiogenesis: Silver nanoparticles exhibit strong anti-angiogenic effects by downregulating vascular endothelial growth factor (VEGF) signaling pathways, thereby restricting the formation of new blood vessels that supply nutrients to tumors. This inhibition limits cancer cell growth and metastasis.

vi. Intrinsic Cytotoxicity: Silver nanoparticles can release Ag^+ ions, which induce oxidative stress, mitochondrial disruption, and DNA damage in cancer cells, resulting in inherent cytotoxicity. Gold nanoparticles, although generally biocompatible, can be engineered with cytotoxic or therapeutic agents to enhance anticancer activity.

6. Mechanism of antimicrobial in AgNPs AuNPs

Cell Membrane Disruption and Increased Permeability Nanoparticles: Silver nanoparticles (AgNPs) exhibit antimicrobial activity mainly by disrupting bacterial membranes. Their positive charge allows them to bind with negatively charged cell surfaces, weakening structural integrity. AgNPs also interact with phosphate groups in phospholipids, disturbing the lipid bilayer and reducing membrane stability. Due to their small size and high surface area, they easily penetrate membranes, altering fluidity, increasing permeability, and causing leakage of intracellular contents. Coated AgNPs, such as those modified with SDS, further enhance these effects by deeply penetrating bacterial membranes and inducing complete rupture.

AgNPs against biofilm: Biofilm formation begins with bacterial adhesion to surfaces, but treatment with silver nanoparticles (AgNPs) prevents this attachment, thereby inhibiting the development of biofilm communities. AgNPs neutralize adhesive substances required for biofilm formation and can also disrupt the bacterial actin cytoskeleton. This disruption alters the structural protein MreB, causing morphological changes, increasing membrane fluidity, and eventually leading to membrane rupture. Accumulation of AgNPs on the bacterial surface further compromises the bilayer, resulting in cell damage. In addition to surface effects, AgNPs can penetrate bacterial cells and interact directly with essential organelles and enzymes. Silver ions inactivate respiratory enzymes by binding to thiol and disulfide groups, while also stimulating the generation of reactive oxygen species (ROS).

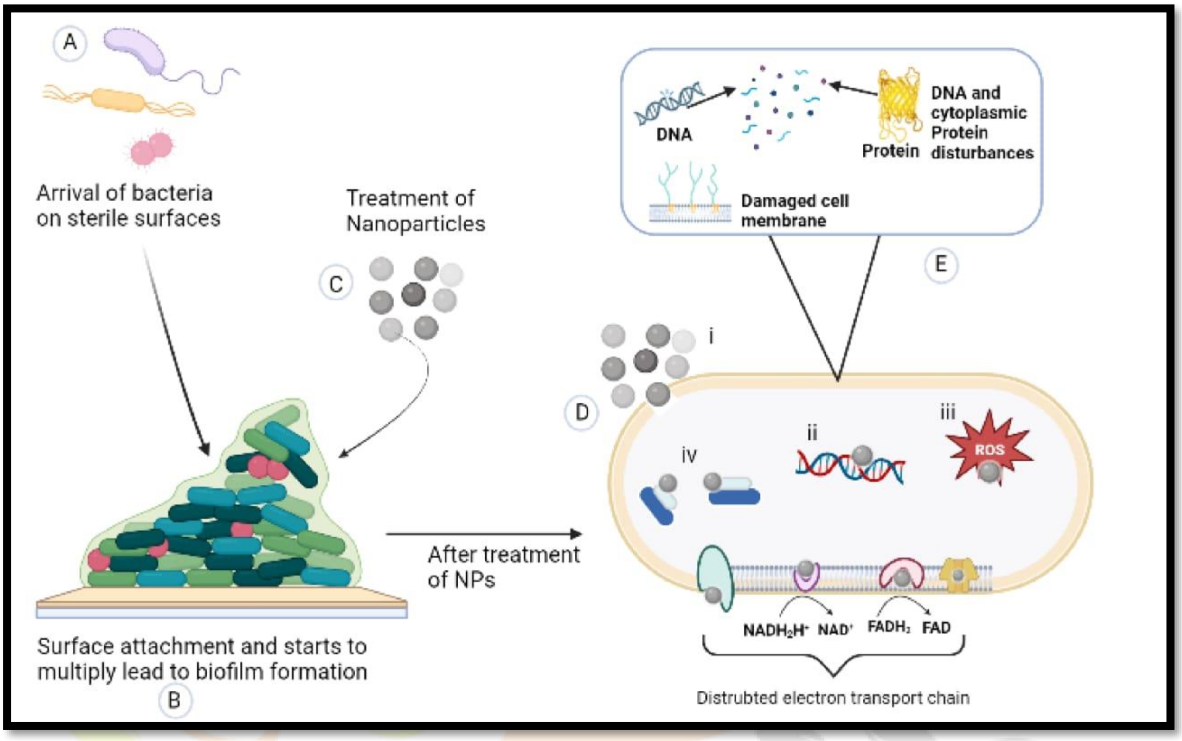

Figure 1 : The Activity of AgNPs in Biofilm

Cell damage: Silver nanoparticles (AgNPs) can penetrate bacterial cells and interact directly with genetic material, leading to DNA damage that contributes to their antimicrobial effect. Once inside the cytoplasm, AgNPs and released Ag^+ ions bind to negatively charged phosphate groups in the DNA backbone, destabilizing the double helix and interfering with replication and transcription. In addition, the strong affinity of silver for nitrogen and sulfur atoms allows it to interact with DNA bases, causing structural distortion and strand breaks. AgNPs also generate reactive oxygen species (ROS), which oxidize nucleic acids and induce mutations, cross-linking, or fragmentation of DNA strands. Together, these interactions impair genetic integrity, block protein synthesis, and inhibit cell division, ultimately resulting in bacterial death.

Cell membrane Interaction and Distribution: Gold nanoparticles (AuNPs) exhibit strong affinity toward the bacterial cell wall due to electrostatic attraction. When they adhere to the membrane surface, they disturb the structural integrity of the lipid bilayer. This interaction alters membrane fluidity and permeability, leading to leakage of essential ions and intracellular components. In addition, smaller nanoparticles can penetrate directly through the cell envelope, further intensifying damage to the membrane system. The overall effect results in loss of membrane potential, impaired transport processes, and eventual bacterial cell death.

Protein Binding and Enzyme Inhibition: Gold nanoparticles have a high affinity for sulfur-containing groups, especially thiols (-SH) present in bacterial proteins and enzymes. When AuNPs attach to these groups, they disturb protein folding and stability, which causes conformational changes or complete denaturation. This structural alteration results in the loss of enzymatic activity. For example, the inhibition of ATP synthase reduces ATP production, ultimately leading to energy depletion in the bacterial cell. In addition, disruption of other thiol-containing enzymes can block electron transport, interfere with nutrient metabolism, and suppress redox homeostasis. Collectively, these effects compromise vital cellular processes and accelerate microbial cell death.

Generation of reactive oxygen species: Gold nanoparticles can stimulate the form.ation of reactive oxygen species within bacterial cells. The excessive build-up of ROS disrupts the redox balance, creating oxidative stress. These reactive molecules attack and damage vital biomolecules such as nucleic acids, structural and functional proteins, and membrane lipids. The resulting cellular injury compromises metabolic integrity and can trigger apoptosis-like responses or direct necrotic death of the microbial cell.

7. Mechanism of Anticancer in AgNPs AuNPs

Generation of Reactive Oxygen Species (ROS): Silver nanoparticles (AgNPs) induce excessive ROS in cancer cells, leading to oxidative stress. This damages cellular macromolecules such as DNA, lipids, and proteins, which results in mitochondrial dysfunction, cell cycle arrest, and activation of apoptotic signaling. ROS also reduce angiogenesis by suppressing VEGF and inhibit metastasis by lowering MMP activity. Additionally, AgNPs enhance the sensitivity of cancer cells to chemo- and radiotherapy by weakening antioxidant defense systems.

Mitochondrial Damage: AgNPs disrupt mitochondrial integrity by increasing ROS levels, damaging mitochondrial components, and causing loss of membrane potential. This triggers the release of apoptotic factors like cytochrome-c and AIF, activating caspases and leading to programmed cell death. Disrupted calcium balance and reduced ATP synthesis further accelerate cell damage.

DNA and Cellular Interference: Inside cancer cells, AgNPs release Ag^{+} ions and generate ROS, causing DNA strand breaks and impairing repair pathways. This genomic damage, combined with mitochondrial dysfunction, triggers intrinsic apoptosis through caspase activation.

Programmed Cell Death Pathways: AgNPs trigger multiple cell death mechanisms depending on concentration and cell type. Besides apoptosis, they can induce necrosis (due to ATP depletion), autophagy (via mTOR/AMPK regulation), necroptosis, and pyroptosis through inflammasome activation.

Cell Cycle Arrest: DNA damage and oxidative stress caused by AgNPs activate checkpoints regulated by proteins like p53 and p21. Cells are commonly arrested at G2/M or sub-G1 phases. If damage is irreversible, apoptotic pathways are triggered to prevent survival of defective cells.

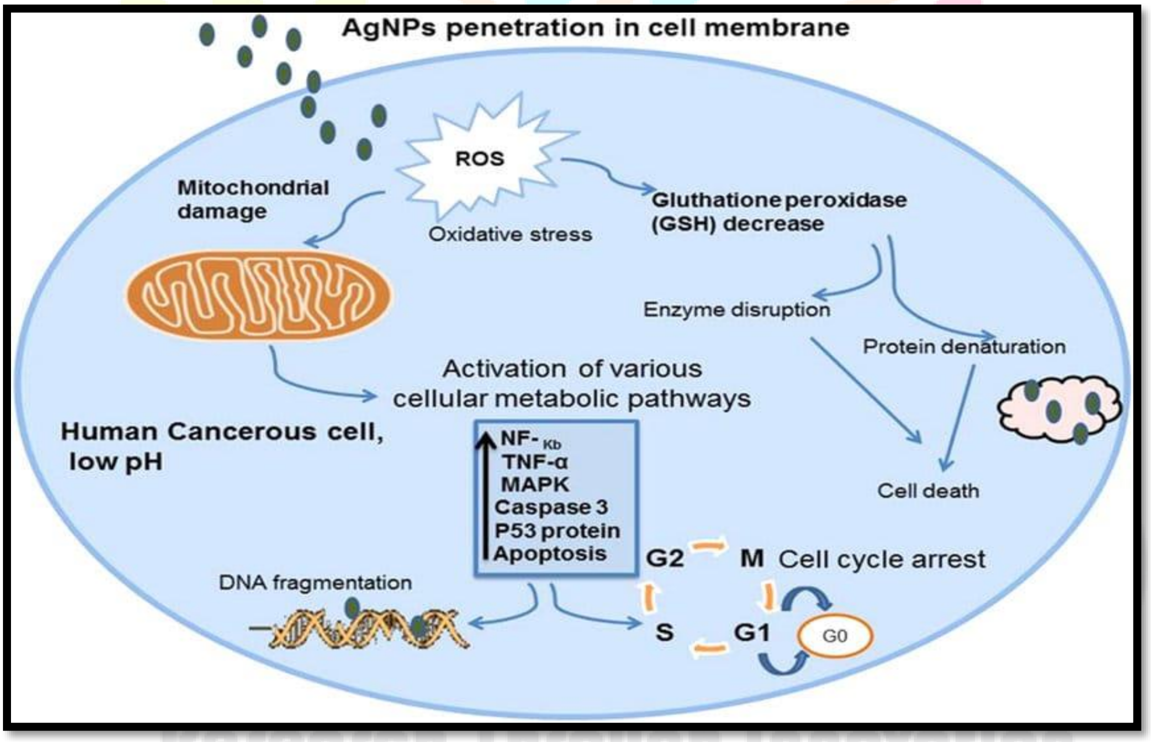

Figure 2 : Mechanism of Anticancer in AgNPs

Photothermal therapy (PTT): Photothermal therapy (PTT) using gold nanoparticles (AuNPs) works by exploiting their unique surface plasmon resonance properties, which allow them to absorb near-infrared (NIR) light and efficiently convert it into heat. When AuNPs accumulate in tumor tissues via the enhanced permeability and retention (EPR) effect or through ligand-based targeting, NIR laser irradiation generates localized hyperthermia (42–48 °C) around cancer cells. This elevated temperature causes protein denaturation, disruption of cell membranes, mitochondrial and lysosomal damage, and DNA injury, ultimately leading to apoptosis or necrosis. In addition to direct tumor ablation, the release of tumor antigens during cell death can stimulate anti-tumor immune responses, making AuNP-mediated PTT a highly selective and minimally invasive anticancer strategy.

Radiosensitization: Gold nanoparticles (AuNPs) act as potent radiosensitizers due to their unique physical, chemical, and biological interactions with ionizing radiation. Firstly, at the physical level, gold has a high atomic number (Z = 79) and strong photoelectric absorption coefficient, which enhances local energy deposition when exposed to X-rays or gamma rays. In addition, AuNPs can modify the tumor microenvironment by increasing oxygenation and reducing hypoxia, thereby overcoming one of the major limitations of radiotherapy. Recent studies also indicate that the immunogenic cell death triggered by radiation in the presence of AuNPs can release tumor-associated antigens, promoting an anti-tumor immune response. Taken together, these combined physical dose enhancement, ROS-mediated chemical damage, and biological interference with repair and survival pathways make AuNPs highly effective radiosensitizers. They allow for improved tumor control at lower radiation doses, thereby minimizing collateral damage to surrounding healthy tissues.

Drug Delivery and Targeted Therapy: Gold nanoparticles (AuNPs) enhance cancer therapy through multiple mechanisms. Their nanoscale size allows them to preferentially accumulate in tumor tissues via the enhanced permeability and retention (EPR) effect, increasing localized drug concentration. The surfaces of AuNPs can be functionalized with ligands such as antibodies, peptides, or small molecules, enabling precise targeting of cancer cell receptors. They can also be engineered for controlled drug release in response to stimuli like pH or temperature, ensuring that therapeutic agents act specifically at the tumor siteBeyond single-drug delivery, AuNPs are also valuable in combination therapies, as they can carry chemotherapeutic agents alongside modalities like radiotherapy, photothermal therapy, or photodynamic therapy, thereby enhancing overall treatment efficacy, overcoming drug resistance, and potentially stimulating anti-tumor immune responses. Collectively, these properties make gold nanoparticles highly effective as multifunctional platforms for advanced and targeted cancer therapy.

Apoptosis: Gold nanoparticles (AuNPs) exert strong anticancer effects by inducing apoptosis through multiple interconnected pathways. Their interaction with tumor cells leads to excessive generation of reactive oxygen species (ROS), which cause oxidative stress, DNA damage, and lipid and protein oxidation, thereby activating cell death signals. The intrinsic (mitochondrial) pathway is prominently involved, where ROS disrupt mitochondrial membrane potential and increase the Bax/Bcl-2 ratio, resulting in cytochrome c release into the cytosol.

8. Gold Nanoparticles Used in Cancer Therapy

Photothermal Therapy (PTT): Photothermal therapy uses gold nanoparticles (AuNPs) to selectively destroy cancer cells by converting near-infrared (NIR) light into heat. After administration, AuNPs accumulate in tumors through the Enhanced Permeability and Retention (EPR) effect and may also be surface-modified with targeting ligands to improve cancer-cell specificity. When exposed to NIR light (650–900 nm), AuNPs absorb the energy due to Surface Plasmon Resonance (SPR) and rapidly convert it into heat, increasing the local temperature to approximately 40–45°C. This controlled hyperthermia disrupts membrane integrity, denatures proteins, damages mitochondria, and causes DNA fragmentation, leading to apoptosis or necrosis. Because heating occurs only where nanoparticles are present, surrounding healthy tissue remains unaffected, making PTT a precise and minimally invasive cancer treatment.

Drug Delivery System (Chemotherapy): Gold nanoparticles act as efficient drug carriers for anticancer agents such as doxorubicin, paclitaxel, and cisplatin. Their nanoscale size enables selective tumor accumulation via the EPR effect, reducing systemic toxicity. Surface functionalization with ligands allows active targeting of cancer-specific receptors, improving drug uptake by tumor cells. AuNPs also enable controlled and stimuli-responsive drug release, triggered by pH changes, heat, or NIR light. They can deliver multiple therapeutic molecules simultaneously and help overcome drug resistance by improving intracellular drug retention. Overall, AuNP-based drug delivery enhances bioavailability, tumor selectivity, and therapeutic efficiency compared to conventional chemotherapy.

Immunotherapy: Cancer immunotherapy aims to activate or restore the body's immune system to eliminate tumor cells. Strategies include immune checkpoint inhibition, cytokine therapy, adoptive cell therapy, monoclonal antibodies, and oncolytic viruses. Immune activation is further enhanced by recognition of damage-associated molecular patterns (DAMPs) released from stressed or dying tumor cells. Gold nanoparticles are emerging as promising platforms in this field due to their tunable size, biocompatibility, and ability to deliver antigens, antibodies, cytokines, and other immune-modulating agents. By improving targeted delivery and enhancing immune activation, AuNPs support stronger and more controlled anti-tumor immune responses with minimal off-target effects.

Photodynamic therapy: Photodynamic therapy is a cancer treatment that relies on the combined action of light, oxygen, and photosensitizing agents. In this method, photosensitizers are delivered into the bloodstream and tend to accumulate selectively in tumor tissues due to their natural targeting properties. Once the tumor has absorbed a sufficient amount of the photosensitizer, the area is exposed to light of a particular wavelength. This activates the photosensitizer, which transfers energy to the surrounding oxygen, producing reactive species that can damage and destroy cancer cells. Gold nanoparticles, especially in smaller sizes, have been investigated as carriers to improve the delivery and accumulation of photosensitizers in tumors. One of the unique advantages of gold nanoparticles is their capacity to support both photodynamic and photothermal therapy simultaneously. For example, methylene blue loaded onto mesoporous silica-coated gold nanoparticles has been used in dual therapy approaches, combining the effects of light-induced toxicity and heat generation to achieve enhanced anticancer outcomes. This synergistic approach has shown promising results in increasing the effectiveness of cancer treatment.

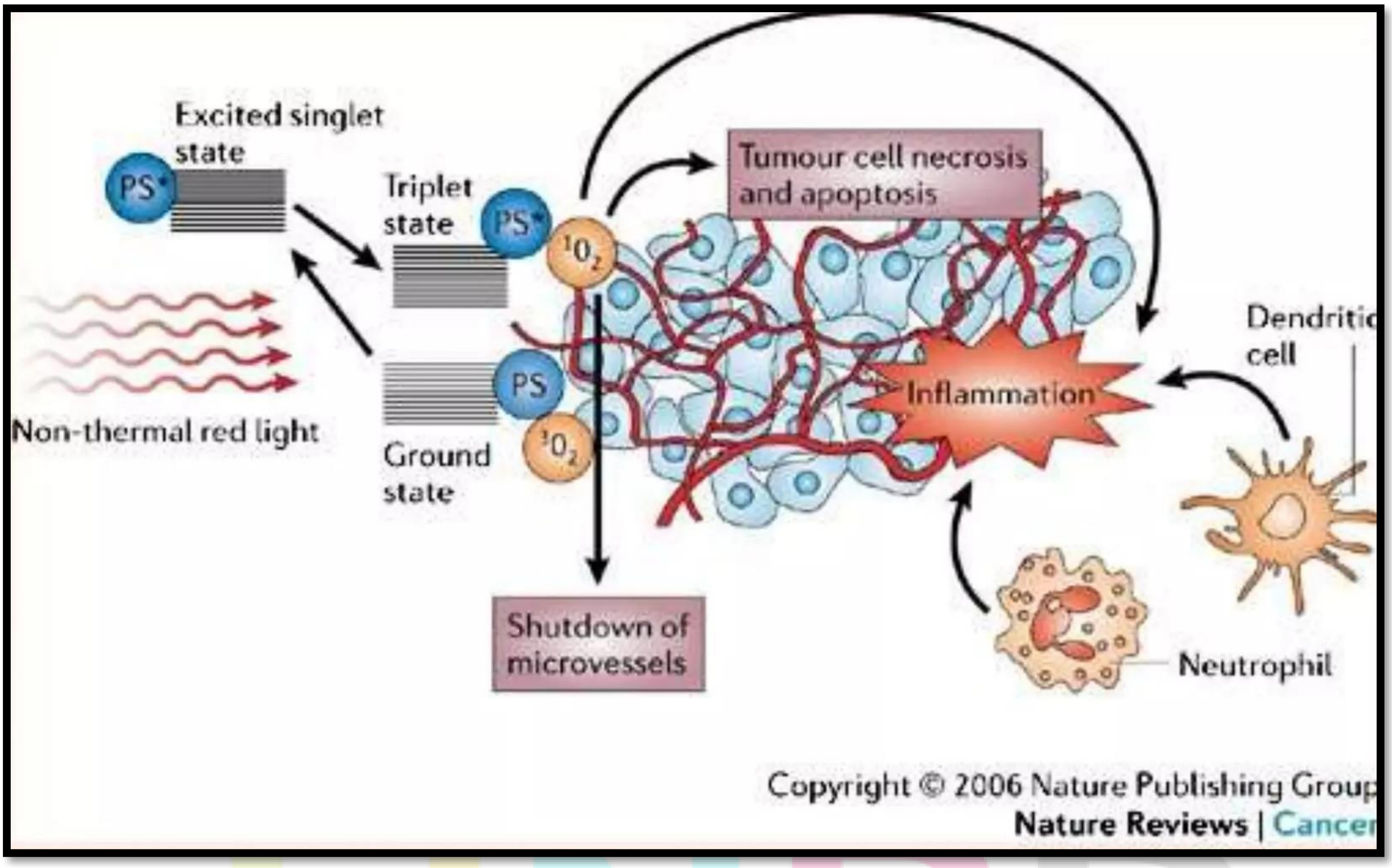

Figure 3 : Photodynamic therapy

9. Summary

Gold and silver nanoparticles (AuNPs and AgNPs) have gained significant attention in modern biomedical research due to their unique physicochemical, optical, and biological properties. Their nanoscale size, high surface-to-volume ratio, and ability to interact with biomolecules make them versatile candidates in antimicrobial and anticancer therapies. Antimicrobial activity: Both AuNPs and AgNPs exhibit broad-spectrum action against bacteria, fungi, and viruses. AgNPs mainly disrupt microbial membranes, generate reactive oxygen species (ROS), inactivate proteins, and damage DNA, making them highly effective even against multidrug-resistant pathogens. AuNPs, meanwhile, interfere with bacterial membranes, inhibit enzymes, induce ROS, and enhance the action of conventional antibiotics. Anticancer activity: AgNPs induce oxidative stress, mitochondrial dysfunction, DNA damage, and cell cycle arrest, leading to apoptosis, necrosis, or autophagy in cancer cells. AuNPs act through targeted drug delivery, radiosensitization, photothermal and photodynamic therapy, and induction of apoptosis. They are also being explored for immunotherapy and gene therapy applications.

9. Conclusion

Gold and silver nanoparticles represent powerful nanomedicine platforms with dual antimicrobial and anticancer potential. Their ability to selectively target pathogens and tumor cells while sparing healthy tissues, coupled with multifunctional applications in diagnostics and therapy, highlights their role as next-generation therapeutic agents. However, challenges such as cytotoxicity, long-term safety, and regulatory concerns must be addressed before large-scale clinical use. With advancements in green synthesis, surface modification, and nanocarrier design, AuNPs and AgNPs hold great promise for safer, more effective, and eco-friendly alternatives to conventional antimicrobial and anticancer treatments.

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